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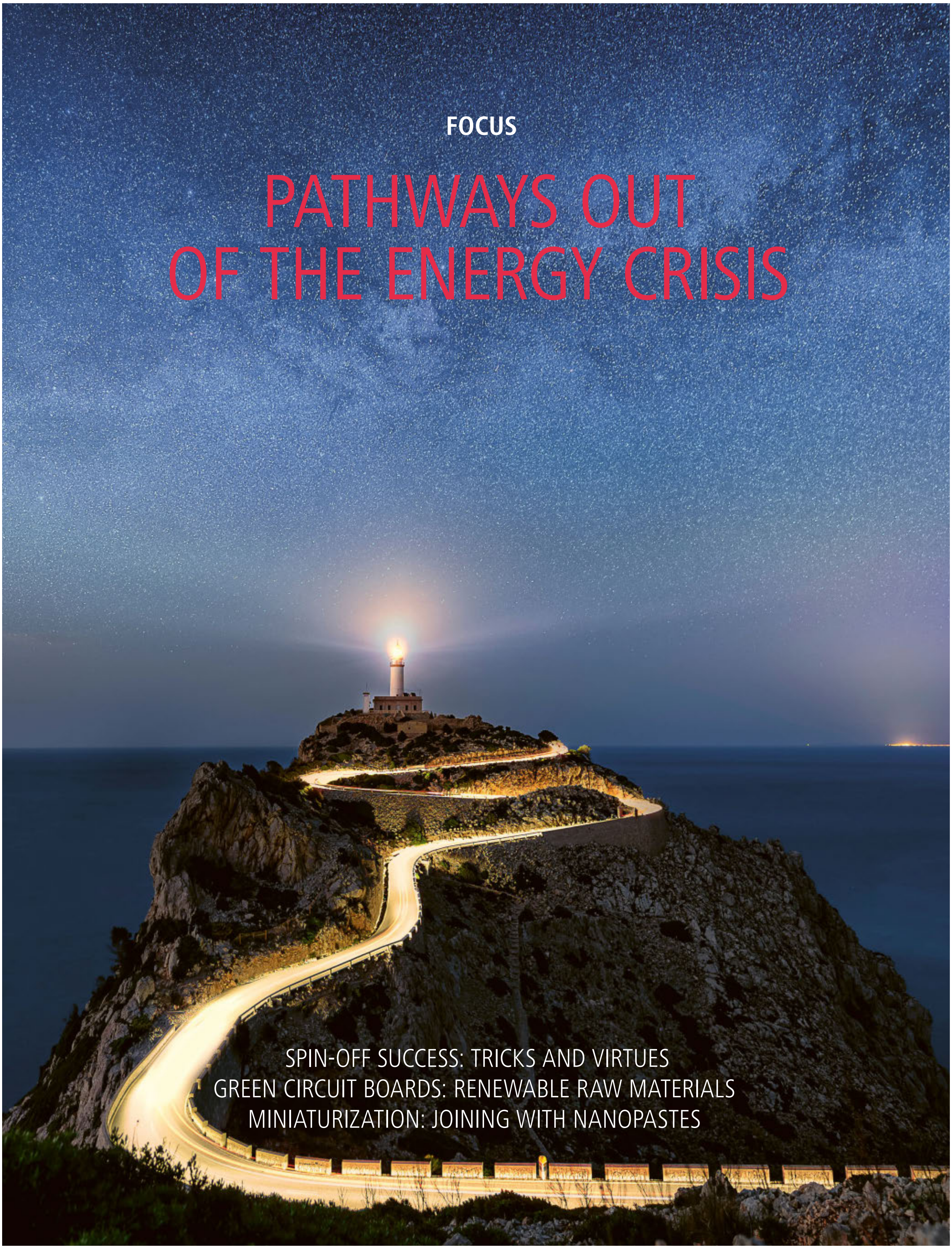

[CONTENT]

[FOCUS: PATHWAYS OUT OF THE ENERGY CRISIS]

Photos: iStockphoto, V-Zug AG, Marion Nitsch, Gian Vaitl, Urs Bünter / Empa

[COVER]

The energy crisis triggered by the Ukraine war will keep us on tenterhooks for months to come.
But researchers are not lamenting, they are looking for solutions. You will find some helpful approaches for the steep path from start to finish in this issue.
PS: the cover photo shows the Far de Formentor lighthouse, in the far north of Mallorca.
Image: Adobe Stock

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www.paul-and-cat.com
CONTACT Phone. +41 58 765 47 33
empaquarterly@empa.ch
www.empaquarterly.ch
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PEDAL TO THE METAL – NOW!

