1/2021

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ELEMENTS

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An issue about the circular economy

The Circular Economy

Systematic recycling

The term "circular economy" refers to an organizational model of production and utilization in which the materials and energy that are used are continuously recycled—for example, through durable design, optimal maintenance, and recycling. The objective is to lengthen the life cycle of products, prevent waste, and reduce energy consumption. The counterpart of this model is the "linear economy," which has largely prevailed in Western societies as a result of industrialization and has characterized them down to the present day. The circular economy has attracted increasing attention in recent decades. For example, in the 1990s researchers such as David W. Pearce and Michael Braungart developed a variety of circular systems in response to the challenges posed by climate change.

The linear economy A model of economic organization in which raw materials are dumped and burned after they have been used

Pearce, David W. (1941–2005) British economist and co-author of the book *Economics of Natural Resources and the Environment*

Braungart, Michael (*1958) German process engineer and chemist who worked together with the U.S. designer William McDonough to develop the concept of "cradle-to-cradle" design

DEAR READERS,

Can you imagine a life without plastic? Your toothbrush, your sunglasses, your sports equipment—could all of these things be made of metal, wood or glass? Probably not. Plastics are part of every aspect of our lives, and they are becoming ever more pervasive: in lightweight construction, medicine, and all the products that make our lives easier and better.

The production of plastics is constantly growing, and our need for new solutions increases along with it year by year. That's because the rising popularity of this material is accompanied by the dramatic proliferation of old and worn-out plastic products. Far too often, plastic waste ends up in landfills, rivers, and oceans—and ultimately in our food and our drinking water.

Refusing to use disposable products we don't actually need can certainly help to mitigate the problem, but it's not really a solution. Consequently, for all the products we cannot do without there's only one last resort: recycling. Recycling. The circular economy. Old plastic products are broken down and reprocessed with the help of chemical or mechanical solutions. Waste becomes a raw material.

For products made of pure or simply structured plastics, such as PET bottles, some of the processes we need already exist. But for soiled and mixed plastics, we don't really have the right solutions. However, there are many new ideas and research projects that could bring us much closer to the dream of a genuinely circular economy in the years ahead. This issue is all about these projects, as well as the best ideas and the biggest obstacles they're dealing with.

I wish you a thought-provoking reading experience.

Matthias Ruch
Editor in Chief

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

Anything but rubbish: Thanks to the right technologies, collected plastics can be reintroduced into the materials cycle

THE CIRCULAR ECONOMY

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Plastics make life easier, safer, and more comfortable. But what happens to all that plastic after it has served its purpose? Evonik already offers many solutions for the recycling sector, and it's working to help close plastic material cycles in the future

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The Evonik additive VESTENAMER® gives discarded tires a future as a raw material for road construction. The advantages for the environment can now be demonstrated by the data in a detailed life cycle assessment

Goal achieved: By means of a life cycle assessment, the environmental benefits of VESTENAMER® in road construction can be proved in detail

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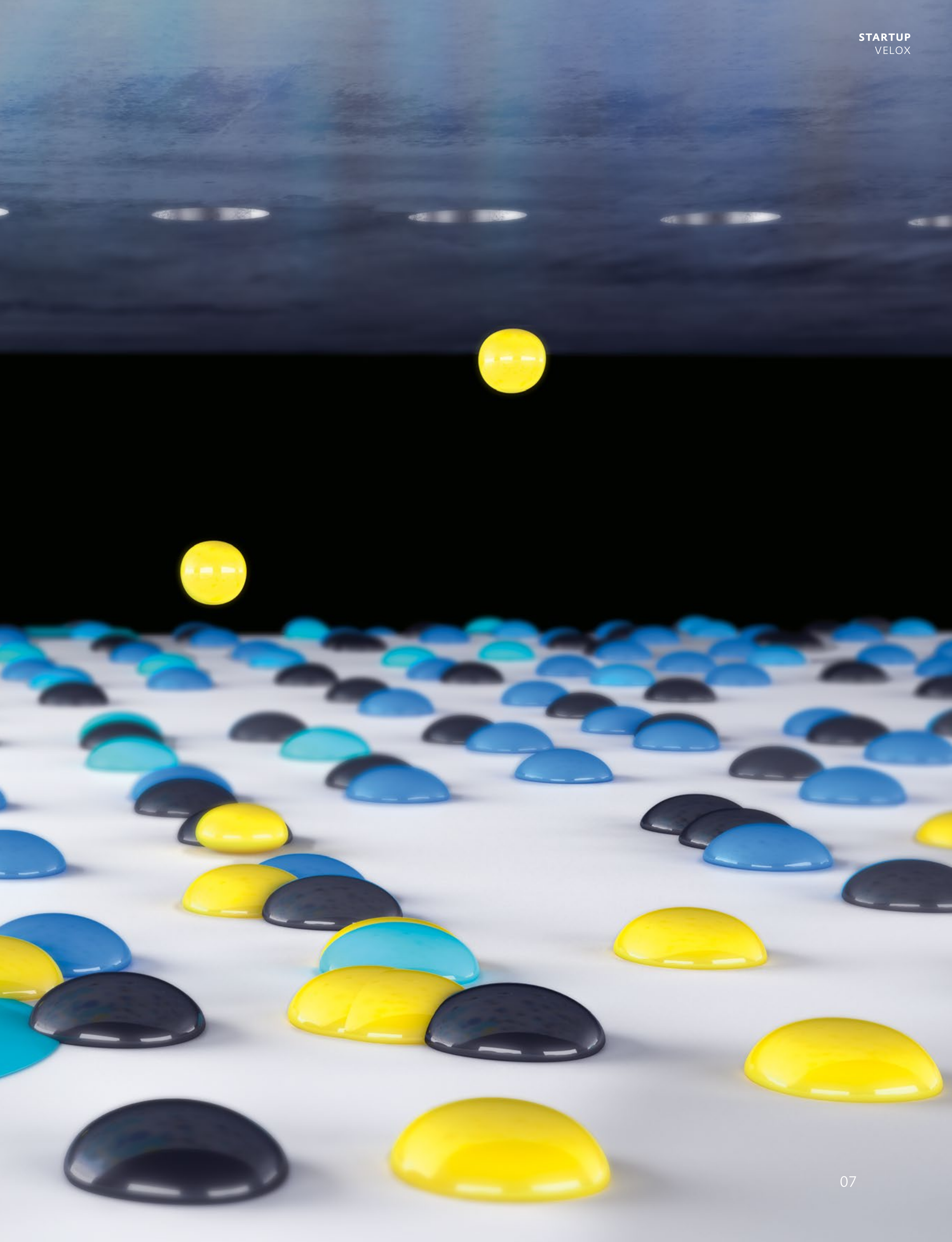
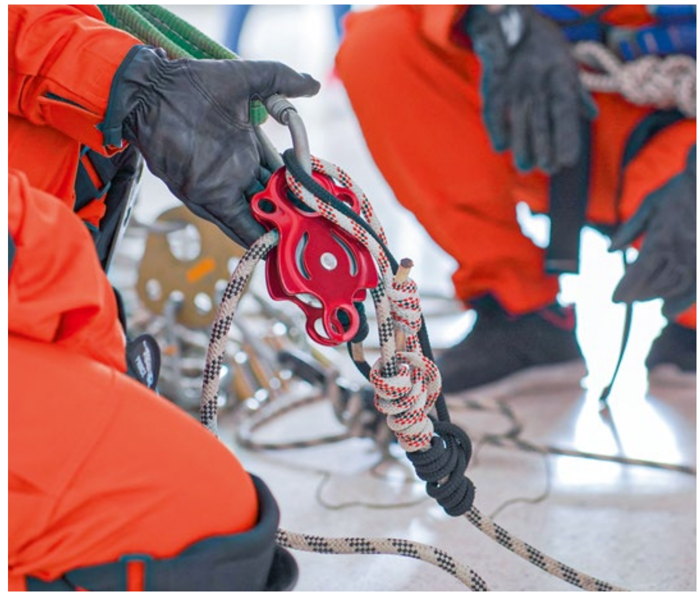
A PRECISION LANDING

Print head nozzles jet microscopically small droplets of ink onto a decorated surface at high speed and with maximum precision. This computer simulation shows the “direct-to-shape” digital printing process from the startup Velox. The process is controlled by software algorithms and dedicated hardware that precisely defines the spot each individual droplet must occupy. Velox, an Israeli company in which Evonik has held shares since 2018, has also developed special ink formulations for digital printing on plastics, metal, and glass. These innovations reduce ink consumption, improve sustainability, and open up new scope for creativity in packaging design through the ability to apply high-resolution images to surfaces.



White = hot

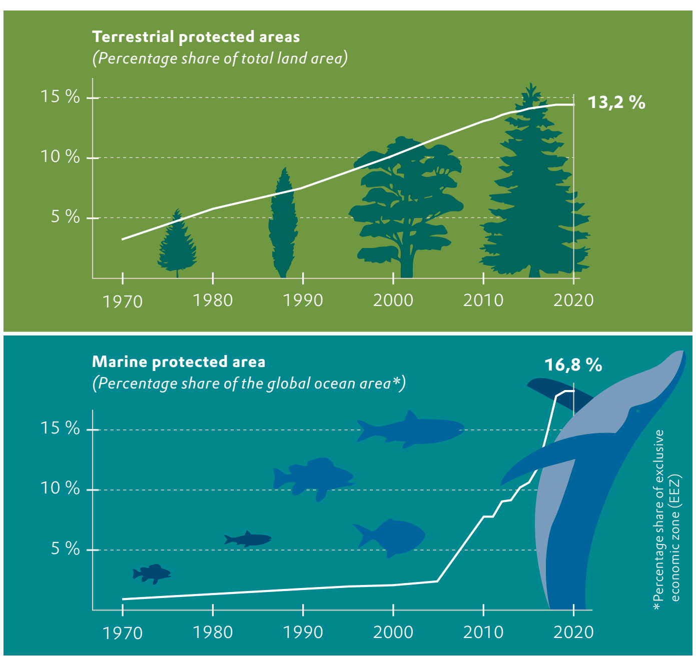
Researchers in Switzerland have developed a high-performance fiber coating that changes its color when subjected to heat



At high very temperatures, high-performance fibers tend to lose their mechanical properties. This loss often goes unnoticed and, in the worst case, can cause lifelines to tear when fighting fires, for example. As a result, a research team from the Swiss Federal Laboratories for Materials Science and Technology (Empa) and the Swiss Federal Institute of Technology (ETH) in Zürich have developed a new coating system that will help to prevent this from happening in the future. What makes this possible is that the coating changes its color when it reacts to intense heat and thus shows whether the underlying material is still strong enough to withstand the stress. The change in color is caused by a physical phenomenon known as interference. The coating consists of three layers. A metallic base of silver is first applied to the high-performance fiber. This is followed by a stability-enhancing layer of titanium nitrogen oxide. The final layer is a 20-nanometer-thick application of germanium-antimony-tellurium, or GTS for short. At high temperatures, the GTS crystallizes and the perceived color changes, for example from blue to a whitish hue.

THAT'S BETTER

Natural growth



Nature reserves are a key means of promoting biodiversity and protecting the climate. The good news is that the share of the total land area that is covered by nature reserves has risen from 2.6 percent to 13.2 percent over the past 50 years. Although the protection of the world's oceans commenced relatively late, it then progressed very quickly. As a result, 16.8 percent of the global ocean is now classed as a protected area.

Source: OECD

60 %

of the plastic that accumulates in India was recycled in 2015, according to a US study. It's one of the highest recycling rates worldwide. Experts think that this is due to the "informal sector," in which poor people collect plastic waste and then resell it.

DEEP LEARNING...

...will also enable us to partially forecast the future in quantum chemistry. The California Institute of Technology in Los Angeles has developed an artificial intelligence (AI) system called "Orbnet." It will be able to predict the properties and reactivity of molecules much faster and more precisely than was previously the case in the analog world. The predictions are based on precise analyses of a molecule's electronic structure. Like any other AI, Orbnet has to be "trained." To do this, the researchers continuously give it new tasks to perform in order to gradually expand the system's range of potential applications.

Printed pills

A combination of innovative printing processes is making it possible to produce new pharmaceutical products

Conventional 3D printing processes are generally restricted to materials that are shaped in a liquid state and subsequently harden. However, if the solid matter contains liquid components, the latter have had to be added subsequently in a complicated process. Chemists at Martin Luther University in Halle-Wittenberg have now developed a process that combines 3D printing and traditional printing methods so that both of these steps can be carried out in parallel. While the product's casing is being printed, the liquid is added drop by drop. This technique has already enabled the researchers to integrate a liquid active ingredient into a biodegradable material without diminishing the former's effectiveness. This method could be used to manufacture depots of pharmaceutical active ingredients, such as pills and tablets that gradually break down within the patient's body.

PEOPLE & VISIONS

"Our technology converts CO_2 and methane gas into syngas"

THE PERSON

Even when she was a teenager growing up in Canada, Alexandra Tavasoli knew she wanted to promote sustainability and mitigate climate change. But how? At first she considered becoming a journalist or a politician. "However, I soon realized that scientific solutions interested me the most." That's why she began by studying chemical engineering and then worked at a research institute before deciding to study for a doctorate. The subject of her dissertation was the conversion of carbon dioxide and organic waste into new chemicals.

THE VISION

This kind of transformation requires energy—which frequently comes from fossil sources. Tavasoli, by contrast, relies on solar energy. Together with her team, she has developed a special photocatalyst. "This technology transforms CO_2 and methane gas, which is generated by the fermentation of organic waste, into versatile syngas," she explains. Syngas can be processed to form methanol, for example. It's also used as a basis for the production of hydrogen. In 2018 Tavasoli founded her own company, Solistra. Since then she has worked as the company's CEO to make this technology fit for the market.

GOOD QUESTION

"How do you make disinfectant from apple residues, Dr. Kaiser?"

Many hand disinfectants largely consist of ethanol, which can be extracted from the residue (pomace) that is left over from apple juice production. Apple pomace is rich in carbohydrates such as sucrose, starch, and cellulose, all of which are ideal starting materials for fermentation into ethanol. To do so, the pomace is mixed with water, yeast, and cellulases and then blended in a fermenter for two days at 37 degrees Celsius. The resulting ethanolic solution is then distilled. The remaining residue is fed back into the fermentation process. This makes the research approach that my team and I are using sustainable in two ways: It enables ethanol to be produced from a waste material and it doesn't generate any new waste.

Dr. Doreen Kaiser, a technical chemist at the Technical University Bergakademie Freiberg, co-authored a research paper titled "Enzymatische Hydrolyse und Fermentation von Apfeltrester" ("Enzymatic Hydrolysis and Fermentation of Apple Pomace").

A new life: Collected plastic packaging waits to be reprocessed at the incoming warehouse of the Hündgen waste sorting company near Bonn. Ideally, it will be used to produce new packaging

RECYCLABLE MATERIAL

Products made of plastic make our lives easier and safer. However, too much plastic is still ending up in the environment. In order to solve this problem, we need better recycling systems worldwide and a genuinely circular economy. New research projects are giving us cause for hope

TEXT **TOM RADEMACHER**

The modern-day Sisyphus is called ROBB-AQC. He's a black-and-yellow robot whose jagged arm movements tirelessly extract plastic bottles and foil from an endless stream of garbage. Sensors and artificial intelligence tell him where recyclable plastics are flowing by on the conveyor belt. Nonetheless, many recyclable items remain on the belt. "This is a test operation! He's still learning," shouts Frank Arleth above the noise as he pulls a fleece jacket off the conveyor belt after it has got stuck under the robot's arm. Arleth and the robot both work for the Hündgen waste management company in the town of Swisttal near Bonn. This family-owned company has been run as a waste management facility for more than 70 years, and in the past 30 years it has sorted the contents of yellow recycling sacks for waste made of plastic, metal or composite materials.

The company has 140 employees, including many truck drivers. They collect the category of waste known here as "recyclables" from a wide region—up to 450 tons of it per day. Their field of operation ranges from the northern Ruhr region down to the Hunsrück Ridge in the south. Piled up in the incoming warehouse you can even see stacks of waste packaging from Denmark. Two years ago the owners of this midsized company spent about €15 million to install one of the most modern sorting facilities in Germany. This facility has to operate at full capacity. The machines run day and night, seven days a week. Saturday is also cleanup day.

Collecting, sorting, shredding: In the halls of the Hündgen waste management company, tons of plastic waste are processed every day

THE JOB OF THE CENTURY

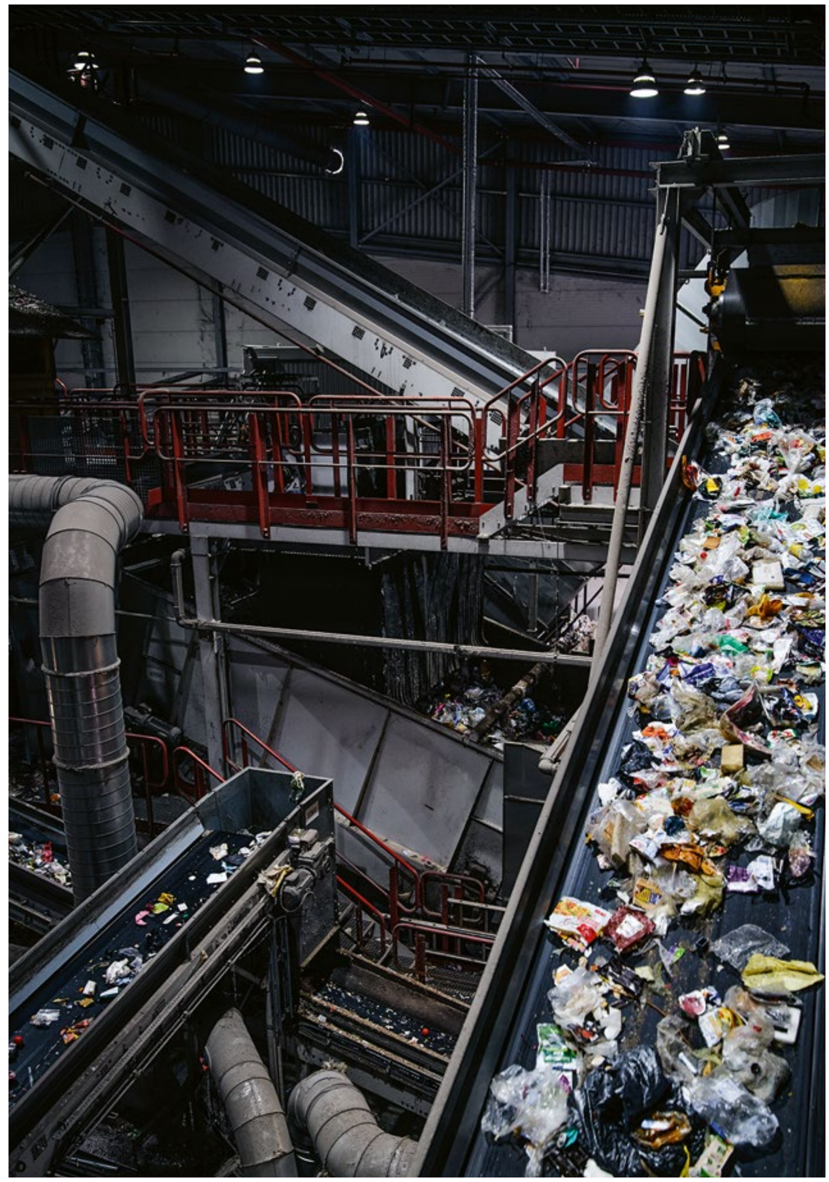
More than 350 million tons of plastic are produced annually all over the world—more than 200 times the volume produced in 1950, when the age of plastic really took off. Since then about ten billion tons of plastic have been produced, more than half of it since 2000 (see the infographic on page 17).