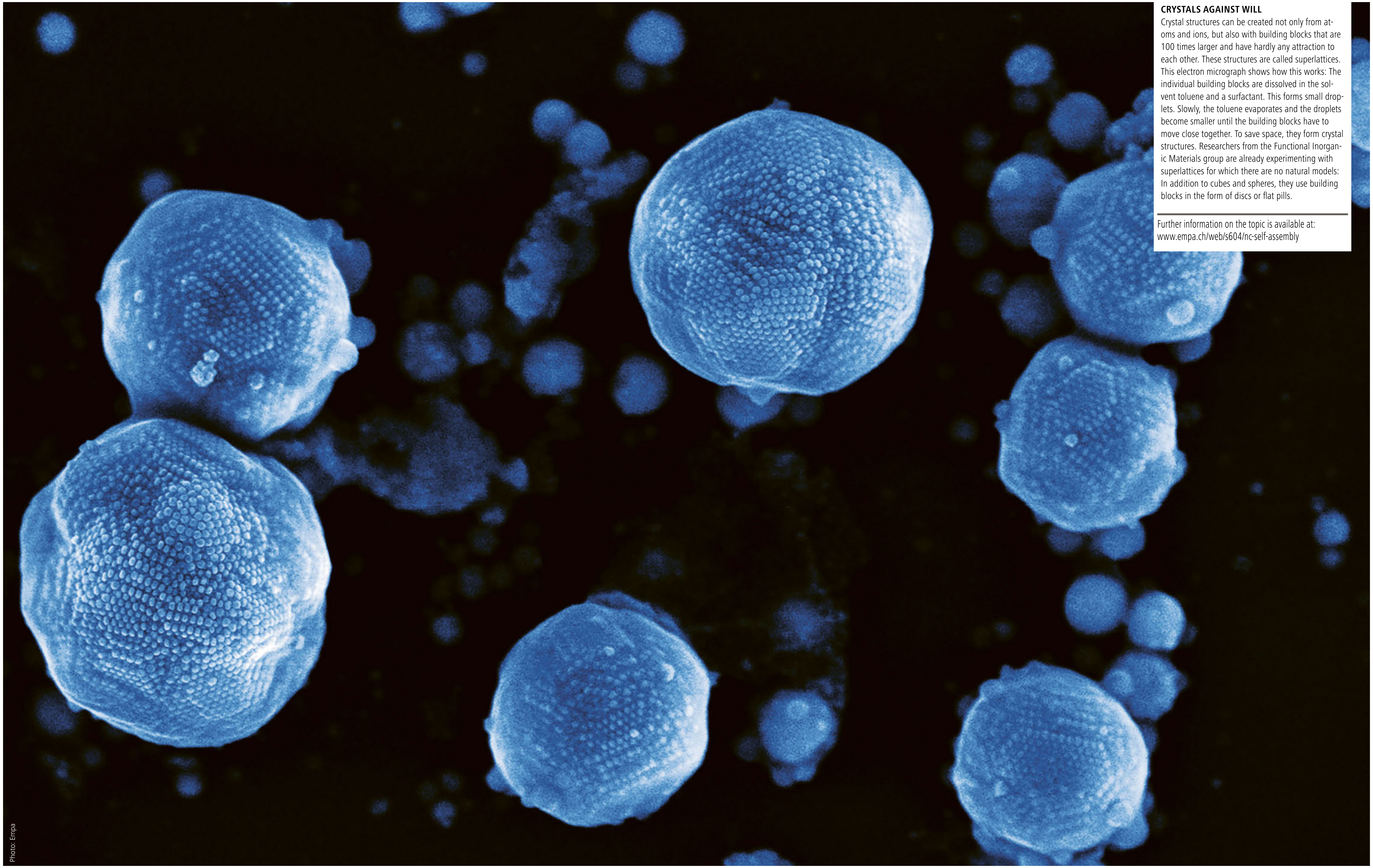
Dear Readers,

Global problems demand global solutions. Because they concern us all. But when everyone is (partly) responsible, no one acts. Instead, we rather sit and wait for others to do something about it. When it comes to the really big issues of our times, though, time is running out. So waiting seems the worst option – especially when technologies are readily available that could significantly reduce our giant carbon footprint, as Empa Deputy Director Peter Richner explains on page 13.

But Switzerland is indeed not capable of solving the energy and climate problem on its own; energy self-sufficiency is utopian. There are, however, clever ideas around about how we could harvest enough energy in the earth's sun belt and then – after converting it into chemical energy carriers such as synthetic methane (p. 19) – store it, distribute and use it wherever we need it. And if we do this as described on page 16, this could even result in negative CO_2 emissions; in other words, CO_2 would be removed from the atmosphere in the process. But, as I said, this cannot be implemented without international cooperation.

Closed material cycles, however, are not only a good idea for carbon, emphasizes Empa's new department head Lorenz Herrmann in an interview (p. 8). In line with this closed-loop concept, Empa researchers are working, among other things, on developing circuit boards for the electronics industry from renewable resources that can simply be disposed of in the green garbage can at the end of their service life (p. 10) – a big step towards green electronics.

Enjoy reading!
Your MICHAEL HAGMANN



CRYSTALS AGAINST WILL

Crystal structures can be created not only from atoms and ions, but also with building blocks that are 100 times larger and have hardly any attraction to each other. These structures are called superlattices. This electron micrograph shows how this works: The individual building blocks are dissolved in the solvent toluene and a surfactant. This forms small droplets. Slowly, the toluene evaporates and the droplets become smaller until the building blocks have to move close together. To save space, they form crystal structures. Researchers from the Functional Inorganic Materials group are already experimenting with superlattices for which there are no natural models: In addition to cubes and spheres, they use building blocks in the form of discs or flat pills.

Further information on the topic is available at:
www.empa.ch/web/s604/nc-self-assembly

GO-AHEAD FOR THE JOURNEY TO CO_2-NEGATIVE CEMENT

ENVIRONMENTAL FACTOR
The production of cement should cause less CO_2 emission.