In the past few decades, only a fraction of this amount has been recycled. Even most of the plastic materials that are produced worldwide today finally end up in landfills—or, in the worst of cases, in the natural environment (see Data Mining on page 15). Because plastics do not deteriorate even after hundreds of years, the mountain of garbage is steadily growing—with devastating effects on habitats all over the planet. Plastic is everywhere. Finely ground into microplastic particles, it has even entered our food chains.

For a long time now, it has been obvious that this situation is untenable. One approach to a solution that almost everyone can agree on is "collect, process, recy-

"It's practically impossible to separate multilayer films made of several different plastics"

MONICA HARTING PFEIFFER,
PROJECT MANAGER AT RE PLANO



Almost fully automatic: Cameras, artificial intelligence, and robots are helping to identify and separate different kinds of plastic

cle" (see the debate on page 28). "Circular plastics" denotes the dream of a closed cycle in which plastic materials are reused over and over again. The specialty chemicals company Evonik wants to help reach this goal on several different levels. All of these efforts were recently consolidated in Evonik's Global Circular Plastics Program (see the information box on page 14).

Environmental protection associations are calling on people to use less plastic overall. But even they don't expect us to ever do entirely without plastics. Without the use of plastic, medical equipment ranging from disposable syringes to rubber gloves would no longer be safe. Plastic materials insulate buildings and refrigerators, help to reduce fuel consumption by means of lightweight components in vehicles, lengthen the shelf life of foods when used in packaging, and thus reduce food waste. Electric vehicles, wind power, solar energy—many promising technologies for conserving the natural environment would not exist without plastic.

However, almost half of the plastic produced today is processed into packaging materials that become garbage practically overnight. In order to get this torrent under control, old packaging has to be turned into new. But in many places the existing laws make it difficult to reach this goal. For example, in Germany the plastics that are collected in special yellow sacks may not be recycled to make food packaging, because the possibility of contamination by pollutants at some point in the process cannot be fully excluded. But recyclates from old plastic are seldom used even for packaging that does not come into contact with food, because the quality of these recyclates varies greatly.

Three types of plastic play a major role in packaging today: polypropylene (PP), various types of polyethylene (PE), and polyethylene terephthalate (PET). Together, they account for by far the largest proportion of all the materials used to make bags, tubs, foils, bottles, and other types of packaging, as well as objects for everyday use (see the infographic on page 18). After being used, each of these three plastics can be easily melted and reprocessed more than once.

The only problem is that they should not be mixed. Even a few percent of PP in a foil made of PE make it impossible to tightly seal a piece of packaging. This is why companies such as Hündgen use state-of-the-art technology to sort out these three kinds of plastic and keep them strictly separate. Recently robots have been brought in to supplement the sorting machines, →

whose cameras use near-infrared and ultraviolet light to distinguish between the different plastic molecules and then blow the respective plastic parts out of the stream of garbage with targeted blasts of air.

Every scrap of plastic that Hündgen cannot identify, pull out, and market as a recyclable material is incinerated, either in refuse incineration plants or as a “substitute fuel” in cement plants, for example. These residual amounts, whose recovery Hündgen must pay for, account for just over 40 percent of the contents of a yellow sack. That’s why the company has recently started to use some technical refinements to extract an additional two percent of mixed plastic scraps from the waste flow. The gray agglomerate is used to make park benches, playground equipment, and terrace substructures. This is certainly good for the recycling ratio, but it’s still not a contribution to a genuine circular economy.

The huge balls of PP, PE, and PET that roll out of the Hündgen company’s courtyard offer old plastics better opportunities for having a new life as packaging materials. They are reprocessed by companies such as RE Plano in the town of Lünen near Dortmund. RE Plano is part of the Remondis Group, a giant in the recycling and waste sector that employs 36,000 men and women at 900 locations. The Lippewerk waste recycling center in Lünen, which covers an area of 230 hectares, is considered the biggest in Europe. Here a million tons of garbage, ranging from organic waste to electronic parts and metal slag, are reprocessed annually. RE Plano mainly handles PE and PP, while a sister company treats PET.

WASHING, SORTING, BLOW-DRYING

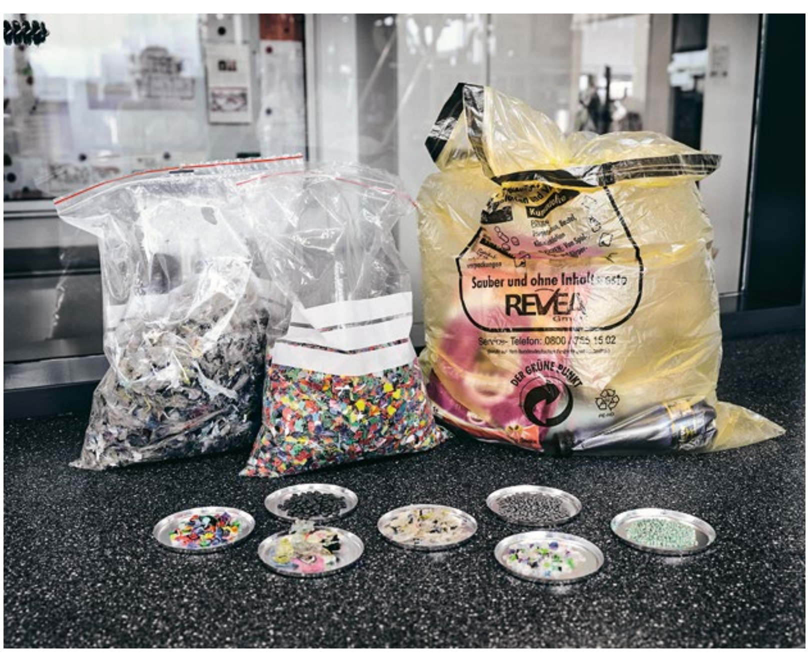
In the first step, the bales of plastic waste are shredded and washed so that the presorted packaging materials can be transformed into recycling granulate that is as pure as possible and thus can be processed like new plastic. “The exact details of the process are a trade secret,” says Monica Harting Pfeiffer, a process engineer who works as a project manager at RE Plano. But she does divulge that “we produce a lye that we use to remove glued-on labels and imprints.” After that, the washed and dried flakes of plastic are sorted again in order to separate shredded PE bottles from chopped-up labels, for example. One of the methods used for this purpose is air separation, which exploits the differences between the particles’ shapes and flight characteristics.

“The materials that are practically impossible to separate are multilayer films made of several different plastics,” Harting Pfeifer explains. However, these multilayer films are the current front-runners in the packaging market. For the packaging of wet or oily products ranging from coffee to dog food, manufacturers use pouches that may consist of more than a dozen layers of glued or vapor-deposited plastic. Such pouches are light-proof, odor-proof, and very robust. In general, very little material is needed to produce them. There’s only one problem: It’s nearly impossible to separate and recycle their component materials.

Continued on page 16 →

Global Circular Plastics Program

Evonik is consolidating its plastic recycling activities in the new Global Circular Plastics Program. The company offers solutions for improving the efficiency and quality of mechanical recycling and is working on various technologies for chemical recycling. At the same time, Evonik is investigating how raw materials derived from plastic or organic waste, for example, and CO_2 from biogas and industrial emissions can be used for the production of chemicals. By increasing its use of renewable raw materials for its own production processes, Evonik is improving its own CO_2 footprint and raising the proportion of sustainable materials used by its customers. Evonik serves the entire value chain of the plastics cycle and expects its sales to increase by more than €350 million annually starting in 2030.



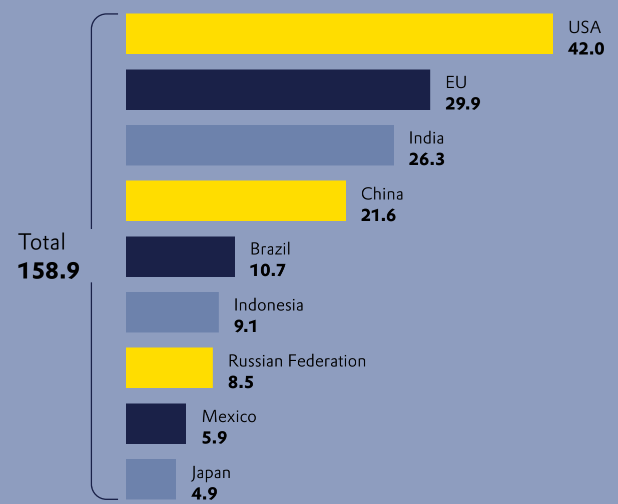
A path out of the impasse: In the Evonik laboratories on Goldschmidtstraße in Essen, researchers are developing processes for improving the yield from the recycling sacks

WHAT WILL THEY BECOME?

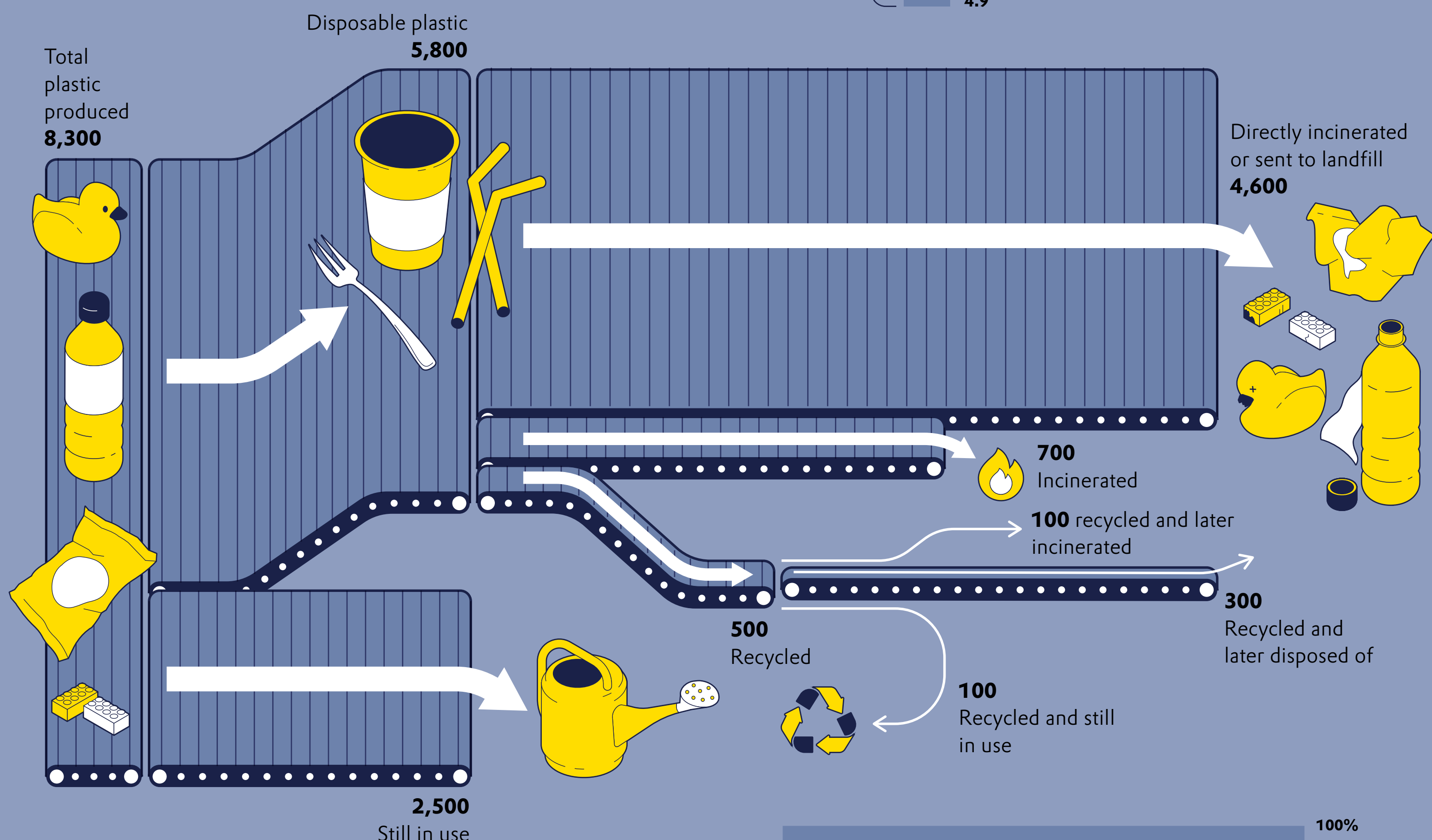
A life without plastics is hard to imagine today. But what should we do with the many millions of tons of used plastic products? The solution is to increase recycling

INFOGRAPHIC **MAXIMILIAN NERTINGER**

Into the bin
Plastic waste according to country, in millions of tons, 2016

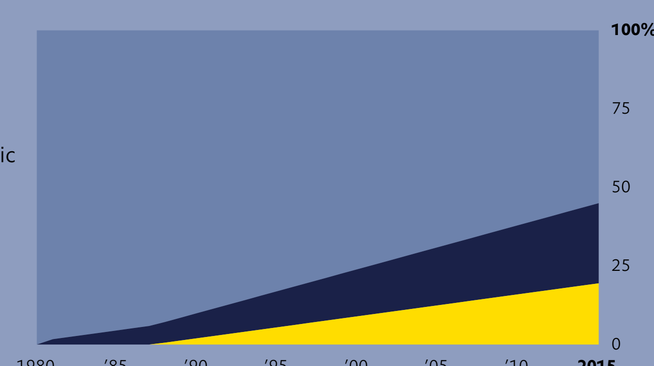


Dumped, incinerated, recycled, in use
Utilization of all plastics produced worldwide between 1950 and 2015 (polymers, resins, synthetic fibers, and additives) in millions of tons



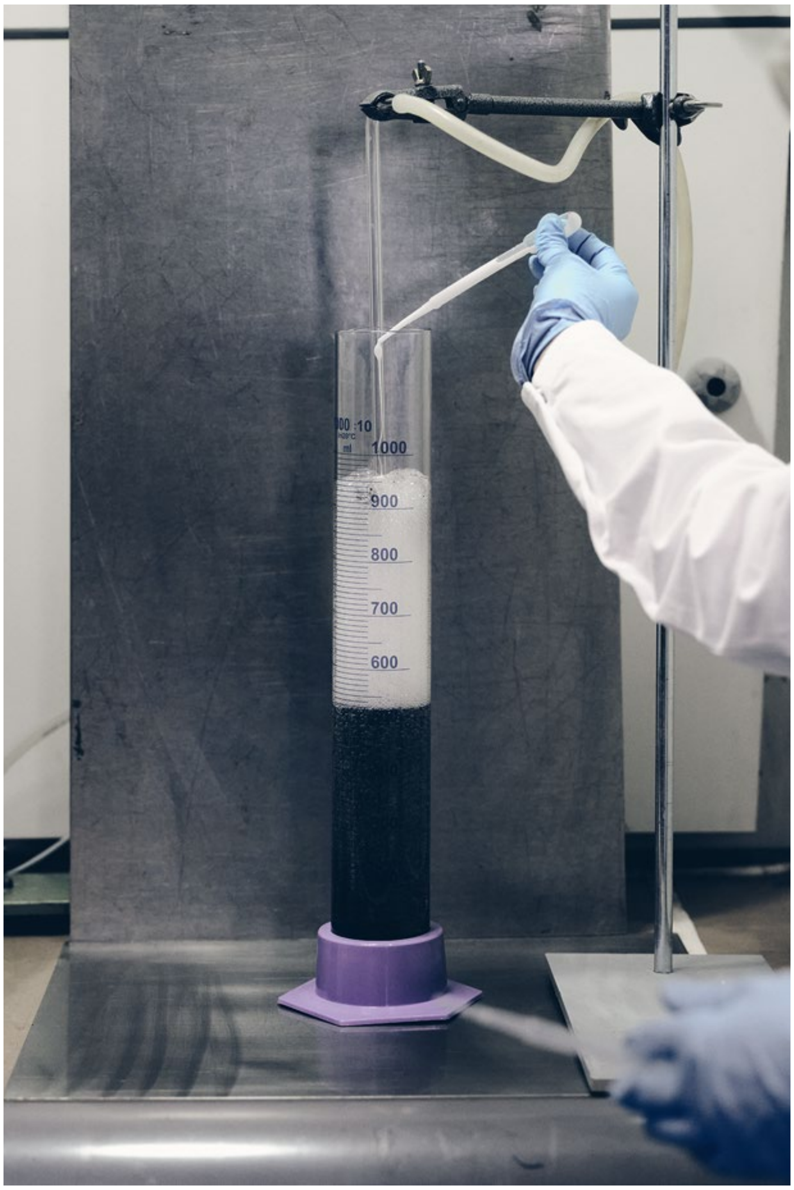
Too good for the landfill
Proportion of recycling or disposal paths of plastic waste worldwide (estimated)

Landfill Incinerated Recycled



Sources:
Roland Geyer et al.: "Production, use, and fate of all plastics ever made" (2017), Science Advances

Anti-foaming agents from Evonik help to significantly improve the washing process in plastic recycling facilities (below). Chemical lab assistant Janina Kilian checks the odor of a sample of recycled plastic



At Evonik's Goldschmidtstraße location in Essen, these are very familiar difficulties. Three years ago, the specialty chemicals company expanded the location's application laboratory and its adjacent technical center so that it could examine the recycling companies' problems in depth. "Until a few years ago, these companies were practically not a market for us," says Kathrin Lehmann, Technical Director Polymer Specialities. "But today we're seeing a huge change."

CUSTOMIZED FORMULATIONS

Evonik has supplied additives and auxiliary materials to the plastics industry for decades. These materials improve the properties of the end products, for example by making them flame-retardant, more fluid, scratchproof or more pleasant to the touch. Of course many of these properties would also be in demand when recyclates are being processed. "However, the details of the requirements are different, and we're finding out that we can bring even more of our know-how to bear in the recycling sector," Lehmann says.

One of these areas is that of washing and sorting. Lehmann's team regularly analyzes samples of washing lyes that are sent to it by companies such as RE Plano. The team members develop customized formulations for surfactants that are used in de-inking and de-labeling processes that quickly remove inks and labels without leaving any residue. Anti-foaming agents simplify the washing process by preventing foam from overflowing. Wetting agents enable the lye to slip between the surfaces more easily, and desiccants help to save energy in the subsequent drying process. "This process know-how, which we have accumulated over decades

"Until a few years ago, recycling companies were practically not a market for us"

KATHRIN LEHMANN, TECHNICAL DIRECTOR POLYMER SPECIALTIES for other processing industries, is now being combined and used in the recycling business," Lehmann says.

Next door, a team headed by Sebastian Heßner is working with extruders and foil-packaging machines to determine how additives from Evonik can play a role in the preparation and processing of plastics for recycling. "Some of the requirements are the same as those for virgin plastic—in other words, new materials," explains Heßner, who is the head of the testing facility. "But there are additional requirements as well." For example, because the starting materials are more diverse, their flowing and melting properties must be fine-tuned more often.

LOCKED-IN ODORS

Another typical problem involves odors. "If recyclates contain organic compounds or adhesive residues and they are heated during the extruding process, they generate volatile and strong-smelling degradation products that take a long time to dissipate," Heßner explains. That's why you can sometimes simply follow your nose in a DIY store if you're looking for inexpensive recycling products such as buckets or garden furniture. "Some recycling companies deal with this problem by adding aromatic substances," Heßner says. "By contrast, our odor absorbers don't simply mask the odor temporarily. Instead, they permanently keep the volatile molecules inside the material."

Today Evonik may even have two solutions ready for the multilayer films that are driving recycling companies to despair. Kathrin Lehmann goes to a cupboard and pulls out a rolled-up film that was recently sent to her by a packaging manufacturer from Asia. Before the covid-19 pandemic, the two of them had started talking at a trade fair. Lehmann now points with visible satisfaction at a beaker in which two extremely thin films are floating around companionably—one is plastic, the other one is aluminum. "By using the right surfactants, we can separate even this kind of film with 100 percent precision. No problem!" she says.

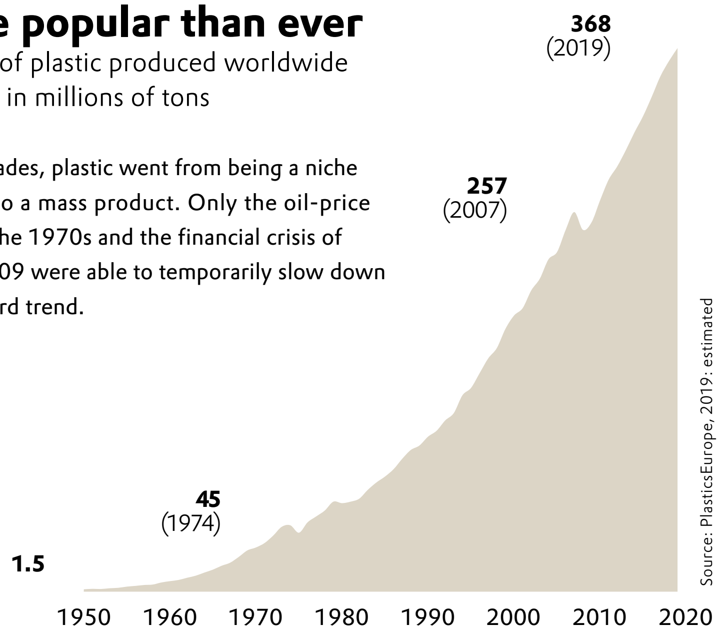
Whenever this kind of separation is impossible, the job is turned over to Sebastian Babik. "Sometimes materials that are chemically different can be married and then recovered together," he says. Babik's title at Evonik is "Director Technology Platform Polyolefins," and the name of his solution is VESTOPLAST®. This polyolefin, which was developed in-house at Evonik, is a component of the hot glues that are used today to keep diapers, sanitary pads, and cartons in one piece. As a chemical relative of PE and PP, VESTOPLAST® can also make these two materials compatible with each other, Babik explains. "In tests we conducted in cooperation with TU Wien, we were able to generate new recycling materials consisting of two thirds PE and one third →

Tearproof: Evonik also tests its recyclates for use as material for sacks and films—two of the most popular applications

More popular than ever

Volume of plastic produced worldwide annually in millions of tons

In six decades, plastic went from being a niche material to a mass product. Only the oil-price shock in the 1970s and the financial crisis of 2008/2009 were able to temporarily slow down this upward trend.



Evonik researchers' goal: Recycled plastic granulate that is just as good as new material

PP that have significantly improved physical properties," he says. This is good news for all companies that plan to use more recyclates themselves in the future and still find it difficult to procure enough high-quality material today.

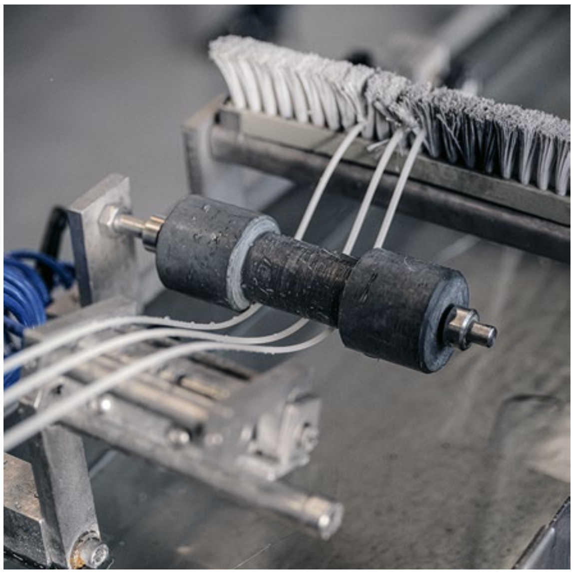
For example, in 2019 the Henkel Group used a total of 769,000 tons of packaging material for its consumer products, including well-known brands such as Pattex, Persil, Schwarzkopf, and Sidolin. About half of this packaging was made of plastic. Henkel plans to make all of its packaging reusable or recyclable by 2025, and at least 30 percent of it will consist of recyclates. This will be a challenge for the product designers. "Consumers have high expectations," says Thorsten Leopold, Director Global Packaging Innovation in the Home Care business unit at Henkel. "They want sustainable products and packaging, but they don't want to make any compromises regarding the color, odor, tactile qualities or functionality of the packaging."

RETHINKING AND LEARNING

Meanwhile, the group's adhesives unit is also providing support for supplier companies: Labels, cartons, and lots of multilayered packaging owe their sturdiness to

Make it from plastic

Production of polymers according to types and uses in percent, 2019



Just like a factory: At the Evonik Technical Center in Essen, recyclates are handled in industrial processes, but on a smaller scale

adhesives from Henkel. "Our customers have recently experienced a genuine change of heart," says Dennis Bankmann, Senior Manager Circular Economy at Henkel Adhesive Technologies. "Until a few years ago, they always wanted everything to be even more solid, more temperature-resistant, and more long-lived. Today customers are also asking how all these things can be dismantled." As a result, they're now using plastic banderoles that are only attached at a few points instead of fully glued-down paper labels, for example. Henkel has developed an adhesive for outer packaging that eliminates the need to shrink-wrap cartons in order to keep them from rolling off a pallet.

Here Evonik is needed yet again, because it's a supplier upstream in the value chain. Evonik supplies not only VESTOPLAST® but also countless other components for adhesives that hold all kinds of things together, ranging from yogurt containers to cardboard boxes. "For a long time now, gluing and ungluing have not been the only issues," says Babik. "There's also the question of how the glue itself behaves in the recycling process. Nowadays customers are simply looking much more closely."

This rethinking, as well as the sum total of countless small solutions to problems, is giving people hope. Legislators all over the world are creating pressure, increasing the waste collection and recycling quotas, and calling industries, trading companies, and consumers to account. Sorting companies, recyclers, packaging manufacturers, producers of consumer goods, and the chemical industry are reacting by looking for new paths out of the current impasse. The outlines of a circular economy for the packaging industry are still vague, but they are discernible. Closing the global circle once and for all will be the job of the century. There's still a lot to learn. Not just for the busy robot by the conveyor belt.

om Rademacher is a
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mong others

Round and Round

Around 370 million tons of plastic per year are produced worldwide. Only a fraction of this is recycled. This overview shows which technologies can help to establish a circular economy for plastics, thus saving valuable resources while reducing CO_2 emissions at the same time

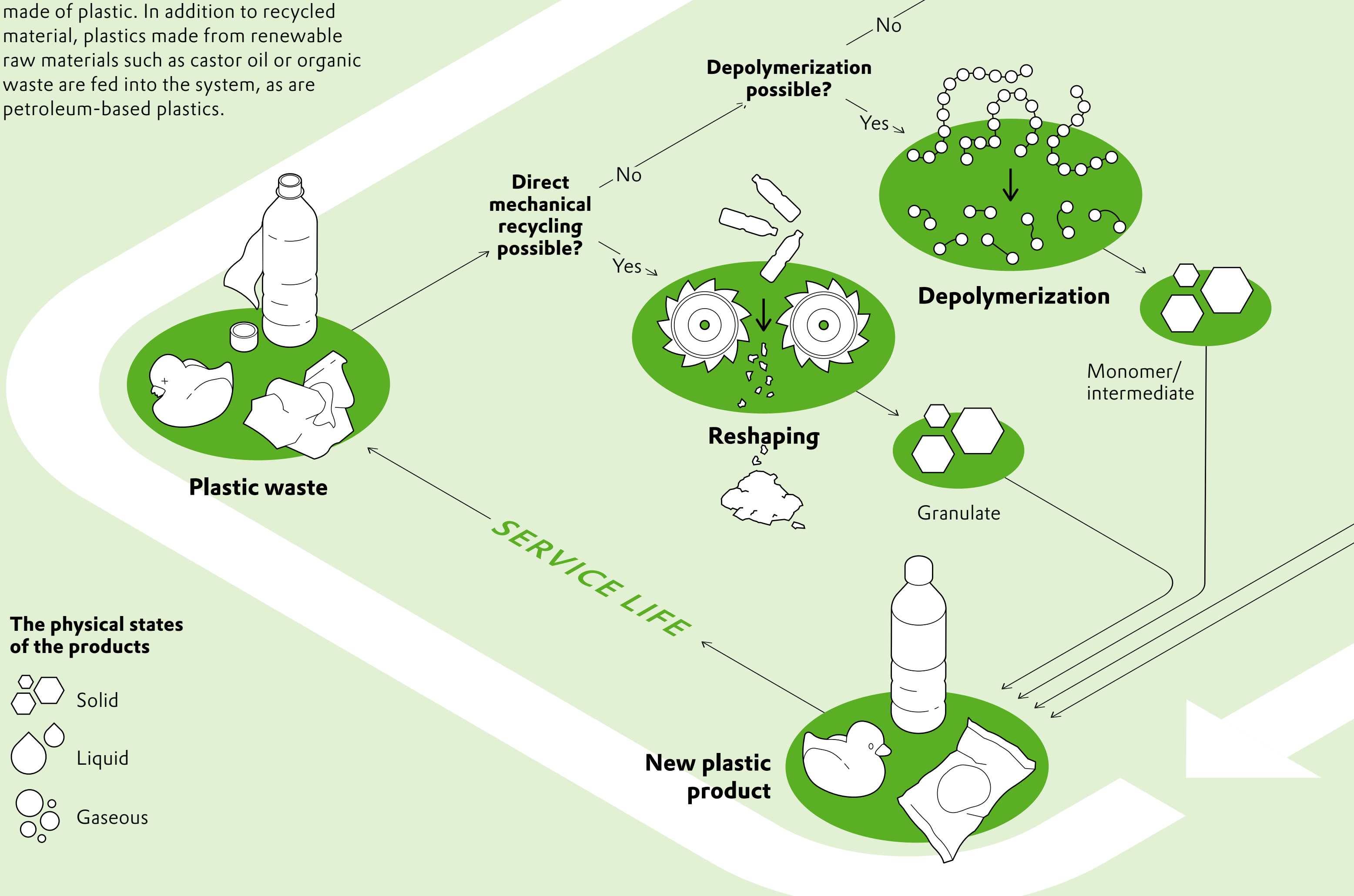
INFOGRAPHIC **MAXIMILIAN NERTINGER**

Mechanical and chemical recycling

Different processes are available for reprocessing plastics, depending on the material, type of processing, product condition, and degree of soiling. In addition to mechanical recycling, in which the polymer remains intact, various chemical processes are also used.

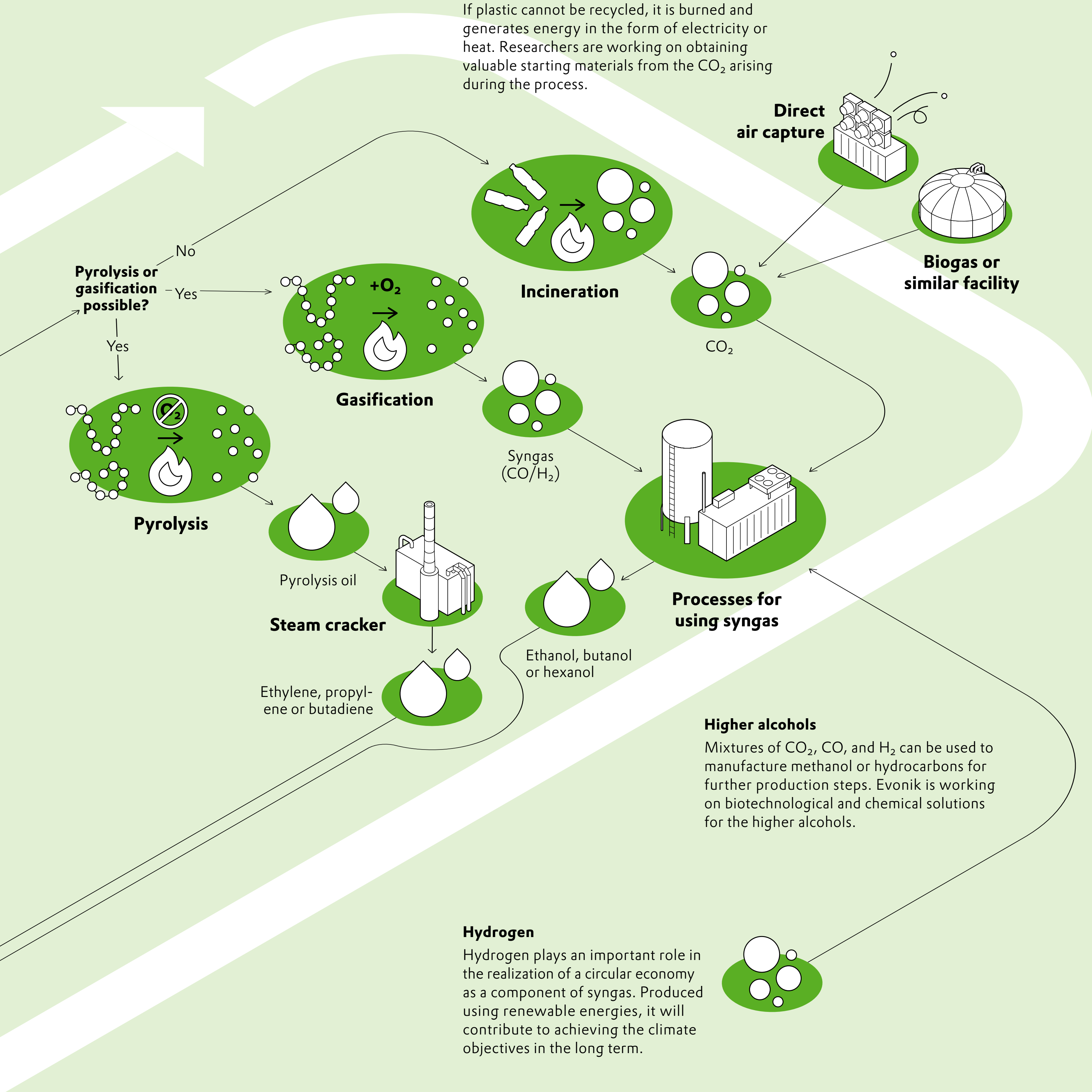
Start and finish

The cycle begins and ends with products made of plastic. In addition to recycled material, plastics made from renewable raw materials such as castor oil or organic waste are fed into the system, as are petroleum-based plastics.



Thermal utilization

If plastic cannot be recycled, it is burned and generates energy in the form of electricity or heat. Researchers are working on obtaining valuable starting materials from the CO_2 arising during the process.



Higher alcohols

Mixtures of CO_2, CO, and H_2 can be used to manufacture methanol or hydrocarbons for further production steps. Evonik is working on biotechnological and chemical solutions for the higher alcohols.

Hydrogen

Hydrogen plays an important role in the realization of a circular economy as a component of syngas. Produced using renewable energies, it will contribute to achieving the climate objectives in the long term.

In the autoclave building at the Evonik location in Lülsdorf, Laboratory Manager Jutta Malter and her team conduct experiments to find the most efficient processes for the chemical recycling of plastics

THE TIME IS NOW

Chemical recycling can recover even plastics that previously would have landed in an incineration plant or a landfill, depending on the country. Evonik is working to develop a process for very dirty PET—and is making it possible to recycle entirely new material flows

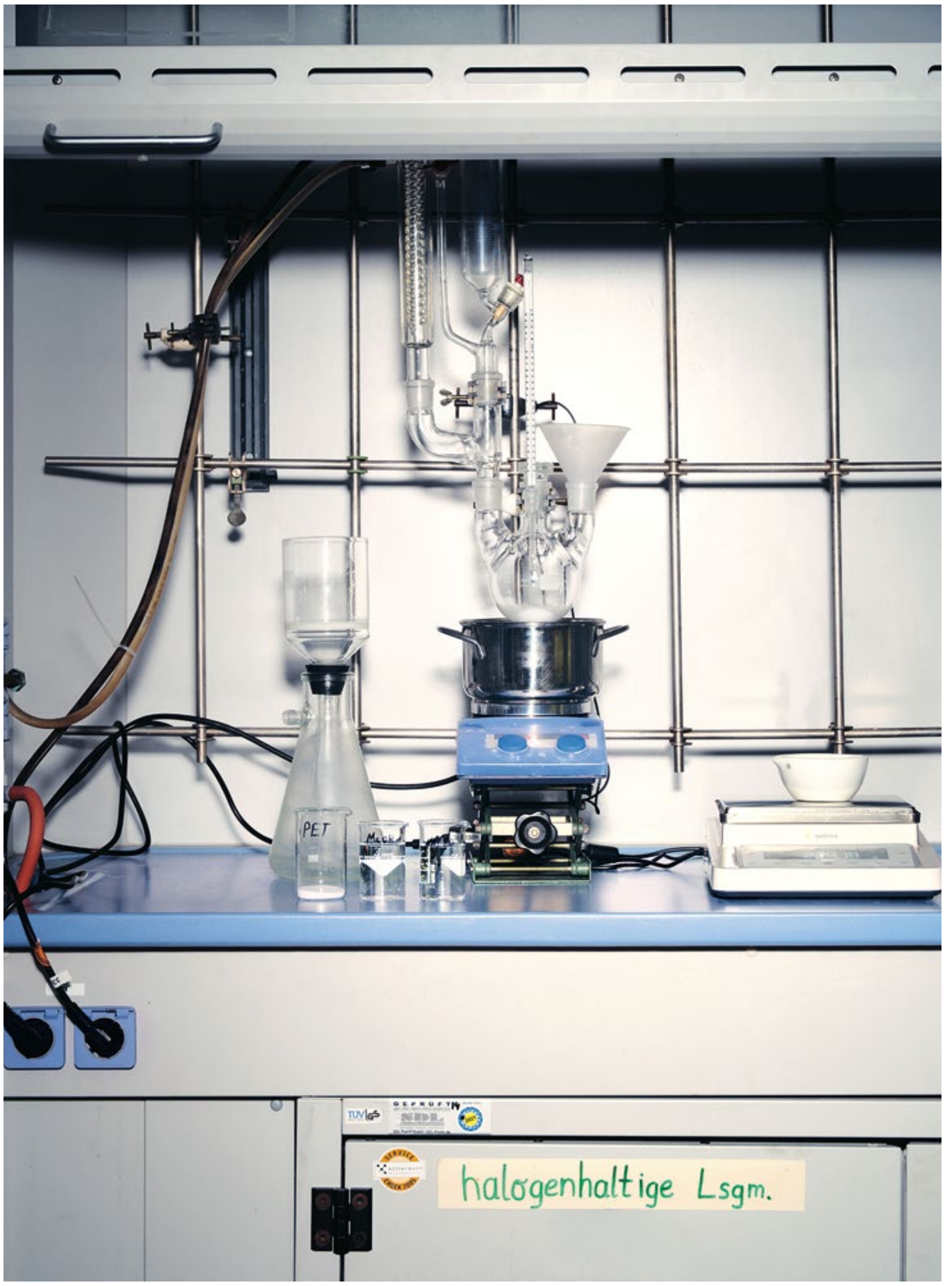
TEXT **DENIS DILBA**

The shreds of PET whirling around behind a thick pane of borosilicate glass look a lot like they're in a snow globe. A stirring unit inside the stainless-steel pressure vessel is driving the polymer flakes through the colorless liquid in an endless dance. The show, which is visible only when a flashlight is shined into it, initially continues unchanged. But after a while the shreds begin to dissolve. After a temperature far above 100°C has been reached and a high pressure has built up inside the vessel, it doesn't take long for the shreds to completely disappear. The liquid inside the test reactor now has a bluish color. "That's what usually happens with this raw material, which is strongly colored PET," says Dr. Jutta Malter, the Laboratory Manager at the Evonik facility in Lülsdorf, a district near Cologne. Unless there is a further purification step, the blue dye will also be present later on in the PET's monomer component, which the researchers are aiming to separate out by using an alcoholysis process after the sample has cooled off. The dye will be present in only a tiny concentration—but the resulting dimethyl terephthalate, or DMT for short, will also have a slight blue cast.