The cement industry emits large amounts of climate-damaging carbon dioxide – but alternative binders based on magnesium carbonate could even bind CO_2. Concrete as a carbon sink? Cements based not on limestone, aka calcium carbonate ($CaCO_3$), but on magnesium silicates are one source of hope. A research project by Empa researcher Barbara Lothenbach, who recently received one of the first Advanced Grants from the Swiss National Science Foundation (SNSF), is to lay the foundations for this as of early next year. Unlike conventional cements, whose hardening has been investigated down to the tiniest details, these materials still raise many questions. In seven focal areas, Empa experts and partners from the Finnish University of Oulu will thus explore what is happening at the molecular level. How do such cements harden and with which formulations? What is the effect of temperature, pH and other factors such as reaction accelerators? Does the volume of magnesium concrete remain stable over the long term? And how resistant is it? In the end, the findings from laboratory tests and thermodynamic modeling should flow into a digital twin of magnesium carbonate cement – a simulation of the processes involved in hardening and the basis, Empa experts hope, for formulations of robust concretes that bind as much CO_2 as possible.

www.empa.ch/web/s308

EXCITING TASK
Empa expert Barbara Lothenbach will lead the challenging research project.

Photos: iStockphoto, Empa

Photos: Marlies Thurnheer, Empa

SUCCESSFUL FUNDING ROUND FOR EMPA SPIN-OFF

The company Nahtlos, an Empa spin-off, has received one million Swiss francs in a first round of financing from a network of business angels from Switzerland and Liechtenstein and from the Startfeld Foundation. This is intended to drive the market entry of an innovative textile-based electrode for medical applications. In the past two years, the company had developed such components, among other things for recording heart activity through electrocardiograms (ECG) – for example, to be able to detect atrial fibrillation. Textile-based electrodes enable gentle and skin-friendly application, even if the electrodes have to be worn for several days or even weeks. They are thus a real alternative to the gel electrode, which was developed 60 years ago and is still considered the standard for medical applications today.

www.nahtlos.com

OPTIMISTIC
The founders of Nahtlos AG, José Näf and Michel Schmid, with prototypes (front left) of textile-based electrodes for long-term ECGs in their laboratory in St. Gallen

WATER-ACTIVATED PAPER BATTERY AMONG WORLD'S BEST INVENTIONS

MOST IMPORTANT
The paper battery consists of two electrochemical cells connected in series at the two ends of the paper strip, separated by a water barrier (between the letters m and p).

A team led by Gustav Nyström from Empa's Cellulose & Wood Materials Laboratory has made it onto the list of the 200 most important inventions published by Time magazine – with its biodegradable disposable battery, the function of which is triggered by adding a bit of water. The jury awarded the prize to the Empa team in the "Experimental" category; the jury evaluates inventions according to originality, creativity, efficiency, impact and other criteria. The battery developed by Nyström's team consists of at least one electrochemical cell measuring around one square centimeter. What makes it special is that the fact that both paper and zinc and the other components are biodegradable could significantly minimize the environmental impact of disposable electronics with low power consumption – an important step towards green electronics.

www.empa.ch/web/s302

"I HAVE GOT THE BEST OF BOTH WORLDS"

Lorenz Herrmann has been head of Empa's Advanced Materials and Surfaces Department for around six months. In this interview, he describes areas in which he would like to make progress with novel materials and explains why basic research is essential for the innovation process – and how research at Empa differs from that at an industrial research center.

Interview: Michael Hagmann

CARBON LOVER
Lorenz Herrmann in front of his favorite material, carbon, in the form of a 3D model of an atomically precise graphene nanoribbon that could be the basis for completely new types of quantum computers.

Photo: Marion Nitsch / Empa

Lorenz Herrmann, as the new head of department at a materials research institute, a simple question: What is your favorite material?

That's easy: carbon.

That was fast – why this element in particular?

Carbon has been with me throughout my career: I did research in solid-state physics on mechanical and electronic applications of carbon nanotubes. Then I spent a long time in industrial research in the field of electrical engineering, where polymer insulation materials or graphite electrodes for batteries were also based on carbon. On the one hand, carbon is extremely versatile, so it is suitable for numerous applications; on the other hand, it is also extremely important in our materials cycles. Closing the carbon cycle is crucial for our environment and the climate.

How does a trained solid-state physicist like you actually end up in materials science?

I came from basic research and wanted to build a bridge to practical applications. I was extremely fascinated by energy technologies – still a hot topic today. The trigger was the DESERTEC project, which aimed at generating solar power in the desert and bring it to Europe. At that time, I looked around to see where I could combine solid-state physics, materials science, energy research and electrical engineering – that's how I ended up at the ABB Research Center, where I then worked on materials for energy transmission.

How does research at the ABB Research Center, where you were also responsible for a research department, differ from that at Empa?

There are rather few differences among the research staff. The enthusiasm, the passion for research, the interaction with each other – that's very similar at both places. Here at Empa, however, the topics are broader and we do more basic research. In industrial research, on the other hand, you're much more focused on the next generation but one of products for your own company.