How can such discolorations be prevented? And what would be the simplest way to remove such impurities from the monomer later on? These are questions that Malter and her team at the Functional Solutions business line are hoping to answer. The answers they come up with will determine the applications for which the recovered material can be used. Their goal is to find a combination of chemicals and technical processes that will make it possible to chemically recycle waste plastics in ways that save energy, are economical, and lead to high-quality applications.

RECYCLED PLASTICS ARE IN DEMAND

Dr. Patrick Glöckner is firmly convinced that the time for chemical recycling has come. "Many processes have basically been known for decades," says Glöckner, an expert on circular economy who works at Evonik. →



In the laboratory, the methanolysis takes place in three-necked flasks: The mixture of PET, methanol, and the catalyst sodium methylate is brought to a boil in an oil bath

"But only now have these technologies reached the point of maturity where they can soon be implemented on an industrial scale." The signs have changed, according to Glöckner, who is responsible for Evonik's Global Circular Plastics Program. "Many customers are looking for products that are as sustainable as possible," he says. "Even major brand-name companies are increasingly asking for recycled plastics, including PET, for their products." IKEA has particularly ambitious goals. "One of our ambitions is to use only renewable and recycled materials by 2030 for all products where relevant," says Raffaele Giovinazzi, who is researching materials recycling as a member of IKEA's polymer team.

"We're building a platform technology for recycling various polymers"

PATRICK GLÖCKNER, HEAD OF THE GLOBAL CIRCULAR PLASTICS PROGRAM

Political developments are supporting the trend toward the use of more recycled plastic. For example, the European Commission has decided that ten million tons of recyclate should be utilized in the EU by 2025. Moreover, all packaging in Europe should be either reusable or recyclable by 2030. The aim is to make "Recycled in the EU" a mark of top quality.

As a result, efforts to implement mechanical and chemical methods for recycling plastics are intensifying all over the world. "We will need both kinds of processes if we want to reach ambitious political goals and create a sustainable circular economy," Glöckner says. Mechanical recycling is usually the first choice, he adds. "The only problem is that not everything can be mechanically recycled."

The composition of some plastics makes them unsuitable for mechanical recycling. These plastics mainly include film packaging for sausage and cheese, which consists of several wafer-thin layers of various plastics. In Germany, such composite films are currently being incinerated because their clear-cut separation is too expensive. Moreover, even easily recyclable plastics such as PET cannot be mechanically recycled without

Before the practical experiments in the laboratory can begin, Jutta Malter calculates the expected theoretical outcome

any limitations because, for example, they have been colored. And finally, in every round of recycling the molecular chains become shorter and thus can no longer be used for high-quality applications.

CHAINS BECOME SMALLER MOLECULES

That's why only about a fourth of recycled PET materials in Germany can be processed into bottles. Another large proportion of recycled PET materials is used to manufacture other products, mainly fleece sweaters and industrial films. "Mechanically recycling these products is even more challenging," says Glöckner.

Chemical recycling offers a way forward. Unlike mechanical recycling, this process splits the polymer chains of the starting material into monomers. As a result, even polymer material flows that are very dirty, have been colored or contain additives or foreign materials can be recycled as valuable raw materials. The chemical building blocks that are created in this way can then be converted into new polymers for high-quality applications—thus closing the cycle.

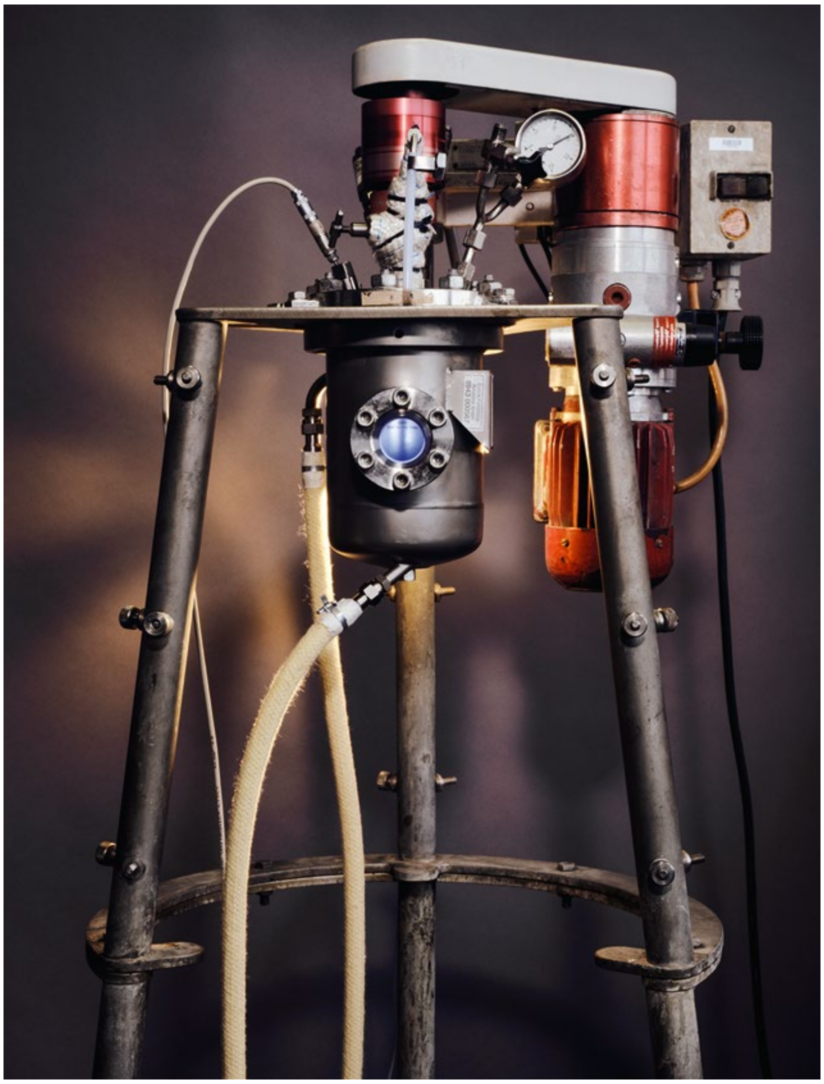
However, such processes are only suitable for practical applications if they can be used on an industrial scale. "The reliable availability of plentiful low-value waste feedstock is the key to more chemical recycling," says IKEA expert Giovinazzi. That's why one focus of Evonik's Global Circular Plastics Program is on technologies whose input materials are available in large quantities. In addition, a positive life cycle assessment must be ensured. That's because processes that are technically feasible are not necessarily good for the environment. The process development of PET methanolysis that Jutta Malter and her six-person team are now working on in Lülsdorf has already made good progress in this direction.

"In terms of the chemistry involved, this process is a transesterification," Malter explains. The PET raw material is combined with a multiple volume of methanol and a catalyst and is then heated. This results in the reaction product DMT and ethylene glycol (EG). If the starting materials are pure and the reaction conditions are ideal, this is not a particularly complicated reaction, says Malter. "For chemists who prefer to synthesize complex molecules, this is probably not the right task." The challenges arise after the reaction in the test tube is over, she adds. Malter's aim is to develop a cost-efficient process that uses various kinds of PET starting materials to produce high yields of DMT and EG that are as pure as possible. And of course the entire process should have an optimized life cycle assessment.

The main product of the PET methanolysis conducted by the lab assistants is a white solid, dimethyl terephthalate (DMT)

ONE PROCESS—MANY POSSIBILITIES

One important fixed point of Malter's trials is the catalyst, and sodium methylate is her catalyst of choice. This alkoxide, which Evonik has been producing in Lülsdorf for a long time, is mainly used today for the production of biodiesel. The efficient PET methanolysis is expected to also open up an interesting new sales market for this business line. →



In an autoclave, a container that is gas-tight when locked, PET methanolysis is conducted under pressure and at high temperatures. This accelerates the reaction process

“The advantage of the DMT recyclate is that we wouldn’t have to explain a new molecule to the customers”

MICHAEL GRASS, DIRECTOR OF APPLICATION TECHNOLOGY & PRODUCT DEVELOPMENT AT THE PERFORMANCE INTERMEDIATES BUSINESS LINE

Since 2014, the researchers have tested all the possible combinations of widely used plastics with the alkoxides produced at the location in order to learn more about potential recycling processes. One of the most promising pairings has been the combination of PET methanolysis with sodium methylate.

Another advantage of this reaction is that Evonik could make use of the resulting DMT in-house. “By using this DMT we could produce plasticizers that are even more sustainable,” says Michael Graß from Evonik’s Performance Intermediates business line. His unit is already producing a plasticizer made of dimethyl terephthalate today. “An alternative consisting of DMT recyclate would have the advantage of possessing the same properties as a conventionally manufactured product,” Graß says. “We wouldn’t have to explain a new molecule to the customers.” Besides, the authorizations under the EU’s REACH chemicals regulation could continue to be used unchanged.

Graß emphasizes that the success of a sustainable plasticizer would depend on the establishment of a competitive price. After all, every recycled raw material competes with the price that is asked for a new petroleum-based material. And of course the DMT used for such an application shouldn’t have a blue cast either. Jutta Malter is now responsible for meeting all of these requirements. “That is certainly technically feasible,” she says. But there’s still a whole list of details to investigate. Does the process require one, two, or three purification steps—or none at all, depending on the pressure and the temperature? Can ultrapure DMT also be produced using other PET sources that might be less expensive? How strongly do the impurities in each starting material affect the reaction product?

And after all these questions have been answered, Thomas Richter will be asking new ones. Together with other experts from the Process Technology & Engineering unit, he is working to develop efficient and scalable processes for exploiting the economic potential of chemical recycling for Evonik. The unit expects its efforts to ultimately result in a viable large-scale plant. “For most reactions, the catch is that they can’t be scaled up one-to-one from laboratory dimensions to industrial production,” says Richter.

TOWARD A PLATFORM TECHNOLOGY

Like Jutta Malter, in his research Richter is looking for the optimal setup for PET methanolysis. “Simply using bigger stirrer tanks is not going to work,” he says. The reaction would take too long, and the process would be too expensive relative to the achievable yield. It would also be problematic to increase the pressure in order to accelerate the reaction. “The associated follow-up costs would be too high,” he explains.

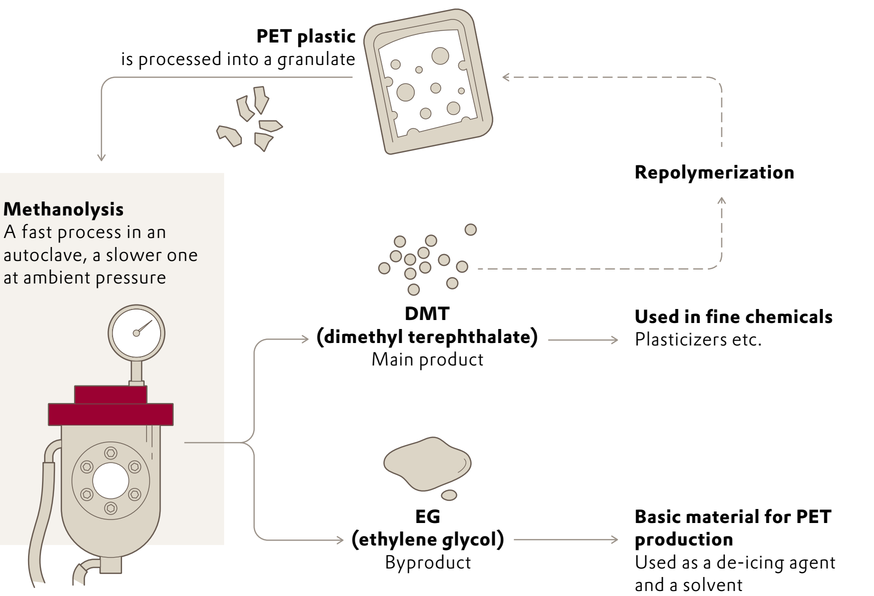
The experts on the team, who come from various units at Evonik, believe that developing the best process requires the construction of a pilot plant.

On this basis they could make different offers to customers later on: Do they need all of the process know-how for their own plants—or only the ideal catalyst? Patrick Glöckner is already thinking beyond the PET recycling process. “We’re using the knowledge we are accumulating here to create a platform technology,” he says. “It can be used not only to recycle other classes of polymers but also to produce other monomers.” Glöckner points out that Evonik wants to play as large a role as possible in making recovery technologies faster, more efficient, and less expensive. “The ultimate goal is to leave the oil in the ground.”

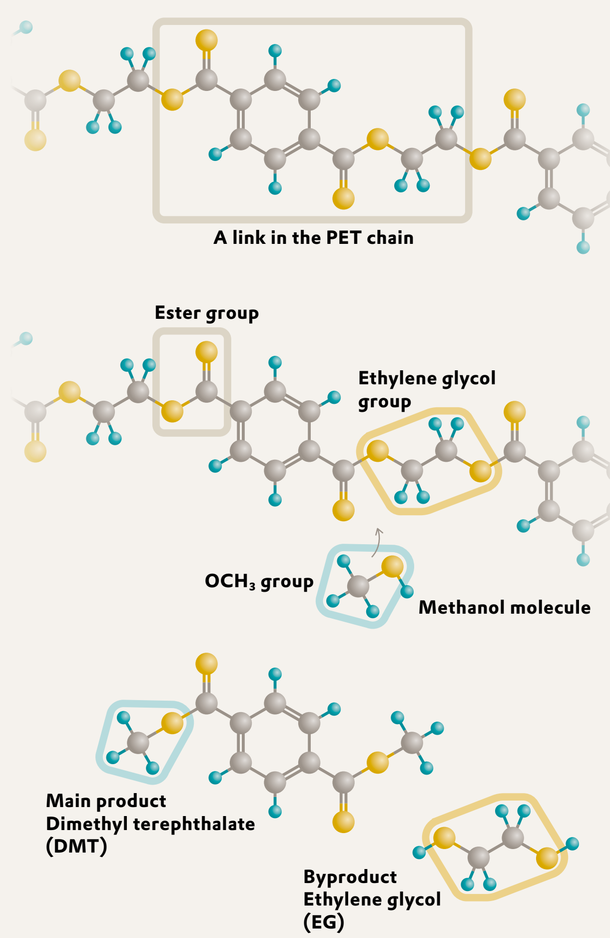
Denis Dilba is an engineer and a journalist. He generally writes about science and technology topics—and the more complex they are, the better

Recycling raw materials

To date, the plastic polyethylene terephthalate (PET) has been mechanically recycled. The collected material is shredded, cleaned, melted down, and once again molded into bottles. However, this process cannot be used with PET that is very dirty or colored. The aim is to use chemical (raw-material) recycling for this purpose in the future.



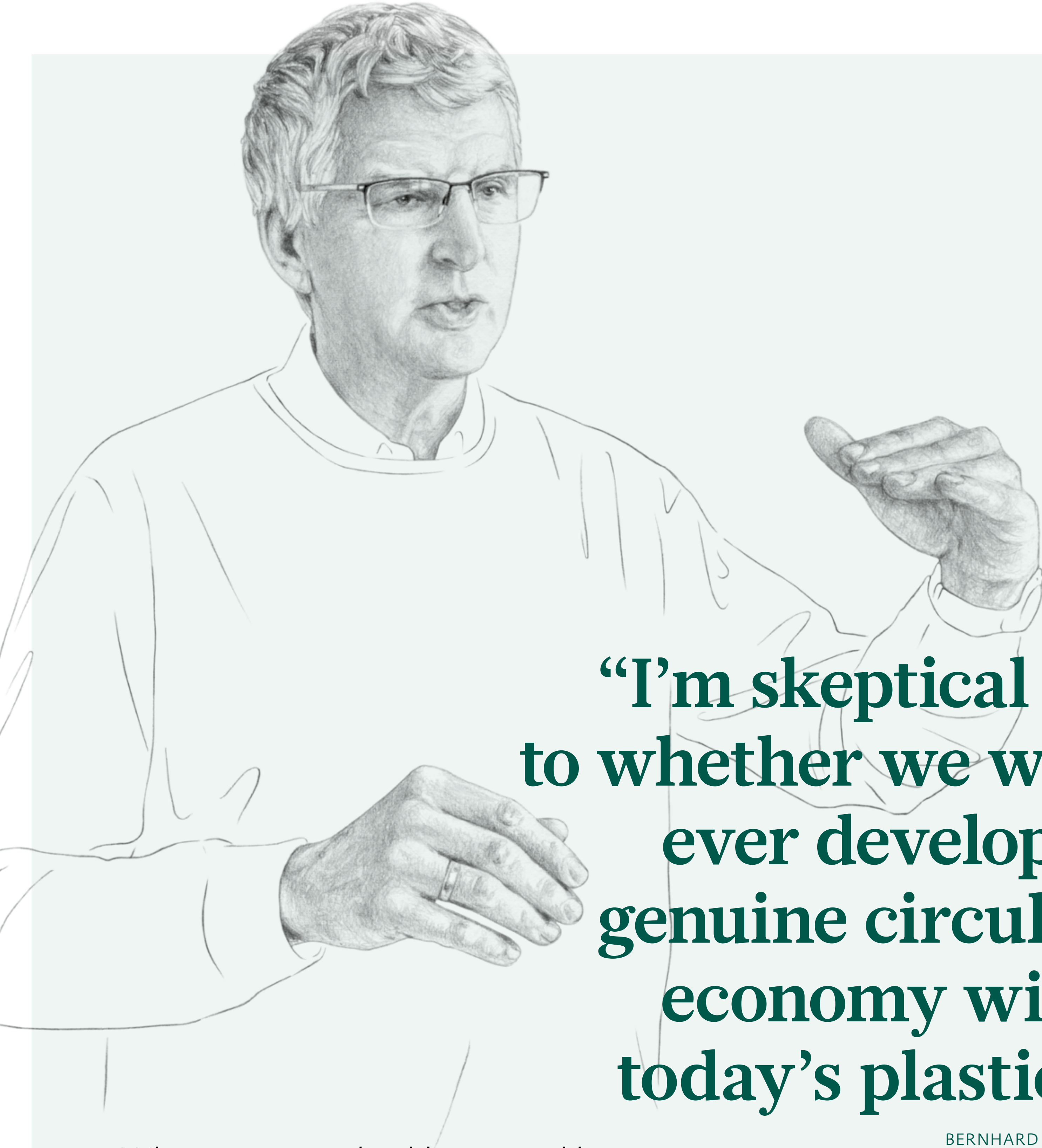
How PET methanolysis works



1. The basic material
Polyethylene terephthalate—or PET for short—consists of long chains of a repetitive chain unit consisting of molecules of terephthalic acid and ethylene glycol

2. Methanolysis
PET is reacted with methanol and sodium methylate. In the process, the ester bonds in the PET chain molecule are split and the ethylene glycol groups are replaced by OCH_3 groups

3. Reaction products
The main product of PET methanolysis is the crystalline solid dimethyl terephthalate (DMT), the byproduct of the liquid dihydric alcohol ethylene glycol (EG)



"I'm skeptical as to whether we will ever develop a genuine circular economy with today's plastics"

BERNHARD BAUSKE,
PROJECT COORDINATOR OCEAN WASTE AT WWF

What properties should a material have in order to be optimally recyclable? What is the true value of plastic waste? And where do we need prohibitions? A debate about pathways toward a more sustainable plastics economy

HOSTS **TOM RADEMACHER** & **MATTHIAS RUCH** ILLUSTRATION **ORIANA FENWICK**

"Plastic is versatile and effective—qualities that also benefit the environment"

INGO SARTORIUS,
MANAGING DIRECTOR, PLASTICSEUROPE DEUTSCHLAND

Mr. Sartorius, your association is now celebrating the hundredth anniversary of plastic. Let's take a quick look at the future: Will the world still need plastic 100 years from now?

INGO SARTORIUS Plastic is an irreplaceable part of our daily lives. This material is versatile and effective—qualities that also benefit the environment, by the way. Lightweight construction in cars decreases emissions and thus reduces the strain on the climate. That also applies to building insulation. In the fields of medicine and packaging, plastics are highly efficient materials that offer safety and hygiene protection.

BERNHARD BAUSKE Ever since the 1950s, plastics have had an incomparable career of success. The amount of plastic we produce annually corresponds roughly to the weight of the entire human race. That's because this material is very versatile and effective—in that regard I agree with Mr. Sartorius. The crucial disadvantage of plastics is that they aren't biodegradable. Even in Germany, where waste management works fairly well, almost 450,000 tons of plastic end up in the environment every year. Three quarters of that is in the form of microplastics.

What does that mean?

In the places where plastic ends up in the environment, it accumulates. As a result, the burden on the natural environment is steadily increasing. We're even finding plastic particles and used packaging materials in the Arctic and the deep sea. No matter how many nature preserves you set up, plastics always find a way to get inside, harming the ecosystems and the animals that live in them.

SARTORIUS It's unacceptable for plastic waste to enter the environment and the oceans. It's a fact that we need to find solutions. And our industry is helping to develop them.

BAUSKE But surely the first step must be to stop producing plastics in the first place! And that means there where you find large volumes of plastic that quickly become waste: disposable products. In the case of a single-use bag it doesn't matter whether it's made of plastic or paper. The life cycle assessment of a paper bag might even be worse. That's why one of our demands is for the complete avoidance of single-use bags. →

Dr. Bernhard Bauske is responsible for the topic of plastic waste in the oceans of the world for the environmental organization WWF Deutschland. He studied biology at Universität Hamburg and received his Ph.D. from the university's Institute of Soil Science. Bauske has worked at the WWF for the past 28 years. His main areas of interest are packaging and recycling. His work for the WWF includes supporting development projects in the area of the collection and sorting of recyclables in several South Asian countries

Theoretically, we could reuse plastic over and over again.
BAUSKE Theoretically, yes. But I'm skeptical as to whether we will ever develop a genuine circular economy with plastics while maintaining the ways we produce and use them today.

Why?
BAUSKE Plastic is effective, but it's also very complex. Some plastic products contain between 40 and 200 different additives. Because of the differing material properties, it's not easy to recycle this material. This is where we have to harmonize our efforts.

When researchers develop new materials in order to meet very specific requirements, they often work with plastics—for packaging just as for bone implants. Are we running the risk of having to limit these possibilities in the future?
SARTORIUS Absolutely! Of course plastics are developed and produced not in order to become waste at some point, but because of the benefit they bring to their respective applications. The Gesellschaft für Verpackungsmarktforschung (Society for Packaging Market Research) in Wiesbaden has found out that in Germany innovations alone have saved about a million tons of industrial packaging materials annually over the past 20 years. To put it another way, over a fourth of potential plastic content is avoided before the product even goes to market. However, it's true that the greater complexity of these optimized packaging materials creates a difficulty. For example, there are specialized multilayer composites that make it difficult to recycle these materials.
BAUSKE This is an important pair of conflicting goals. A very thin packaging material requires fewer fossil resources. But because the layers can't be separated or usefully recycled together, the packaging ultimately ends up in a waste incineration plant. If the current development continues, in the future between 10 and 13 percent of the CO2 budget we're permitted to use for reaching the 1.5°C climate target will be taken up solely by the production and incineration of plastics.

Will new bioplastics bring us closer to a solution?
BAUSKE Unfortunately, no. Just the production of bio-based raw materials for plastics can be problematic. I'm thinking of the use of pesticides, social problems in the countries where the raw materials are extracted, and competition with food production. In addition, bio-based plastics are not biodegradable in themselves. The most important factor is keeping plastics in circulation for a long time.

"We have to make sure that plastic foils and other materials are sufficiently valuable to ensure that they will be collected"

BERNHARD BAUSKE

And what about biodegradable plastics?

BAUSKE Even biodegradable plastics harbor problems. When they are in cold saltwater, they don't disintegrate anywhere near as fast as they do in warm compost heaps. Besides, they are not welcome in industrial composting plants, because the decomposing times there are much too short. Today German composting plants usually screen out every bit of plastic because they can't know whether a given type of plastic breaks down or not. In other words, even a biodegradable plastic bag is fished out and incinerated. Moreover, consumers feel encouraged to simply discard packaging made of biodegradable plastics somewhere outdoors. Biodegradable plastics should be used only in areas where it's difficult to retrieve them, such as in agriculture and forestry.

SARTORIUS Of course consumers should definitely not be encouraged to litter. However, we can't compare the waste disposal system in Germany with those of other countries. We've got extremely varied waste disposal systems in Europe. In Italy, for example, there is an established protocol for dealing with plastics that are certified as compostable, ranging from production to handling and all the way to composting or fermentation facilities. It's important to make sure that collection and sorting systems are adapted to these materials and that they don't interfere with other established recycling routes.

So what does the path toward a circular economy look like?

BAUSKE The first step, which is also being promoted by the WWF, would be an international treaty that obligates states to prevent the dumping of any more plastic waste into the oceans. That's actually a relatively simple and manageable demand. But it requires countries to get to grips with their waste management systems.

In order to do that, they need support and the transfer of know-how. Secondly, we urgently need an expanded system of producer accountability, and a legal framework must be created for this at the national level. Thirdly, McKinsey and the Ocean Conservancy environmental protection association discovered a few years ago that in Southeast Asia about 80 percent of the plastic in packaging waste holds very little value for garbage collectors. As a result, it's usually disposed of at illegal dump sites, and from there it seeps into the environment. That's why we have to make sure that plastic foils and other materials are sufficiently valuable to ensure that they will be collected and reprocessed into similar products.

What can the producers do in order to reach this goal?

SARTORIUS Product design is one of the essential keys that producers need in order to improve their performance in this area. Take for example the familiar pouch bags that are used as refill packs for liquid soap and dog food. They have to fulfill extremely stringent requirements in supermarkets. They're not supposed to burst or leak, even if they fall from a great height. Here it would be possible to make sensible compromises in order to find simpler and more environmentally friendly solutions. Instead of needing to last for two years, this kind of packaging might need to last for only six months.

In that case, you would no longer need nine layers of foil; you'd only need five. The crucial difference is that we could bind these different layers together so that the materials are compatible with each other. Then, after the packaging has been used, everything can be recycled together. →

“It’s important to develop new recycling solutions in a process that is open to all types of technology”

INGO SARTORIUS

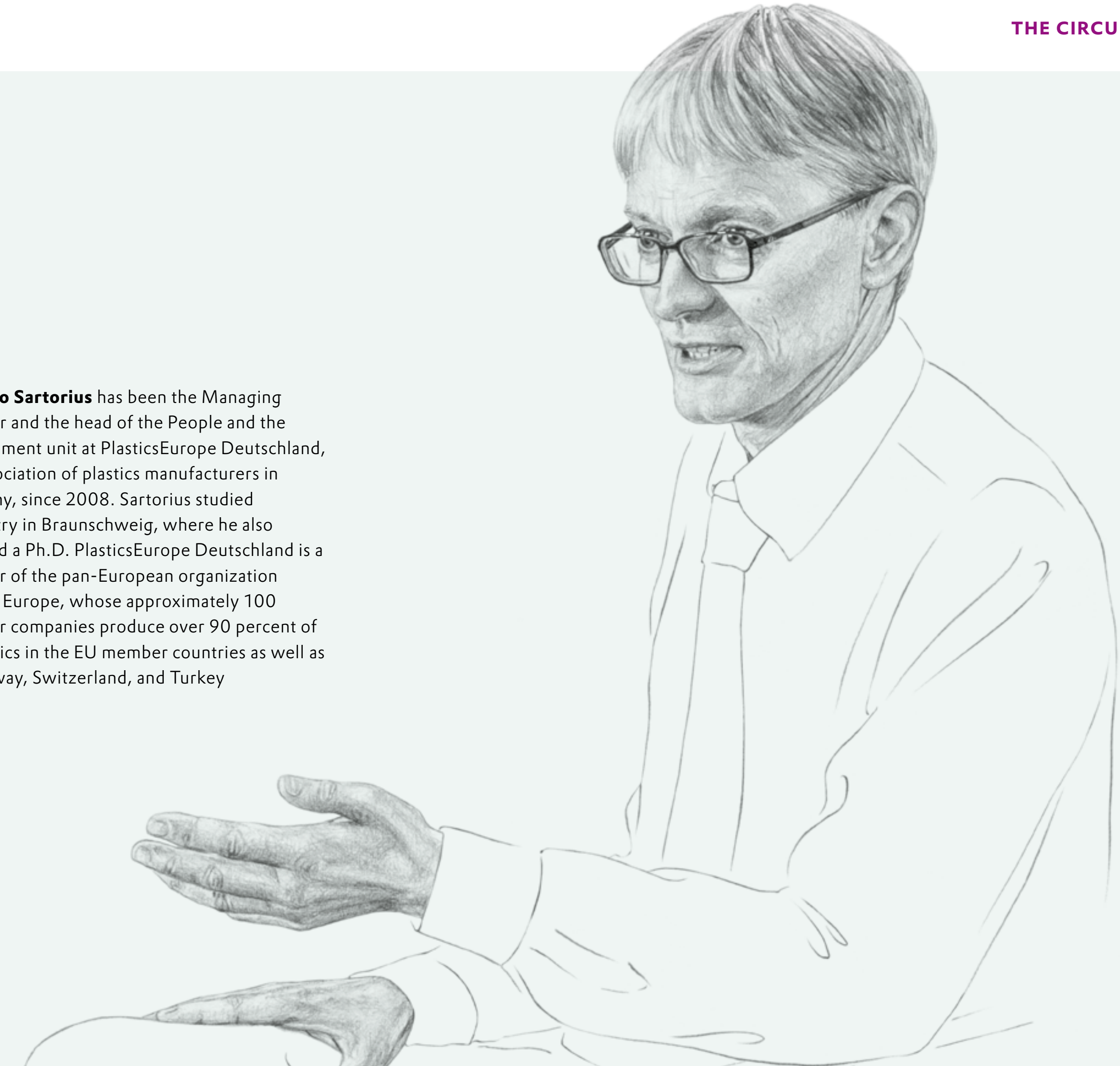
Can you manage to do that?
With our know-how, that’s completely doable. It’s essential for the material developers and the designers to work together. That’s why we participate, among other things, in the Eco Design of Plastics Packaging Round Table, which has already developed guidelines for such collaboration. But products like these also have to be paid for.

How can chemical recycling help to solve the compatibility problems?
SARTORIUS We want to retain the material properties of plastic as much as possible. That’s why we have to initially give priority to mechanical recycling processes—whether that means melting and then granulating the plastic or using new processes to dissolve the long-chain polymers, filter out impurities, and precipitate the polymers once again. That scarcely changes the polymer chain.
This process is different from chemical processes, in which polymer chains are split apart and then the tiny components are used to produce new plastics.

Wouldn’t that be an alternative?
SARTORIUS Of course, there’s a lot of potential there. The research is ongoing, and the plastic producers are working on various scientific projects together with the chemical industry, users, and recyclers. At the moment we’re mainly focusing on technologies such as solvolysis, depolymerization, and pyrolysis.
BAUSKE We are rather skeptical about this method. Chemical recycling is being proposed again and again as the solution to our waste problems, but it’s actually not a new idea. Processes such as pyrolysis are very complex. These facilities, and especially their input, need to be very precisely managed. Simply collecting waste and dumping it into the facility doesn’t work. If I need to painstakingly sort the incoming materials, I might as well be doing mechanical recycling. But I don’t mind admitting that the promise of producing new materials consisting of “clean” molecules sounds very appealing.

But…?
BAUSKE But the questions remain: Can this be technically implemented on a large scale as well? Are the costs competitive? What happens to the production waste? Ultimately we also need to take a critical look at the energy balance sheet and other environmental parameters.
SARTORIUS Of course many questions still remain unanswered. But we shouldn’t lump all chemical recycling processes together in the same basket. Depending on the individual process, the life cycle assessments can turn out to be very different. In particular, we’re addressing residual waste fractions that are generated in households as well as industrial and commercial facilities. Then we’ll find ways to extract valuable materials that until now could only be utilized as fuel. We are conducting intense research to this end, for example at the Karlsruhe Institute of Technology, where we are participating in a major consortium.

BAUSKE Research is good, and I’m not opposing it. However, it won’t save us in the next ten years. There’s no alternative to avoiding waste, replacing materials, and expanding mechanical recycling by every means possible—especially by improving collection and sorting systems.



Dr. Ingo Sartorius has been the Managing Director and the head of the People and the Environment unit at PlasticsEurope Deutschland, the association of plastics manufacturers in Germany, since 2008. Sartorius studied chemistry in Braunschweig, where he also received a Ph.D. PlasticsEurope Deutschland is a member of the pan-European organization Plastics Europe, whose approximately 100 member companies produce over 90 percent of all plastics in the EU member countries as well as in Norway, Switzerland, and Turkey

If you could write the laws yourself, how could these problems be solved?

BAUSKE In countries whose waste management systems are not well developed, we need a legal framework for expanded producer responsibility, like the one we have in Germany. Companies that put products and packaging on the market are responsible for collecting these materials at the end of their life cycle, sorting them, and recycling them. The WWF is providing focused support to Southeast Asian governments as they acquire the necessary know-how and build the systems they need. A licensing system for packaging could provide support for the waste management industry, which is currently underfunded, as well as providing the necessary steering effect. We also should see whether it makes sense to tax petroleum-based plastics in the same way we tax other petroleum products.

Additional taxes? Why?

Fresh materials compete directly with recycling materials, which become more attractive as a result. This is important, especially in countries that have a large informal waste management sector. For example, in Indonesia and Vietnam many people make a living by collecting valuable plastic materials and bringing them to recycling facilities. If this work ceases to pay, they will stop doing it. As a result, the market will suddenly collapse, and so will the waste collection process. And then we will once again find these materials in the environment.

So we should we tax petroleum-based products in order to make fresh plastic more expensive?

SARTORIUS I think this option is problematic. It would also raise the prices of the plastics that are used in lightweight construction materials to protect the climate or are wonderfully easy to recycle, for example. We're familiar with the discussion about paper bags and plastic bags—in which plastic bags are in a much better position in terms of the circular economy. That also applies to PET bottles, which consist of a single plastic and for which there has long been an established materials cycle. It's important to continue expanding the existing circular economy and to develop new recycling solutions in a process that is open to all types of technology. Further possibilities should also be expanded in other application areas besides the packaging sector. That will enable us to create a genuine circular economy faster. Plastic in particular has what it takes to do that.

Lauren Kjeldsen head of Evonik's Specialty Additives division

The Circular Economy's Time Is Now

by Lauren Kjeldsen

Transformation from linear to circular will be a key part of achieving climate targets. To make it work we need cross-industry cooperation, innovation, and smart policy making, as well as a good balance between the economics, the environment, and quality of life.

A couple of years ago, I was at an industry event here in Europe where we were shown an image of stacks upon stacks of used mattresses in a landfill. It was a disturbing sight and the image has stayed with me. The experience triggered a desire to find a solution. As a chemical engineer, I know that these materials will be around in that form in the environment for a long time unless they are burned. And while burning provides some thermal energy, I am convinced that we can develop innovative ways to get more out of such materials. Today, I am proud to be part of this initiative and responsible for Evonik's global circular plastics program, which is pooling diverse projects and expertise from around the company to drive circularity forward.

Circular economy has enormous potential. Imagine being able to turn trash into a valuable raw material. The world has carbon-based materials in abundance, including CO_2 and the vast majority of plastics. We literally have "valuables" in our bins at home, the used equipment we discard, the cars we once drove. If we can regenerate these materials at the end of their useful lives and give them a new life, we can transform from linear—make, use and dispose, to circular—make, use, repurpose. A fully functioning circular economy would eliminate to a large extent the need to extract fossil fuels and it would reduce the production of CO_2.

This is relevant now. Circular economy is part of the Green Deal, the European Union's plan to become climate-neutral by 2050 and generate economic growth through greater sustainability. Beyond Europe, China's recent pledge to become carbon-neutral by 2060 will include circular carbon solutions. Circular economy will play a key role in fulfilling the Paris Agreement, the international treaty on climate change, which the USA is now rejoining.

EXPLORING NEW WAYS OF RECYCLING

To make circularity a reality we need four things to come together. The first is innovation. Companies like Evonik contribute to this. We have the tools and expertise to ex-

"We need both mechanical and chemical recycling to fulfill ambitious political goals. Neither of these technologies is inherently better than the other one. In fact, they are complementary"

plore new ways of enabling the recycling of plastics. The second is a level playing field. There can be no discrimination between certain technologies or materials. The challenges are so massive and diverse that we need all recycling methods available. This is where smart policy-making comes in. The third is cross-industry cooperation. The transformation to a circular economy can't be achieved by one company, or even one industry. We need all the players along the value chain. The fourth factor is finding the right balance between the people, the environment, and economic aspects. We can't place one on a pedestal and throw the other two to the wind. It would be great if instead of forgoing things we could develop a circular system that enables quality of life and balances the burden on the planet. We need to weigh up which available solution is best as a whole.

The economic part is important. Many recycling processes are at the fledgling stage and need to become efficient enough to make them attractive. Often it has been too costly to extract carbon materials. And "new" hydrocarbons in the form of oil, coal or natural gas have been cheaper. But smart policy-making can help overcome this cost hurdle. Innovation in chemistry is cutting costs. In fact, our customers are demanding these innovations and we are delivering them. With our current ideas for circular plastics, Evonik estimates additional sales of more than €350 million from 2030 annually. And that is just the start.