What appeals to you particularly about your new role? ▶

NEW ON BOARD
Lorenz Herrmann, new head of Empa's Advanced Materials and Surfaces Department since August 2022

LORENZ HERRMANN

CAREER: After studying physics at the University of Regensburg and the École normale supérieure in Paris, Lorenz Herrmann completed his doctorate at these two universities on carbon nanotubes and their application in nanoelectronics. In 2010, he moved to the ABB Research Center in Dättwil, where he most recently headed the Energy Technologies department. Since August 2022, he is head of the Empa department Advanced Materials and Surfaces.

Up to now, I have been moving between two worlds, if you like – basic academic research and applied research in industry. Here at Empa I can bring the two together – I have got the best of both worlds, so to speak. What I find extremely fascinating about the "Empa model" is, on the one hand, the high scientific standards and, on the other, the focus on practical applications.

What role does basic research play in a research institution that describes itself as applications-oriented and close to industry?

At Empa, our ultimate goal is to create technological added value for industry and society: in other words, to develop the fundamentals for as yet unknown applications, but also to support Swiss industry in the here and now. In my experience – especially in industry – you have to do top-notch science to be able to really help companies. They don't need us for incremental developments; in fact, they can usually do that better. So you can't just duplicate "development" for a company, you really have to bring in new aspects – what you might want to call disruptive innovation. And that's exactly what companies want – something they don't have or can't do in-house themselves. This can only be achieved through first-class research. Our work is upstream of the development process, so to speak, but then it has to be transferable and applicable – that's the art.

In which fields of application do you see the greatest potential to make a difference with novel materials?

In the area of digitization, for instance, novel graphene nanostructures could provide the basis for completely new devices, with their industrial manufacturing being considered right from the outset. At the core of this development are robust quantum materials for future applications such as quantum computers and sensors. This differs fundamentally from previous approaches, in which the production and robustness of the devices tend to take a back seat and quantum physical effects are primarily investigated in model systems, often at extremely low temperatures. In the area of sustainable materials, we need to implement the recycling concept more consistently; I am thinking, for example, of polymer composites, which are difficult to recycle today. And in the field of energy, for example, I see great potential in the production of new types of cheaper solar cells, for example through simple printing processes. I also see a lot of opportunities in power-to-gas and in battery technologies.

What's the next thing on your agenda right now?

II was given a very warm welcome here at Empa, and I was very pleased about that. I initially focused on networking internally and getting to know as many topics and projects as possible. Now the focus is more on external networking with our stakeholders in industry, research, politics and the administration. And then, of course, I would like to give the first strategic impulses and help to take the above-mentioned topics a step further. ■

Further information on the topic is available at: www.empa.ch/web/s200

Photo: Marion Nitsch / Empa

CIRCUIT BOARDS FROM RENEWABLE RAW MATERIALS

Can ecologically sustainable circuit boards for the electronics industry be produced from cellulose fibers? Empa researcher Thomas Geiger looked into this question. He is now part of a multinational EU project called Hypelignum. Its goal: biodegradable electronics.

Text: Rainer Klose

For many years, Thomas Geiger has been conducting research in the field of cellulose fibrils – fine fibers that can be produced from wood pulp or agricultural waste, for example. Cellulose fibrils hold great potential for sustainable production and the decarbonization of industry: they grow CO_2-neutral in nature, burn without residues and are even compostable. They can be used for many purposes, for example as fiber reinforcement in technical rubber products such as pump membranes.

THE LOOK OF IVORY
Geiger has produced housing parts for computer mice from cellulose fibers on a trial basis. The surfaces shine like precious ivory; the components are completely compostable.

But can cellulose fibrils perhaps also be used to make circuit boards that reduce the ecological footprint of computers? Printed circuit boards (PCBs) in particular are anything but innocent ecologically: They usually consist of glass fibers soaked in expoxy resin. Such a composite material is not recyclable and can so far only be disposed of properly in special pyrolysis plants.

COMPUTER MOUSE WITH AN IVORY LOOK

Geiger had already produced circuit boards from cellulose fibrils and investigated their biodegradation. Mixed with water, the bio-fibrils produce a thick sludge that can be dewatered and compacted in a special press. Together with a colleague, he produced 20 experimental boards, which were subjected to various mechanical tests and finally fitted with electronic components. The test succeeded, and the cellulose board released the soldered-on components after a few weeks in natural soil. Geiger had previously been involved in an Innosuisse project together with the OST University of Applied Sciences in Rapperswil, which produced housing parts for computer mice. The housing parts have a silky sheen and are similar in color and feel to workpieces made of ivory. But no manufacturer could be found who wanted to adopt the method. The price competition for small electronics is still too great for this – and conventional plastic injection molding processes have a clear advantage in this respect.

CIRCUIT BOARDS MADE OF WOOD WOOL OR CELLULOSE FIBERS AND FIBRILS

Recently, the opportunity arose to build on existing findings: Empa sustainability specialist Claudia Som was asked if she would like to collaborate on the EU research project Hypelignum. This is led by the Swedish materials research institute RISE and is looking for new ways of sustainably producing electronics. Claudia Som enlisted the help of her colleague Thomas Geiger. ▸

Photo: Gian Vaitl / Empa

BIOWASTE
Experimental board after composting.