But the economics aren't enough on their own. Circularity must be environmentally friendly. By giving plastics a second life, we avoid incineration and preserve fossil reserves. We must come up with sophisticated recycling methods that don't consume more energy than the production of a new material. That's why scientific life-cycle assessments are needed to measure the environmental impact of a product from beginning to end. The life-cycle analysis goes beyond measuring a product's environmental footprint during its useful life. It includes everything from raw material extraction through manufacture and delivery to the customer.

Besides economics and the environment, there are people, or society. Circular economy solutions need to improve peoples' quality of life. To name just one example, people all over the world need access to transport that will take them from A to B. And just as quality of life is important today, it is important for our children and future generations. Circular economy can help stimulate innovation, create jobs, and boost economic growth in general.

To sum up, the framework we need to make a circular economy work includes innovation, cooperation, and smart policy-making, as well as a good balance between the economics, the environment, and quality of life.

But what about the tools to make plastics circular? Taking a closer look at the recycling toolbox, two promising methods we need to advance are mechanical and chemical recycling. When people think of recycling, they mostly think of old plastic bottles being made back into new plastic bottles. That's an example of mechanical recycling. It's the processing of plastic waste which includes many steps such as grinding, washing, separating, and drying.

Chemical recycling is a process where the polymer chain is converted into chemical building blocks including monomers that are then used again as a raw material in chemical processes. This type of recycling can even allow plastics to have a second life as a higher-quality substance not limited to one specific plastic application. As a specialty chemicals company, we could make many of our products with raw materials made from waste instead of fossil-based ones.

NEED FOR A POLITICAL FRAMEWORK

We need both mechanical and chemical recycling to fulfill ambitious political goals. Neither of these technologies is inherently better than the other one. In fact, they are complementary and suitable for different waste streams. Chemical recycling would enable the recycling of mixed waste streams that haven't been recycled so far.

Our industry needs a political framework for chemical recycling. The term should be anchored in legislation and chemical recycling needs to be included in recycling quotas of European countries. Like other recycling methods, chemical recycling could contribute a lot to the goal of keeping fossil resources in the ground.

Of course, the best waste is stuff that doesn't become trash in the first place. Products, regardless of the material they are made of, can often be used much longer. Our specialty chemistry helps make our customers' products tougher and more scratch, heat and corrosion-resistant, thus lengthening their useful lives.

But when products really do reach the end of their lives, we can help right along the plastic industry's value chain and enable the transition from linear to circular. When we're talking about elements such as carbon and enabling recycling, the chemical industry is the right address. Chemistry is, after all, our core competence.

A BRIGHT SPOT FOR THE CLIMATE

TEXT **KARL HÜBNER**

A thyssenkrupp blast furnace in Duisburg at night: Steel production generates carbon monoxide, carbon dioxide, and hydrogen, which could be used in the future for the sustainable production of chemicals

Using the emissions of the steel industry to produce plastics: That's the long-term goal of Evonik and its partners in the collaborative project Carbon2Chem. To reach this goal, they are working with higher alcohols such as ethanol — and catalysts that are being developed in Hanau

The night sky above the Ruhr district no longer glows as brightly as it used to. But when the blast furnace at the steelworks in Duisburg is tapped, it can still be seen from afar. This is where thyssenkrupp produces about ten million tons of steel annually. The smelting process, which extracts the oxygen from iron ore with the help of coking coal, generates huge volumes of smelter gas.

This mixture of gases consists of 40 percent nitrogen, as well as carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen (H_2). Smelter gas is already used today as an important raw material for the generation of energy. By burning the smelter gas, thyssenkrupp generates enough heat to completely cover the Duisburg plant's energy needs. However, the plant still emits 20 million tons of carbon dioxide annually. This accounts for about 2.5 percent of Germany's CO_2 emissions. About eight percent of the world's carbon dioxide emissions are generated by steel production.

That's why the research project Carbon2Chem, in which Evonik is participating, is searching for ways to use carbon and other components of smelter gas to produce chemicals. The project's goal is clear: The more effectively smelter gas is recovered, the lower will be the levels of CO_2 emissions and of the fossil raw materials needed for production.

The project has a broad foundation. In addition to thyssenkrupp and Evonik, the Carbon2Chem project partners include almost 20 companies from the chemical, energy, and steel sectors as well as academic research institutes. The German Federal Ministry of Education and Research is funding the project with about €140 million in total. The first phase of the project began in 2016 and was concluded with promising results. The second phase is now beginning (see the box on page 43).

PROVEN TECHNOLOGY, NEW CHALLENGES

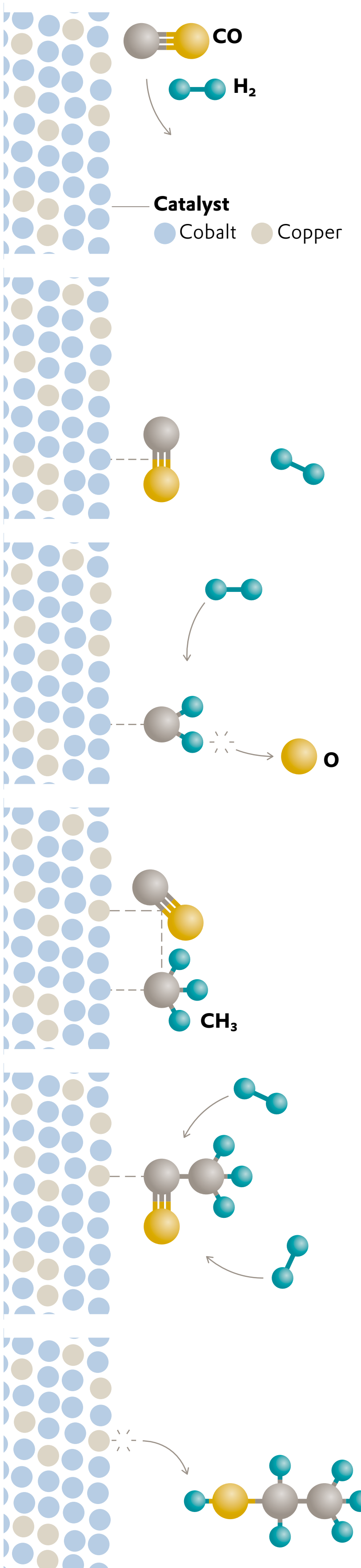
The chemical principles underlying the transformation of smelter gas into a multitude of chemicals have been well known for over a century. The chemical industry has long been using gas mixtures consisting of CO, CO_2, and H_2—known as syngas—on an industrial scale for a variety of processes, including methanol production. One of the basic challenges for the researchers in the Carbon2Chem project involves the treatment of smelter gas and the adaptation of the tried and tested processes to the syngas generated by steel production.

In a subproject of Carbon2Chem, Evonik is doing pioneering work to develop a new technology. The specialty chemicals company is developing catalysts that will be able to transform CO and H_2, which are essential components of smelter gas, into higher alcohols that could not have been produced by this method in the past (see the information box on page 41). In the future, the project team would ideally like to find ways to recover CO_2 directly.

Dr. Bernd Jaeger, who heads the catalyst research unit at Evonik, points out that this research is being driven by the impending transformation of the chemical industry. "The replacement of fossil sources of raw material with sustainable and CO_2-neutral input materials will transform the present-day material flows in our industry," he says. Higher alcohols could play a key role in this value chain. "However, we still don't have a cost-efficient and selective chemical production process for them," says Jaeger. This is where the Evonik researchers' idea comes into play: the design of customized catalysts that enable precisely this missing step toward a sustainable value chain by directly transforming smelter gases and carbon dioxide. →

From syngas to ethanol

A schematic diagram of the reaction processes



1 Syngas ($CO + H_2$) flows into the reactor and then past the catalyst inside it

2 CO molecules adhere to cobalt atoms

3 H atoms gradually adhere to C atoms, while the connection with the O atom loosens. In the process, a methyl group is formed

4 Next to the hydrocarbon unit that has formed, a second CO molecule adheres to a copper atom in the catalyst's surface

5 The second CO molecule bonds with the existing CH_3 group

6 A reaction with additional hydrogen results in the finished alcohol molecule (in this case ethanol), which separates from the surface

Catalysts reduce the amount of energy needed to trigger chemical reactions, thus accelerating them and making them more efficient. Sometimes they make a chemical reaction possible in the first place. And that's what is happening here. "Carbon dioxide and hydrogen molecules would never decide on their own to band together and form bigger molecules," says Dr. Dorit Wolf. "The catalyst gives them the help they need to take this step." Dr. Wolf, a chemist, is the head of Evonik's research department for process catalysts. From her base at the Hanau location, she coordinates the research cooperation between thyssenkrupp Industrial Solutions, Evonik, and research institutes for the Higher Alcohols project.

The team in Hanau has already produced a number of potential catalysts in recent years. The candidate catalysts, which consist of black powder, don't look very spectacular. This draws a visitor's attention all the more toward the container full of a violet substance that is standing under the laboratory's flue. "This is a cobalt salt we use as a raw material," explains Dr. Arne Reinsdorf, the head of development for mixed metal catalysts. And he reveals part of the secret behind all previous catalytic approaches: "There's always some combination of cobalt and copper, embedded in a carbon matrix in each case."

A MIX OF COPPER AND COBALT

In order to synthesize higher alcohols from a molecule such as CO, a catalyst must enable a series of very different reaction steps (see the infographic at left). To this end, the scientists need various active centers on the catalyst's surface. A homogeneous material consisting of a single substance would not be adequate, so the team is using a combination of cobalt and copper.

There are good reasons for this choice. The experts are relying on know-how that was gained previously from similar processes. Cobalt catalysts have proved their worth in the conversion of syngas into longer-chain hydrocarbons by means of the Fischer-Tropsch process.

Copper, in turn, is a tried and tested component of the production process for the simplest alcohol, methanol. "In the synthesis of higher alcohols we are trying to combine these two well-established processes in such a way that they initially form hydrocarbon chains that still contain the alcohol group OH at the end of the process," Reinsdorf says.

At the Evonik location in Hanau, laboratory assistant Mona Müller monitors the intermediate stage of a catalyst synthesis (left). The researchers use a rheometer to measure the flowability of their powders

The idea of using a combination of cobalt and copper was only the beginning of working out the details. These included questions regarding the optimal proportions of the two elements and the optimal chemical structures they should have for the process—for example, as metals or in an oxidized form, separated into individual particles or in a mixed phase. The researchers also knew that a trace amount of manganese would help to kick-start the catalyst, but they still had to find out whether it would be preferable to position it on top of, next to, or between the copper and cobalt particles.

They had already carried out numerous tests to determine the optimal proportion of manganese to use. This testing was supported by the Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT) in Oberhausen. That's where the catalyst samples from Hanau are being tested in a parallel reactor system made of stainless steel. Under precisely defined conditions of temperature and pressure, the experts are guiding syngas through the reactors and subsequently analyzing the results to find out what substances have been produced in what quantities.

Only the catalysts that have successfully passed the testing process at Fraunhofer UMSICHT will now be subjected to the next stage of testing in the project's second phase at thyssenkrupp in Duisburg. The technical center that was built there specifically for the Carbon2Chem project has a test setup that is similar to the first one but has three important differences: the reactors are bigger, the syngas supplied to them is extracted directly from the smelter gas of the neighboring steelworks, and the test series will run much longer so that the lifespan of the catalysts can be examined. →

Higher alcohols

Higher alcohols are defined as alcohols with more than one carbon atom. The simplest variant is ethanol, which is present in alcoholic beverages and is formed during the alcoholic fermentation process. Ethanol also plays a role in many chemical syntheses and as a fuel additive (E5, E10). Other higher alcohols serve, among other uses, as precursors in the production of active ingredients for pharmaceuticals and plant protection agents; surfactants for creams, salves, and cleaning agents; and solvents and plasticizers for plastics. Some alcohols are produced in volumes of several million tons per year.

Until now, some short-chain alcohols have been mainly produced via the fermentation of biomass, whereas the synthesis of longer-chain alcohols has been based on petroleum. In both cases, production using syngas (from waste) could be a sustainable alternative (see also the "People & Vision" section on page 9).

Although the starting materials and the interim steps of synthesis are still quite colorful, the finished catalyst material is always black

The results of the initial test series with more than 40 catalyst variants from Hanau were clear: It is definitely possible to use syngas to produce higher alcohols. This is a major success, but so far the process has generated too many unwanted byproducts—in particular, methane and short-chain alkanes. The newest generation of catalysts results in a more than 50 percent proportion of higher alcohols. “This means we’ve reached the target of the first project phase,” says Wolf. But she’s still not completely satisfied. “We need higher selectivity and even better yields,” she adds.

INTEGRATION OF CARBON DIOXIDE

That’s why the experts are continuing to work on optimizing the catalyst. The first test series showed them that a ratio of four parts of cobalt to one part of copper works well. Now they are specifically investigating process conditions such as the pressure, temperature, and retention time in the reactor. Other significant parameters could include the size of the metal crystallites and thus the incidence of crystal surfaces, corners, and edges in the powder. In order to gain a better understanding of these parameters with the help of experiments, the Evonik researchers are working together with experts from Ruhr-University Bochum and RWTH Aachen.

In parallel to this research, Dorit Wolf and Arne Reinsdorf are addressing another topic: also using carbon dioxide for the reaction. There was no carbon dioxide in the syngas that was used in the tests so far, but carbon dioxide is a major component of smelter gas. “We are now trying to design our catalyst in such a way that CO_2 can be integrated into the synthesis,” says Wolf, adding that “this work is absolutely not trivial.” If this effort succeeds, in the future it could also be possible to use other gas mixtures containing CO_2 as raw materials for the process.

But at the moment the researchers are focusing on increasing the catalyst’s selectivity. They want to not only increase the yield of higher alcohols but also to more effectively control the length of the molecular chains that are produced. So far, the distribution of the chain lengths in the product mixes ranging from ethanol (with two C atoms) to hexanol (with six C atoms) has been sufficient. However, for later users of this technology it would be very useful to be able to precisely control the length of the chains. That’s because, depending on the length of their molecular chains, various alcohols are of interest to very different market participants.

Carbon2Chem

Circulating carbon in a closed loop instead of emitting it into the environment—that is essentially the goal of the Carbon2Chem project. To reach this goal, the project aims to develop technologies that will make it possible to materially recover the smelter gas that is generated during steel production. Almost 20 partner companies from the chemical, energy, and steel sectors, including Evonik, as well as research institutes are devoting themselves to specific issues in a variety of subprojects. One of the areas being investigated is the use of smelter gas components to produce important chemicals such as ammonia, methanol, and higher alcohols. Another subproject is working to develop suitable processes for separating the substances contained in smelter gas.

The first phase of the project, from 2016 to 2020, had a budget of approximately €120 million, more than €60 million of which was provided by the German Federal Ministry of Education and Research (BMBF). The financial framework for the project’s second phase, from 2020 to 2025, is even larger; it will be supported with up to €75 million by the BMBF.

The project is supported by the German Federal Ministry of Education and Research under the grant numbers 03EK3041A (2016 – 2020) and 03EW0008A (2020 – 2023)

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

"We need higher selectivity and even better yields"

DORIT WOLF, HEAD OF THE RESEARCH DEPARTMENT FOR PROCESS CATALYSTS AT EVONIK

Whereas the longer alcohols are especially in demand among producers of specialty chemicals, shorter alcohols such as ethanol and propanol could be used to produce synthetic fuels, and monomers could be used to make monomers for polyolefin production. Bernd Jaeger believes that there is great potential for a catalyst platform in this area. "Ideally, in the future we will offer a whole range of customized versions from which every user can choose the catalyst that matches his requirements," he says.

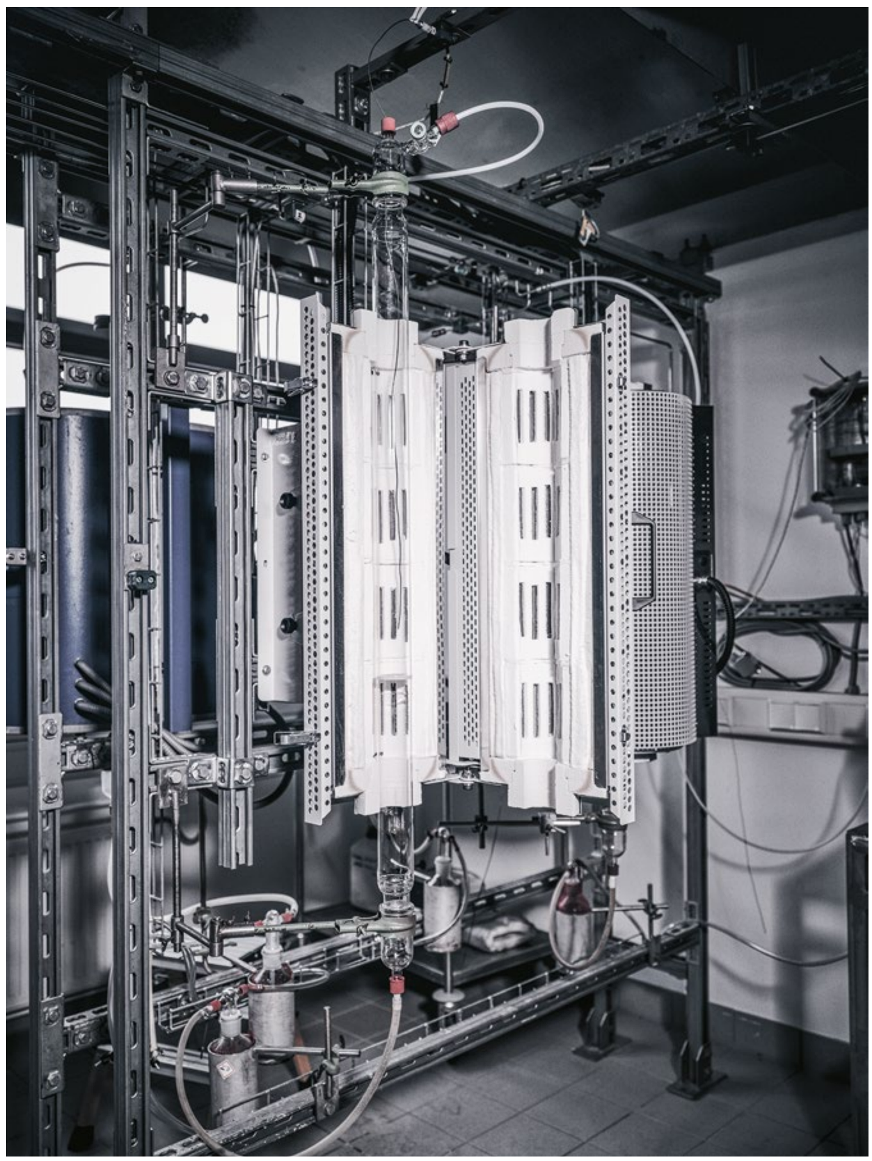
OTHER SOURCES OF RAW MATERIALS ARE POSSIBLE

Jaeger is also thinking one more step ahead. "Of course the ultimate goal must be to close material cycles," he says. And the process developed in the higher alcohols project could one day help to achieve exactly this goal. "We're developing a technology for the recovery of syngas, and this gas can also come from other sources," Jaeger adds. As soon as the process is established, biogas plants could also be considered as a source of raw material.