Photo: Empa

The project started in October 2022, and the research consortium, with participants from Austria, Slovenia, Spain, the Netherlands, Sweden and Switzerland, plans to produce and evaluate eco circuit boards made of various materials: In addition to nanofibrillated cellulose (CNF), wood wool and wood pulp are being investigated as a base; wood veneer is also being used as a base for the circuit boards.

DISPLAYS AND BATTERIES MADE FROM CELLULOSE

In 2022, an Empa research group led by Gustav Nyström succeeded in building a biodegradable display based on hydroxypropyl cellulose (HPC). They used HPC as a substrate and added a small amount of carbon nanotubes, making the cellulose electrically conductive. By mixing in cellulose nanofibers (CNF), they brought the ink into a printable form. The display changes color depending on the applied electrical voltage; in addition, it can also serve as a pressure or tension sensor and has the potential to play a role as a biodegradable user interface in future eco-electronics.

Two Empa labs are collaborating on the project: Firstly, the sustainability specialists led by Claudia Som from the Technology and Society lab. Som will use material databases to calculate the ecological footprint of the eco circuit boards and compare the individual concepts with each other. Thomas Geiger from Empa's Cellulose & Wood Materials laboratory will manufacture the circuit boards from renewable raw materials. Green electronics has long been a research focus of the lab, which is headed by Gustav Nyström; Nyström's team has already developed various printed electronic components from biodegradable materials, such as batteries and displays (see infobox). The requirements for industrially produced computer circuit boards, however, are not trivial: Not only must the boards have high mechanical strength, they must also not swell in humid conditions or form cracks at very low humidity.

"Cellulose fibers can be a very good alternative to glass fiber composites," Geiger explains. "We dewater the material in a special press with 150 tons of pressure. Then the cellulose fibrils stick together on their own without any additives. We call this 'hornification'." The key here is at what pressure, temperature and for how long the pressing process must take place to produce optimal results.

FOUR DEMONSTRATORS PLANNED

The EU project Hypelignum has ambitious goals: It aims not only to study printed circuit boards made from renewable and compostable raw materials, but also to develop conductive inks for the electrical connections between individual components. These inks are often made based on silver nanoparticles. The researchers are looking for cheaper and less scarce substitute materials, as well as an ecological production method for these nanoparticles.

At the end of the project, four demonstrators ought to show what had been achieved: an ecologically exemplary printed circuit board, a large construction element made of wood that will be equipped with sensors and actuators, pieces of furniture that will be equipped with sensors in an automated production line, and finally a demonstrator that will prove the recyclability of all these components. ■

Further information on the topic is available at: www.empa.ch/web/s302

WHERE THERE'S A WILL, THERE'S A WAY

Climate crisis, energy shortage, nuclear phase-out. We need to transform our energy system. That much is clear. We also know that it will be anything but easy – and it will be costly. But a lot is up to us, says Peter Richner, energy expert and Empa's deputy director. After all, many technologies are readily available, but have been underutilized thus far.

Text: Peter Richner

TAKING STOCK OF THE EXPERT
Peter Richner, Deputy Empa Director, in front of NEST, where many environmentally friendly building and energy technologies for the future are being realized and tested.

Photo: Felix Wey / Empa

Throughout the past decades, the permanent availability of cheap energy was taken for granted and was hardly ever questioned. Climate change on the one hand and the planned phase-out of nuclear energy on the other have triggered discussions about a transformation of our energy system, but the necessary measures have so far been implemented only half-heartedly.

In 2022, this situation changed dramatically. In Europe in particular – and thus also in Switzerland – there was a massive shortage of available energy. As a result of the Russian attack on Ukraine, gas supplies from Russia, which previously covered more than 30 % of European demand, dried up almost completely. At the same time, only about 50 % of France's nuclear power plants are currently online, as overhaul work fell behind schedule during the pandemic and, in addition, corrosion problems arose on pipelines, leading to more protracted investigations.

TENFOLD INCREASE IN PRICES

The resulting energy shortage drove up prices massively, especially for gas and electricity. For a short time, electricity prices on the futures markets for the first quarter of 2023 of more than € 1,000 ▶

THE FUTURE OF ENERGY SUPPLY
Wind power and solar cells, hydrogen and other sustainable energy sources are beacons of hope – but the changeover needs ideas and a lot of time.

per MWh were asked for – a tenfold increase within one year! In order to bring supply and demand back into some kind of balance, the focus in the short term is on efficiency and energy savings measures. In the medium and long term, the aim is to make energy available from other sources, which must be renewable and have low CO_2 emissions. Materials science and technology development, as conducted at Empa, forms the basis, on which practical answers to these challenges can be developed.

A profound transformation of our energy system within a few months or even years is hardly possible, even if, currently many of us would like this to happen. The construction of high alpine solar power plants and the associated adjustments to the power grid, the raising of dams of storage power plants and the switch to renewably produced hydrogen for industrial high-temperature applications involve enormous investments and cannot be implemented overnight. Therefore, we should currently focus primarily on efficiency and savings measures. The quickest and easiest way – at least in theory – is to implement behavioral changes; these are often purely a question of will. Lowering the room temperature in winter is the most obvious example, saving around 6–7% energy – per degree.

ARTIFICIAL INTELLIGENCE SAVES AROUND A QUARTER OF HEATING ENERGY

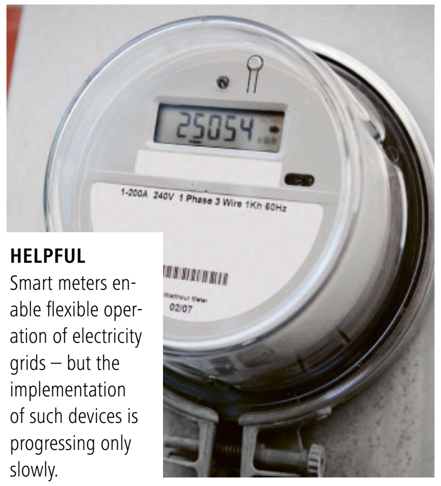
However, voluntarily constraining oneself is difficult, but there are certainly ways to significantly reduce energy demand without noticeable losses in comfort or performance. Digitization, in particular, offers entirely new possibilities here. Felix Bünning and Benjamin Huber from Empa's Urban Energy Systems laboratory have developed a data-based control algorithm for regulating room temperature and put it through its paces in NEST. Using a temperature sensor, a room-specific computer model can be developed within two weeks, which is then used in combination with weather forecasts to control heating and cooling. This is done completely automatically via machine learning, without the need to know the physical parameters of a building. This technology can thus be implemented easily, quickly, and without technical modifications in numerous buildings. Compared to conventional heating control, energy consumption can be reduced by 20–30%, as a large-scale trial in one of Empa's office buildings in Dübendorf in winter 2021/22 showed. What's more, around 90% of employees said they had not noticed any loss of comfort. In the meantime, the two researchers have founded the start-up Viboo and are full of verve to prove once again that "Empa – The Place where Innovation Starts" is far more than just a slogan.

Photos: iStockphoto, Felix Wey / Empa

IF IT PAYS OFF, IT WILL BE USED

Quite a few other solutions are ready and waiting; their potential and feasibility have been demonstrated in the laboratory and in demonstration projects in recent years. However, they have not yet found their way onto the market – simply because they did not pay off at the previous process for energy and CO_2. The NEST unit Solar Fitness and Wellness, for example, is equipped with an innovative energy concept that can reduce energy consumption of saunas and steam baths by a factor of three; and, in combination with storage technologies, it can be powered almost exclusively with solar energy. Only now, when hotels are suddenly confronted with tenfold higher electricity prices, is interest in this technology suddenly skyrocketing, and chances are good that implementation with partners from industry will become realistic.

The same applies to the widespread use of smart meters. Although the technology is well known and appropriate devices are available, Switzerland is taking its time with implementation; by 2027, 80% of all electricity meters are to be replaced by smart meters. These are a basic prerequisite for the integration of decentrally generated renewable energy and load balancing at low grid levels. This, in turn, enables significant efficiency gains at the neighborhood level, as research by Empa and its partners has shown in recent years. In the current situation of an uncertain power supply, the widespread installation of such smart meters would be a prerequisite to be able to control demand in a targeted manner in the event of a shortage by centrally controlling appliances whose operation is not time-critical, such as heating or boilers.



HELPFUL
Smart meters enable flexible operation of electricity grids – but the implementation of such devices is progressing only slowly.

So there are many solutions ready and waiting to be implemented, paving the way for a climate-neutral, reliable and affordable energy supply. However, further efforts are needed to successfully follow the path all the way to the end. The focus is on solutions that allow energy to be stored for various periods of time and transported over long distances. New concepts for batteries based on non-critical raw materials and recycling concepts for high-performance batteries that are crucial for mobility are the focus of various research projects at Empa.

ENERGY SELF-SUFFICIENCY IS UTOPIAN

Complete energy self-sufficiency for Switzerland makes neither economic nor technical sense. In addition to the domestic expansion of renewable energies, ways must therefore be found to import renewable energy, especially in winter. It is doubtful whether this will be possible from nearby countries, as our neighbors' energy systems are likely to develop in a very similar way to ours. In other places in the world, however, the potential for renewable energy production is huge, for instance in the desert regions of North Africa, the Middle East or in Patagonia and Australia. Transporting it over such long distances in the form of electricity is not feasible, though. The electricity generated from wind or the sun must first be converted into chemical energy carriers such as hydrogen, ammonia or synthetic hydrocarbons. This makes energy storable and transportable at the same time. New catalysts and catalytic processes are essential to make the chemical conversion processes as efficient as possible and to produce energy carriers that provide the greatest possible benefit, for example as a substitute for (fossil) kerosene. In all these innovative approaches, their greenhouse gas balance is key. This should be net zero or – ideally – even CO_2-negative, i.e. reduce the greenhouse gas concentration in the Earth's atmosphere.

Thanks to its expertise in materials science and technology development, Empa will continue to develop new solutions that will make it possible to put our energy system on a sustainable footing. However, we as a society must muster the necessary will and the corresponding seriousness to successfully master this challenging path together. ■

Further information on the topic is available at:
www.empa.ch/de/web/empa/engineering-sciences

TOGETHER TOWARDS NEGATIVE EMISSIONS

The Association for the Decarbonization of Industry (AfDI) has set itself the goal of developing rapidly implementable and holistic approaches for CO_2 reduction in industrial processes. The focus is on industrial high-temperature applications. Ideas of a global approach with overall negative CO_2 emissions are also being pursued. Empa researcher Christian Bach represents Empa as a founding member in the association. Together with AfDI project manager Andreas Bittig, he provides insights into the visionary ideas and their practical implementation.