In the future, waste plastics could also supply the desired gas mixture if the plastics were decomposed at a high temperature and high pressure in the presence of small amounts of oxygen. Some companies are currently working to scale up this gasification process to the industrial level. "That would be interesting for processing waste flows that cannot be mechanically recycled, for example," says Jaeger, referring in particular to dirty or mixed waste that contains the plastics polyethylene or polypropylene. "These two polymers in particular are produced in large amounts, but to date they have seldom been chemically recycled," he says.

Both of these polymer types can in principle be produced from two higher alcohols: ethanol or propanol. In this process, the alcohols are initially converted into ethylene and propylene—substances that previously were extracted from petroleum. The individual building blocks ethylene and propylene could then be used to make new polymers—and thus new plastic products. A material cycle would be closed.

Karl Hübner has a doctorate in chemistry and is a journalist. He also works part-time as a freelance author and often writes about research-related topics



After synthesis, the catalyst material must be dried. This process takes place under protective gas in rotary kilns

A NATURAL TALENT

"We turn a seemingly worthless material into a valuable one"

FRANK WEINELT, HEAD OF PRODUCT AND PROCESS DEVELOPMENT AT THE HIGH PERFORMANCE POLYMERS BUSINESS LINE OF EVONIK

For a long time, lignin was considered a waste product of cellulose production. This wood component was mainly burnt to generate energy. However, this natural raw material holds hidden talents—as a component of high performance polymers.

TEXT **NICOLAS GARZ**

For most people, this viscous brown liquid that accumulates in large amounts at cellulose factories looks like waste. However, someone like chemist Dr. Frank Weinelt considers it to be a promising candidate for the development of high performance polymers. Experience has given Weinelt a good eye for a material's potential. As Head of Product and Process Development at the High Performance Polymers business line of Evonik, Weinelt is always looking for raw materials that can be used to produce components for plastics. His goal is to discover natural alternatives to crude oil, which has served as the basis for petrochemical products for decades.

One of Weinelt's most promising natural talents is this brown liquid. It consists of lignin, which is a component of wood. This natural polymer is a waste product that is created during the production of cellulose, which is used, for example, for writing paper and toilet paper. Each year, the paper industry generates more than 50 million tons of lignin worldwide. "Lignin is a renewable resource and inexpensive," says Weinelt enthusiastically. "Nature supplies this material in large amounts for free."

Renewable raw material: The natural polymer lignin is a component of wood and accumulates in large amounts during the production of cellulose

However, because it biodegrades very slowly, lignin has, to date, been mainly dried and burnt to generate electricity. But the polymer specialists at Evonik consider it to have much more potential. "Lignin is a sustainable raw material that is well-suited for the production of interesting monomers," says Weinelt. "For example, it can be used to create substituted adipic acid, which is a possible component of high performance polymers. It hasn't been available to us previously and probably can't be extracted from petrochemical raw materials very easily."

A NEW SOURCE FOR HIGH-TECH MATERIALS

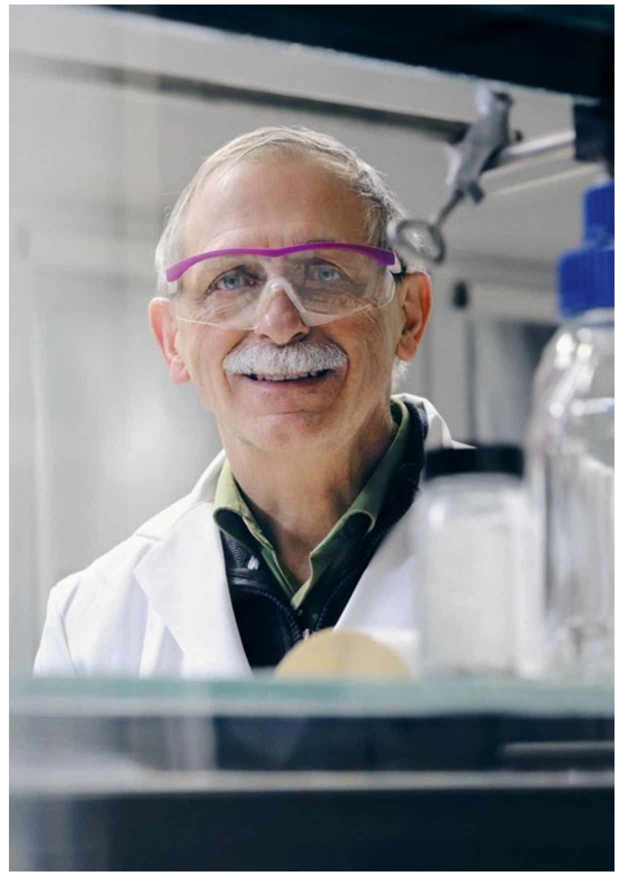
Weinelt's search began in 2017. Back then, Weinelt regularly met Siegfried Waldvogel, a professor at the Johannes Gutenberg University in Mainz and an expert in electrochemistry. Their discussions initially revolved around the renaissance of electrolysis, which is being increasingly used as a result of the big drop in the cost of renewable sources of energy. This method is also employed for the production of basic chemicals. During their meetings at the Marl Chemical Park, the two researchers gradually came up with the idea of using electrolysis to convert the biopolymer lignin into monomers, which can then be processed further into high performance polymers. "That way, we turn a seemingly worthless material into a valuable one," explains Weinelt.

Electrolysis is suitable for this purpose for a number of reasons: "For one thing, the electricity is supplied completely by renewable energy sources that are now readily available," says Waldvogel. Moreover, electrolysis doesn't create any reagent waste as a by-product, as is the case with traditional organic processes." →

One project, 16 partners

The research program LIBERATE (Lignin Biorefinery Approach using Electrochemical Flow) encompasses a total of 16 partners who are working on electrochemical applications of the starting material lignin. In addition to Evonik, the consortium consists of the two chemical manufacturers Perstorp and Oxiris, seven small and midsized companies, four international research institutions including the Fraunhofer-Gesellschaft zur Förderung der Angewandten Forschung (Fraunhofer Society for the Advancement of Applied Research), and two universities. The project receives a total of around €10 million in funding.

The project was supported by the European Union's research and innovation program Horizon 2020 as part of the funding agreement No. 820735.



Evonik researcher Franz-Erich Baumann uses lignin-based adipic acid to develop polyamides

The researchers submitted their idea to the EU funding program Horizon 2020—and their project was accepted at the beginning of 2018. Since then, the company and the professorship have been part of the Europe-wide LIBERATE consortium (you can find more details in the information box). "LIBERATE consists of several subprojects," explains Head Coordinator Angel Manuel Valdivielso, who works at the LEITAT technological center, which is based in Barcelona. "What all of them have in common is their use of electrochemical processes to transform lignin into a variety of basic chemicals."

While Evonik and the researchers in Mainz are extracting monomers from lignin, other partners are working on the transformation of kraft lignin into the flavoring vanillin. Another part of the consortium is forging ahead with the conversion of this biopolymer into oligomer phenol derivatives (see the diagram).

Time is of the essence. Plans call for an electrochemical pilot plant in Trondheim, Norway, in which the electrolysis of lignin can be conducted on an industrial scale, to be commissioned at the end of 2021. "This pilot plant will enable us to electrochemically produce lignin-based chemicals so efficiently that they can compete with conventional products in the future," says Valdivielso. "More and more companies all over the world are converting their production facilities to biogenic materials. As a result, there's a huge need for demonstrably sustainably produced chemicals, and it will continue to grow."

ELECTRIFIED

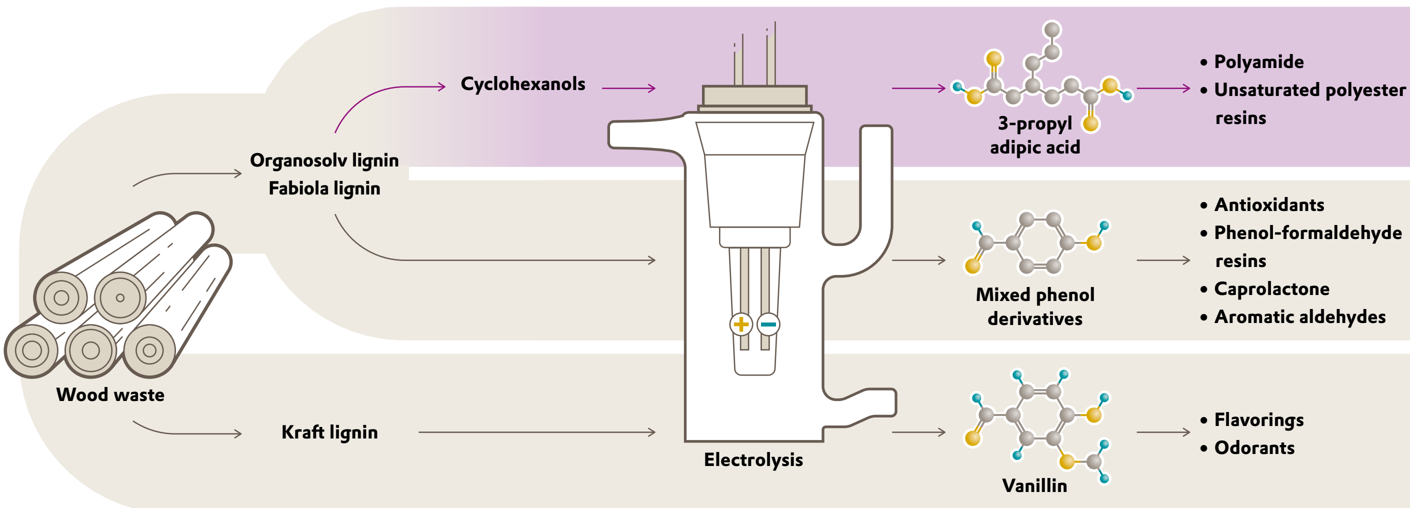
How the process already works on a small scale can be seen in the laboratories at Mainz University. Here Siegfried Waldvogel is working day after day with dissolved lignin, which is sent to him by cellulose manufacturers. The electrolysis of dissolved lignin proceeds in several steps. "First we dissolve out the necessary components from the polymer," says Waldvogel. In order to do that, his fellow researchers pass an electric current through the lignin, which is dissolved in a sodium hydroxide solution in a stainless-steel pressure tank.

This first step, depolymerization, creates phenols, which then react with hydrogen with the help of a catalyst. If this hydrogenation was successful, the researchers obtain wax-like cyclohexanols that are oxidized in the final step in a large glass cell. "Once the oxidation process is completed, we get biogenic dicarboxylic acids, such as substituted adipic acid, which can be used for further processing into copolymers," says Waldvogel.

Because the lab in Mainz is conducting basic research, the amounts produced are correspondingly small. However, the electrolysis of lignin is to be conducted on a large scale in the future. "Whereas the steps needed up to the creation of cyclohexanols are performed externally, we want to carry out the oxidation into adipic acid derivatives at Evonik as soon as

From vanillin to plastic

The LIBERATE partners work on a variety of subprojects throughout Europe: In addition to transforming lignin into high performance polymers, such as the polyamide produced by Evonik (upper path), the partners are testing techniques for converting the biopolymer into mixed phenol derivatives (center) or the flavoring vanillin (bottom).



this is economically feasible," explains Weinelt. "The partnership with the University of Mainz provides us with the best basis for expanding our electrochemical know-how in this direction."

FROM MONOMER TO COPOLYMER

The researchers are currently focusing on optimizing the process and the yield. It's all about the amount and quality of the material, because the purer the products that are supplied from Mainz are, the more the polymer specialists from Evonik in Marl can do with them. One of these specialists is Dr. Franz-Erich Baumann, who has been driving forward the development of base polymers in Marl for more than three decades. Baumann's laboratory is full of measuring equipment and apparatus in which he first checks the dicarboxylic acids that have just arrived. He has to determine if they are suitable for further processing into a copolymer. If this is the case, Baumann begins to study with which potential partners (i.e. other monomers and diamines) they can be combined. "This combination ultimately gives the polyamide its characteristic properties," says Baumann. "The lignin-based adipic acid is an important component for influencing these properties." Depending on the combination, this component can account for up to 62 percent of the entire amount of the substance.

If a compound turns out to be promising, the polycondensation begins. The starting materials are filled into a steel cylinder reactor, where they react at high temperatures and under high pressure. After a while, Baumann opens the cooled-off cylinder and uses tongs to carefully extract a thin tube that contains a solidified whitish melt: a new polyamide. "Our range of building blocks becomes a bit larger every time that we manage to do this," he says.

There are many possible uses for these materials. In the near future, lifestyle products such as sunglasses could be manufactured using polyamides made from lignin-based monomers. The same applies to components that are still made of steel and other metals, in the automotive and construction industries, for example. However, the researchers aren't that far yet.

"We have to become more efficient and intelligently pool the diverse range of know-how if we are to produce on an industrial scale," says Weinelt. To make this possible, he has now stepped up his cooperation with process technology engineers. Moreover, the polymer specialists are keeping their eyes peeled in the search for other biogenic raw materials, including those from unconventional sources. After all, experience has shown that even some murky liquids may hold a naturally talented substance.

Nicolas Garz is an editor at the Hamburg-based communications agency Bissinger+. He regularly writes about topics from the fields of research, digital technologies, and sustainability

Toward New Horizons

It’s no coincidence that Austria is called a “Land of Mountains” in its national anthem: More than 60 percent of its national territory consists of Alpine mountain regions. Mozart’s native country is also distinguished by a rich cultural landscape, as well as companies whose innovations are propelling this republic into the future. Evonik is represented in Austria by four locations

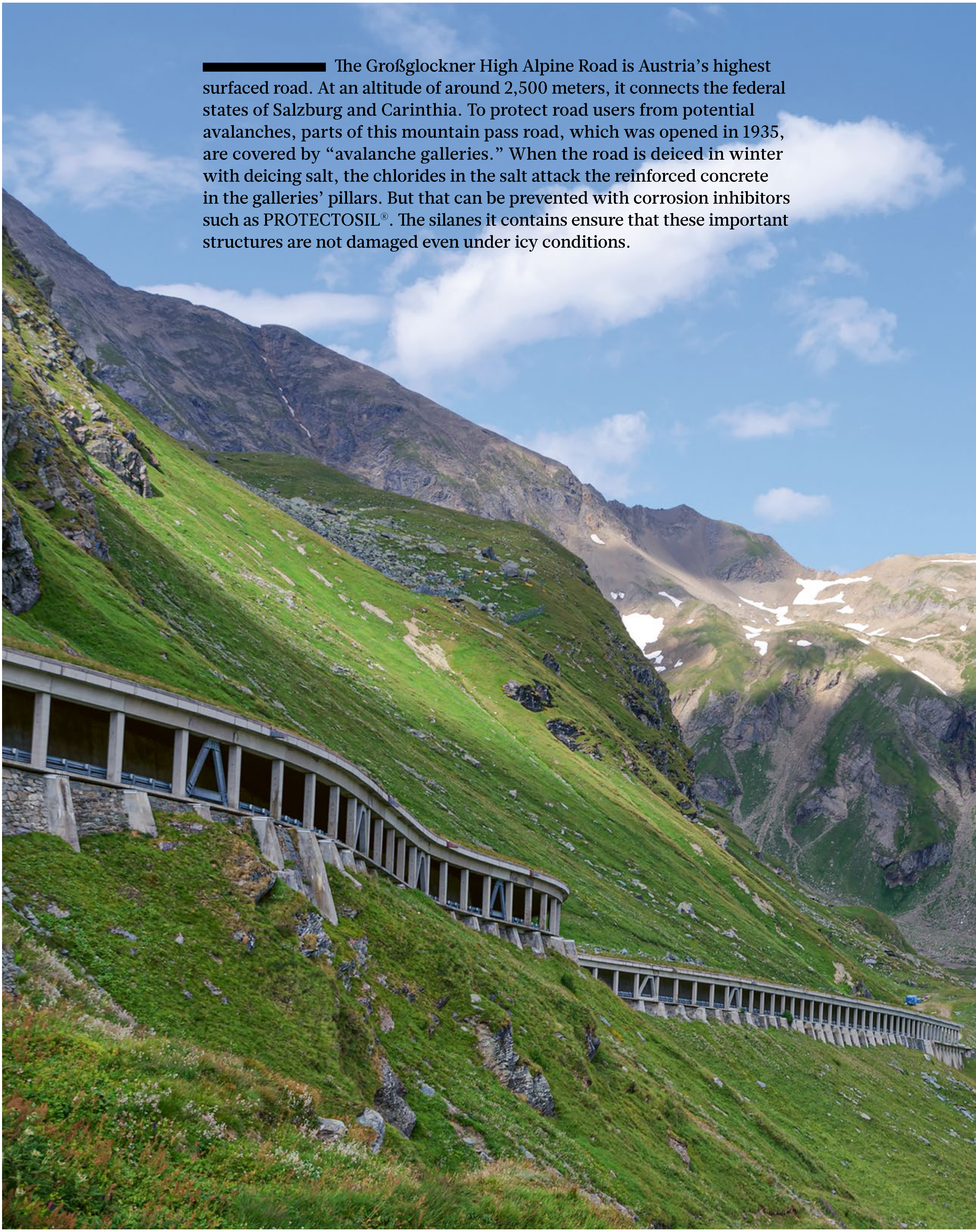
TEXT **ANNA SCHRIEVER** & **NICOLAS GARZ**

From the top of the Schoberstein, a mountain in Upper Austria, climbers have a fantastic view of Lake Attersee. On the lake's northern shore are the municipalities of Schörfling and Lenzing, where textile and synthetic fibers have been produced for almost a century. Evonik has added a sustainable element to this tradition: At its facility in Schörfling, polyimides are processed into fibers and membranes. The plant's highly efficient filtration and separation technologies purify flue gases and refine biogas into ultrapure biomethane, for example.

With the utmost care, Rupert Hofer makes high-quality violins at his workshop in Graz. There's a long tradition of violinmaking in Austria, and the country's string instruments are known for their excellence. To make sure a violin will produce an optimal tone, you need skilled craftsmanship, sound wood, and robust strings, which are generally made of nylon fibers. By comparison with strings made of conventional fibers, strings made of VESTAKEEP®, a high-performance polymer from Evonik, make a new audiophile dimension possible. Their tone is more broad-based, more voluminous, and thus pleasantly warm, yet clear and precise.

The town of Weißenstein is surrounded by an impressive panorama dominated by the Nock Mountains in the north and the Gailtal Alps in the south. And in the midst of it is the Evonik plant where hydrogen peroxide and peracetic acid are produced. The Weißenstein process, which was named after the town, made it possible to produce hydrogen peroxide (H_2O_2) on an industrial scale for the first time. Today H_2O_2 is produced via the anthraquinone process, which is much more efficient. The tens of thousands of tons of H_2O_2 and peracetic acid that are produced annually in Weißenstein are used in bleaching and disinfecting agents, for example.

Austria is a country of culinary delights. The highlights include Wiener schnitzel and Sachertorte, which was created by Franz Sacher in 1832. Today it is baked all over the world, but only the variant served at the Hotel Sacher in Vienna has the right to be called "original." This cake basically consists of eggs, butter, sugar, flour, apricot marmalade (which is called *Marillenmarmelade* in Austria) and, of course, chocolate. The typical crunchy chocolate glaze contains edible oils and fats that are produced with the help of catalysts from Evonik. The catalysts ensure that the glaze sticks to the cake well and melts slowly and lusciously in the mouth.