Interview: Stephan Kälin

CHRISTIAN BACH
Head of the Automotive Powertrain Technologies lab, Empa

ANDREAS BITTIG
Project manager Association for the Decarbonization of Industry (AfDI), Tech Cluster Zug AG

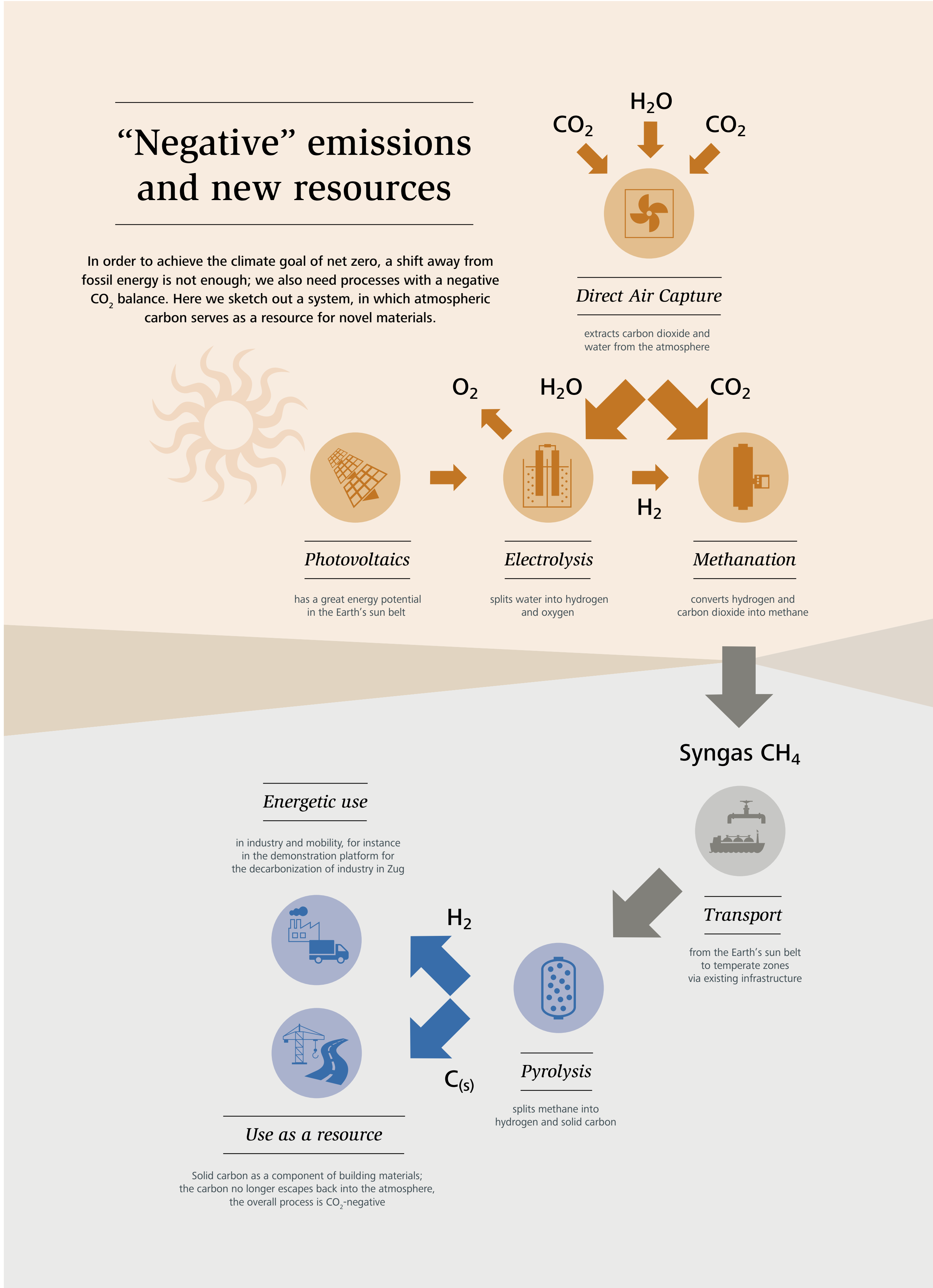
What measures does the association want to take to achieve CO_2 reductions in industrial processes?
Andreas Bittig: While many projects and efforts are underway for heating and mobility, the decarbonization of industrial high-temperature processes, which are often based on natural gas, still remains a niche activity. The AfDI intends to use and further develop methane pyrolysis, an interesting new technology for such applications. The exciting thing about it is that this technology allows the decarbonization of fossil natural gas, which enables rapid CO_2 reductions; it even leads to negative emissions if renewable methane is used.

How can synthetic methane enable negative CO_2 emissions?
Christian Bach: Synthetic methane is produced from renewable hydrogen and CO_2 from the atmosphere and can be transported around the world at low cost. To prevent the re-formation of CO_2 when the methane is being used later on, the carbon is split off from the CH4 molecule beforehand – in solid form! – in a process known as pyrolysis. Solid carbon can then be used as a new raw material in construction and agriculture. Thus, we only use the hydrogen part of the synthetic methane for energy production. Thus, overall CO_2 is removed from the atmosphere for the production of synthetic methane, which is eventually stored in the form of solid carbon in construction or agriculture – and is therefore no longer climate-relevant.