The Großglockner High Alpine Road is Austria's highest surfaced road. At an altitude of around 2,500 meters, it connects the federal states of Salzburg and Carinthia. To protect road users from potential avalanches, parts of this mountain pass road, which was opened in 1935, are covered by "avalanche galleries." When the road is deiced in winter with deicing salt, the chlorides in the salt attack the reinforced concrete in the galleries' pillars. But that can be prevented with corrosion inhibitors such as PROTECTOSIL®. The silanes it contains ensure that these important structures are not damaged even under icy conditions.

SHORT DISTANCES, OPTIMAL COOPERATION

In this Alpine republic, Evonik is represented by four locations in Lenzing, Schörfling, Weißenstein, and the capital city, Vienna. The transport routes between some of them are very short. For example, the Lenzing plant produces the polyimide that serves as the basis of innovative high-performance membranes produced in Evonik's Schörfling plant, which is only a few kilometers away.

Evonik locations
1 Vienna
2 Weißenstein
3 Schörfling
4 Lenzing

The

4

locations have

327

employees.

A pile of problems or a valuable source of raw materials? A tire dump in Reykjavík (Iceland)

TIRE TEST

More than half of all vehicle tires worldwide are eventually disposed of in landfills or incinerated. However, it would be much better if the old rubber could be reused in road construction. Special additives make the resulting asphalt more durable and environmentally friendly. A life cycle assessment confirms this with data

TEXT **CHRISTOPH BAUER**

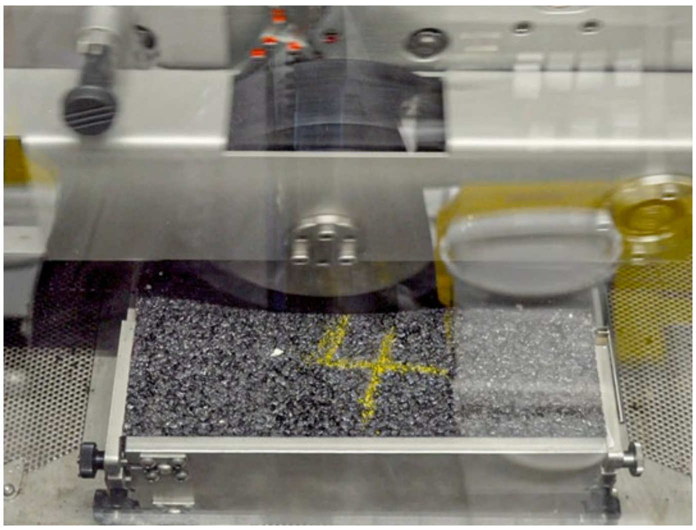
Asphalt enables drivers to get to work safely and goods to be transported rapidly. But it's put to the test before it's actually used. In a cold chamber at the testing firm PTM in Dortmund, engineers simulate winter operation on behalf of Evonik. Although the one square meter of asphalt has been cooled in the chamber to way below freezing for days on end, it withstands the sustained stress and doesn't exhibit any recognizable cracks. Frank Lindner is satisfied with the result. "Our additive VESTENAMER® makes this mixture industrially usable even under tough conditions," says Lindner, who is a road construction expert at Evonik.

The asphalt in the lab is something special, because it is made from ground rubber contained in end-of-life tires as well as from VESTENAMER®, an additive manufactured by Evonik. "The additives ensure that the asphalt layer is strong but still flexible and also give it an optimal degree of compaction," explains Lindner. Thanks to the lab results, data now proves that his observations at many real-world road surfaces since the product was introduced several years ago are correct. This data flows into a comprehensive life cycle assessment (LCA) of the additive. In an LCA, the aim is to assess the impact of a product on the environment in a certain application throughout its service life—from its production and its use until its disposal.

25

MILLION tons of discarded tires are disposed of worldwide each year

"Society in general and customers in particular expect more and more transparency," says Bernd Schlüter, an expert on Evonik's life cycle management team. "Life cycle assessments help to make products more →



VESTENAMER® makes road surfaces more durable even though it only accounts for 0.5 parts per thousand of their volume. This sample is being tested at the PTM lab in Dortmund

comparable." In order to get meaningful data, the technicians subject the VESTENAMER®-enriched asphalt to extreme conditions. Opposite the cold chamber, the PTM laboratory also contains a facility for simulating the height of summer. Temperatures underneath the system's glazed lid measure 60 degrees Celsius. Here, a roller at high pressure goes back and forth tirelessly across a piece of asphalt. At such high temperatures, the sustained stress from trucks causes the dreaded ruts. These ruts pose a danger for car drivers whenever rainwater accumulates in them, for example. In this case too, the data shows that the wear and tear is very limited if the asphalt mixture contains ground rubber and VESTENAMER®.

SUPPORTING ARGUMENTS WITH DATA

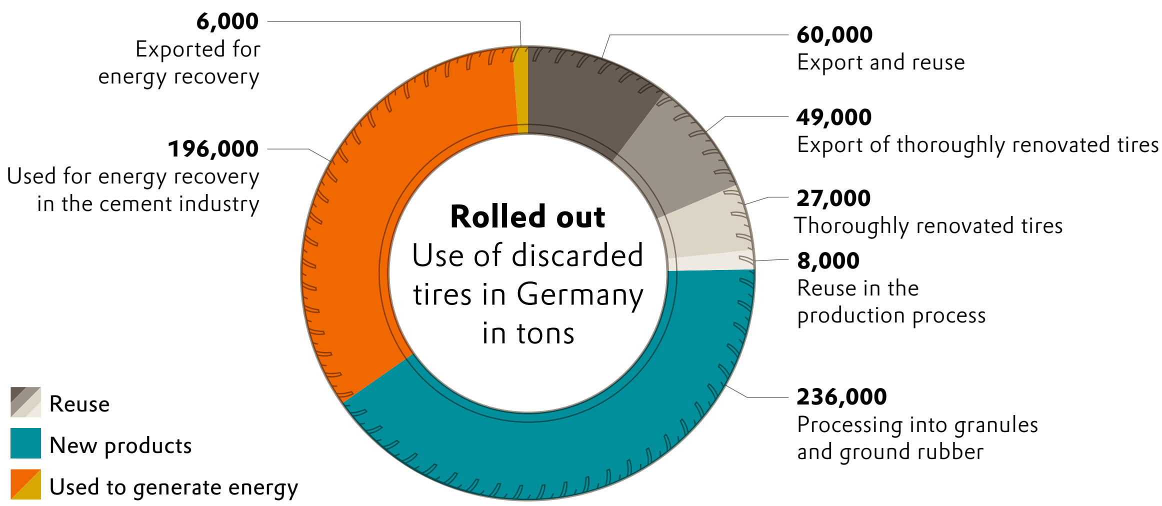
An enormous amount of effort is needed for these tests. But why is so much effort being made for a product that only accounts for 0.5 parts per thousand of the surface of a finished road? "The amount plays a subordinate role," says Lindner and adds, "The crucial thing is what the product does." Statistics, data, and facts help to demonstrate the product's benefits.

50

PERCENT of a road surface can be reused, thanks to VESTENAMER®

A lot of convincing still needs to be done. Although it makes sense to use ground rubber in road construction for a variety of reasons, it never really caught on in the past. However, rubber is cheaply available in large amounts in the form of discarded tires. When ground rubber is added to asphalt it gives the mass the desired level of adhesiveness. Unfortunately, the material also sticks to the machines and trucks of road construction companies. The mixture is very hard to handle at normal working temperatures. Higher temperatures require more energy and cause the ground rubber to begin to break down. "In the past, whenever road builders heard the word 'ground rubber,' they immediately lost interest," says Lindner.

VESTENAMER® demonstrably eliminates these drawbacks. High temperatures are not needed for processing, as mixtures of VESTENAMER® and ground



A new life

Compared to other parts of the world, Germany, and the European Union as a whole, are pioneers when it comes to the reuse of worn-out tires. However, tires are still often disposed of in landfills in many other regions, such as China, Russia, the Arab countries, Africa, and Australia

rubber can easily handle low temperatures as well. Under some circumstances, other mixtures can cool off too fast and can therefore no longer be optimally compacted. In extreme cases this can mean that a road surface that has just been completed has to be entirely renewed.

IDEAL FOR INDUSTRIAL APPLICATIONS

The product from Evonik is a partly crystalline rubber that is known as a trans-polyoctenamer. Its properties are between those of liquid and solid rubber polymers. Before it is vulcanized, it has the characteristics of a thermoplastic. This means that it is hard, heat formable, and easy to work—in short, it's ideal for industrial applications. VESTENAMER® is mixed with the ground rubber in small amounts. When it is heated, it melts and covers the rubber particles like a coat of skin. This greatly reduces the tendency of the asphalt-ground rubber mixture to stick to metal. The material slides smoothly out of a truck's insulated dump body and doesn't clog the road construction company's mixer that turns the asphalt into a road surface.

"Our additive turns tires that are no longer authorized for road use into high-performance raw materials for road construction," says Lindner. The data from Dortmund proves that "if we use tires as a raw material here, we can extend the life of their raw materials eightfold." This effect has a positive impact on the life cycle assessment and also solves the disposal problem. To date, many discarded tires end up in cement factories where they are "energetically recovered" as fuel. There are even some countries that still have tire dumps, which can literally be an inflammable waste of resources.

90,000

TONS
of CO_2 emissions were avoided during road construction worldwide, thanks to VESTENAMER®

FIELD TEST IN PADERBORN

The overall result of the life cycle assessment is influenced by numerous factors, says Schlüter: "We also take into account data about possible resource conservation—because the material is used for a longer period, for example." What this means in practice is demonstrated by Lindner on Detmolder Strasse in the city of Paderborn. This street, which has many shops and restaurants on both sides, is used by several bus lines and witnesses a lot of traffic. In 2012 it was covered with asphalt that contained ground rubber and VESTENAMER® as binders. What's special about this street is that 50 percent of the new road surface consists of reused material from the old one. →

Road construction companies like the asphalt mixture with VESTENAMER® because it is easy to work with and doesn't soil machines despite its rubber component

"Our product turns waste into a valuable raw material"

BERND SCHLÜTER, AN EXPERT ON EVONIK'S LIFE CYCLE MANAGEMENT TEAM

Since 2012, Lindner has regularly visited Paderborn to take a look at the road surface. "It's still like new," he says with satisfaction. Road construction companies are trying to increase their reuse rate. Up to 15 percent of a road's old material can currently be reused for a new surface course. The method that was developed by Evonik can boost this value to 50 percent. If material is no longer suitable for a road surface after it has been reused several times, much of it can still be employed in the underlying base course.
This would benefit the companies as well as the municipalities that commission the building of the roads. If conventional methods had been used, the renovation of Detmolder Strasse would have required 705 tons of new rock and 45 tons of bitumen. As it turned out, only 352 tons of rock and 23 tons of new bitumen were needed—only half of what would otherwise have been the case. This was made possible by seven tons of ground rubber and only 400 kilograms of VESTENAMER®. This reduction also greatly diminishes the logistical requirements. Assuming a truckload of 20 tons and approximately 100 kilometers of distance between the quarry and the mixing facility, for the project in Paderborn the method from Evonik reduced diesel consumption for the delivery of the rocks by a total of 750 liters and thus cut carbon dioxide emissions by around two tons. And this doesn't even take into account the reduced noise and the decline in traffic congestion. Although the project in Paderborn only involved one kilometer of road surface, Germany alone has more than 170,000 kilometers of secondary roads.

0.7

TONS of carbon dioxide emissions are avoided if a ton of tires is recycled instead of incinerated

An even more important consideration for reducing CO_2 emissions is the fact that every ton of tires that isn't incinerated but returned to the material life cycle cuts the amount of carbon dioxide that is released into the environment by 0.7 tons. In the case of the project in Paderborn, this translates into 4.9 tons of CO_2. Moreover, Detmolder Strasse is only one of many road projects worldwide that have been carried out more efficiently and sustainably thanks to VESTENAMER®. If the lengths of all of the renovated roads were added together, the distance would stretch from the factory gate in Marl, where VESTENAMER® in produced, all the way to the Ivory Coast. CO_2 emissions have been re-

New from old

A tire reaches the end of its service life when its tread is worn away. Although it can then no longer be used for safe transportation, the material it consists of is still completely intact. The idea that this material can be reused is by no means new. The simplest way to do this is what's referred to as thermal energy recovery. Discarded tires are incinerated in cement plants, for example, although this often has to be paid for. From a life cycle assessment standpoint, this kind of use is very bad recycling, because an inherently valuable raw material is used in a way for which there would be better alternatives. A more sustainable method is to shred the tires and turn them into ground rubber. The latter can be used as construction material, for example, or be converted into rubber mats. However, the demand for such products is limited, whereas the supply is huge. About 600,000 tons accumulate in Germany alone every year.

duced by 90,000 tons as a result. By way of comparison, a forest consisting of 90,000 beech trees would have to grow for 80 years in order to store this amount of carbon dioxide. The reduction could even be much greater, because more than half of all tires worldwide are still either dumped into landfills or incinerated—a total of about 13 million tons of tires each year (see the information box on the right).

DEMONSTRABLE BENEFITS

Compared to conventional road surfaces, the use of VESTENAMER® could reduce carbon dioxide emissions by 10 to 60 percent during a road's life cycle, depending on the assumptions made. For Bernd Schlüter, this is a compelling argument for using VESTENAMER® on a larger scale. "This is a non-hazardous product that turns waste into a valuable raw material, lengthens the life of the end product, conserves natural resources, and cuts energy consumption," he says. "And all of this is demonstrated by verifiable data."

The admixture of ground rubber and VESTENAMER® extends the life of road surfaces

Christoph Bauer is a journalist who works at Evonik's Communications department

OPEN TO MONO

The Nyguard company produces zipper fastenings whose every component, from the starting piece to the zipper itself, consists of Vestamid Terra, a bio-based plastic from Evonik

Most products for everyday use consist of a mix of materials. That increases their practical utility, but it makes recycling more difficult. Especially for plastics, a switch to monomaterials could make it easier to recycle products—an important step toward a circular economy

TEXT **BJÖRN THEIS**

Year after year, about 20,000 tons of used toothbrushes land in garbage dumps—in the USA alone. The problem is that most manufacturers use several different plastics to make their products. The combination ensures that the toothbrush is lightweight and inexpensive and doesn't irritate the user's gums. However, because it's difficult or impossible to separate its component materials into different types, they cannot be recycled.

It's the same story for toiletries, electronics, clothing, and packaging. In countless manufacturing processes, materials are mixed or bonded in order to make products practical, safe, hygienic or wrinkle-resistant. And that leads to the same problem we saw with toothbrushes—after their useful life is over, these items cannot be recycled in a practical way.

ENVIRONMENTALLY FRIENDLY AND EFFICIENT

"Take-Make-Use-Waste" is the phrase used by experts to describe linear product systems of this type. However, climate change and increasing environmental pollution are making it obvious that if we want a sustainable future we need a new paradigm: the "Make-Use-Recycle-Make" circular economy. One future-oriented principle for realizing efficient circular flows of this nature is the concept of monomaterial design. This type of product is made of a single material that can be easily processed and fed once again into the cycle of production and utilization.

Many examples prove that an approach of this kind is possible. For example, in 2019 the industrial designer Alexia von Salomon presented a toothbrush whose every component, from the bristles to the handle, is made of the same plastic. As a result, this toothbrush can be recycled over and over again. The packaging industry is also investing in a future characterized by monomaterials. For example, for the past year the product range of the Mondi Kalenobel company has included a monomaterial that the food conglomerate Unilever uses for the packaging of Knorr instant soups in Turkey.

The clothing industry has made especially good progress. Several fashion brands are already testing the use of monomaterials. Adidas, for instance, presented its FUTURECRAFT.LOOP sneakers in 2019. From their soles to their shoelaces, these athletic shoes are made of a single plastic, a thermoplastic polyurethane.

The Nyguard company has set itself the goal of creating a circular economy for zipper fastenings. Its Ny2Life zippers also consist of only one material. The company's product range now includes three monomaterial variants. One of them is made of Vestamid Terra, a bio-based plastic from Evonik.

SYNERGIES WITH 3D PRINTING

Although the concept sounds so simple, there's still a long way to go before a diverse and sustainable product range of monomaterials can be marketed. Nonetheless, limiting products to a single material harbors tremendous economic and environmental potential, especially in combination with other technologies such as 3D printing. This type of production makes it possible to dispense with glue or screws. As a result, in the future it could be possible to make even complex products out of monomaterials.

In an effort to identify possible practical applications, the Foresight team at Creavis is developing a variety of scenarios for plastic in the year 2040. In addition, the "Circularity of Plastics" unit, which was formed in December 2020, is working to develop transformative innovations for the creation of plastic material cycles. This is how Creavis is supporting Evonik's global program "Circular Plastics," whose objective is to make plastic material cycles a reality as soon as possible.

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

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Cu
Copper

“The challenge of blue”

LOG **ANNA SCHRIEVER**

Hideki Kubota (50) has worked as a pyrotechnician in Japan for more than 30 years. The largest firework that he has made to date weighed 60 kilograms, had a diameter of 60 centimeters, and flew 500 meters into the air.

I want my fireworks to be colorful—but that is not as easy as it sounds. Blue fireworks, especially, are very complicated to manufacture. We need to use copper, or to be more precise, cupric oxide. It is important that the temperature is not too high when the firework explodes as otherwise, the chemical reaction does not work. It must not be hotter than 1200 degrees Celsius; but in most cases, temperatures of 2000 degrees or more are generated. Also, the blue should not be too dark. It must be visible against the dark night sky. That’s why I’m always working to optimize the formulation for blue fireworks.

Whether it’s red, orange, gold, green or even blue: We need a range of chemical elements to produce our pyrotechnics. We use strontium to create red, barium to create green, and aluminum to create white. But these are not the only components. We need other substances to control the brightness and the combustion period. And what exactly these substances are, that’s our trade secret. Every manufacturer has his own unique formulation.

It has taken me many years to acquire the chemical knowledge that I need for my work. Fireworks are a tradition in my family: Our family business has been manufacturing pyrotechnics since 1909. I obtained a license to produce them when I was 18. To develop new formulations and to produce creative light effects and spectacular explosions, I need to know how the state of chemical elements can change. Chemistry is my passion!

Unfortunately, in many cases, you only find out if the effects are going to work when the explosion occurs. And that’s why I am always very nervous prior to big fireworks shows. Thousands of people stare into the sky, are in awe of the colorful formations that light up the night, and are often moved by the spectacle. We spend from three to six months working on new formulations and we make the fireworks and firecrackers all by hand. After just 30 minutes, it’s all over. Our work literally vanishes into thin air. For me, it’s always an indescribable feeling when the people clap and cheer after the final firework has exploded. The tension just melts away. I think this is my favorite moment.

Masthead

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We cannot solve our problems…

…with the same thinking we used when we created them, according to Albert Einstein. As the originator of the theory of relativity, he was well versed in thinking in new categories. His insight is highly relevant today: In order to conserve resources while extending prosperity to more and more people, we need new approaches.

For example, we need a circular economy for plastics that is based on recycling instead of disposal. Modern processes are helping us obtain valuable raw materials from materials that were previously regarded as trash. That not only protects the environment but also enables the production of innovative high-performance materials.

1/2021 **The circular economy**

EVONIK
Leading Beyond Chemistry