The production of synthetic methane, its transport and pyrolysis involve efficiency losses. How do you deal with this?
Christian Bach: True, around half the energy is lost during the production of synthetic methane, and around another third is lost through the splitting off of carbon. What looks like a disaster from an efficiency perspective nevertheless makes sense – namely when methane production takes place in regions where energy is abundant. This is the case in the sun belt around the globe. There, solar radiation is twice as high as in our latitudes, and there are huge uninhabitable and unused areas. Moreover, the existing infrastructure can be used for transportation. Twice the solar radiation in the Earth's sun belt means a significantly higher yield per square meter of solar cells than here. This puts the high energy losses of this approach into perspective.

What does it take for this global system to become a reality?
Andreas Bittig: Methane pyrolysis is considered one of the most cost-effective production processes for hydrogen. The technology is on the threshold of industrial implementation. For the overall system to become a reality, demonstration plants, such as the one planned in Zug, are needed to gather both data and know-how. Tech Cluster Zug AG provides the ecosystem for demonstrating the feasibility of this approach. We definitely see the Zug demonstrator as the start of industrialization of this system, because we are very well positioned through close cooperation between industry and research.

Photos: Empa



Graphic: Empa

VISIONARY IDEA
V-ZUG AG's enamelling furnaces are to be operated without fossil natural gas in future.

A DEMONSTRATION PLANT AT THE TECH CLUSTER ZUG

The Association for the Decarbonization of Industry (AfDI) was founded on 20 June 2022. Association members include representatives from industry, energy suppliers, the financial sector and research. One of the association's main activities is to build a demonstration plant at Tech Cluster Zug in the coming years, in which methane (CH_4) is split into its components, hydrogen (H_2) and solid carbon (C(s)), by means of pyrolysis. The pyrolytically produced hydrogen is to replace fossil natural gas in the enamelling furnaces of V-ZUG AG. For the solid or powdered carbon, applications in construction and agriculture are being developed and validated – for example as an admixture in building materials or to enrich humus. What is special about this new approach: If synthetic methane is used for pyrolysis instead of fossil natural gas, the overall CO_2 emissions are negative (see interview). However, since Swiss industry alone has an annual energy demand of around 20 TWh, the potential for the domestic production of renewable hydrogen or synthetic methane to meet this demand is insufficient. The situation is different in the Earth's sun belt: Imports of synthetic energy sources from sunny regions could meet the demand for renewable energy and provide new resources for construction and agriculture – with overall negative CO_2 emissions (see graphic on page 17. Empa contributes to the AfDI both with its applications-oriented expertise in the field of synthetic energy sources (for example in its mobility demonstrator, move) and with its expertise in the fields of concrete and asphalt. This would be one option to use the carbon obtained from synthetic methane.

"For the national system to become real, demonstration facilities are needed to generate data and expertise."

Further information on the topic is available at:
www.empa.ch/web/s604/decarb-industry

Photo: V-ZUG AG

ROBUST AND FLEXIBLE TO SYNTHETIC METHANE

Synthetic energy carriers are carbon-neutral and make renewable energy transportable and storable in the long term. Synthetically produced methane is one of them. The problem: The production involves rather high energy losses; moreover, existing processes require the methane to be purified. To change this, Empa researchers have developed a new, optimized reactor concept for methanation.

Text: Annina Schneider

A successful energy transition requires energy sources that are climate-friendly; this means: as few CO_2 emissions as possible – ideally none at all – during production and use. Synthetic energy carriers – i.e. those that are obtained from renewable energy through chemical conversion processes – are one of the most promising options. The use of such energy carriers only produces as much CO_2 as was previously removed from the atmosphere for their production.

Artificially produced methane falls into this category. "Synthetic gas offers enormous potential if it is produced from atmospheric CO_2 and renewably generated hydrogen," explains Christian Bach, head of Empa's Automotive Powertrain Technologies lab. "However, for hydrogen production you need a lot of water as well as renewable electricity. In our mobility demonstrator move, we thus want to extract not only CO_2 but also the water for hydrogen production directly from the atmosphere with the help of a CO_2 collector from the ETH spin-off Climeworks." In future, such concepts could be implemented in desert regions lacking liquid water supplies. However, the production of synthetic methane from hydrogen and CO_2 – so-called methanation – has its pitfalls.

A FLEXIBLE ENERGY SYSTEM THANKS TO SYNFUELS

Synfuels can be used in conventional petrol, diesel or gas vehicles. The drawback of synfuels is high conversion losses: Today, around 50% of the primary energy is lost during the production of synfuels from renewable electricity. These losses can probably be reduced to 40 to 45 % in future. Economic analyses show that synfuels only make sense where a direct electrification is not possible – for instance, in long-distance and heavy goods transport, for cargo ships and airplanes. However, if one looks at the entire energy system, synfuels have a decisive advantage: They can be easily transported over long distances, which is why even distant renewable energy resources can be tapped. Moreover, they can be stored over longer periods of time without any losses. They thus make our domestic, renewable energy system much more flexible.

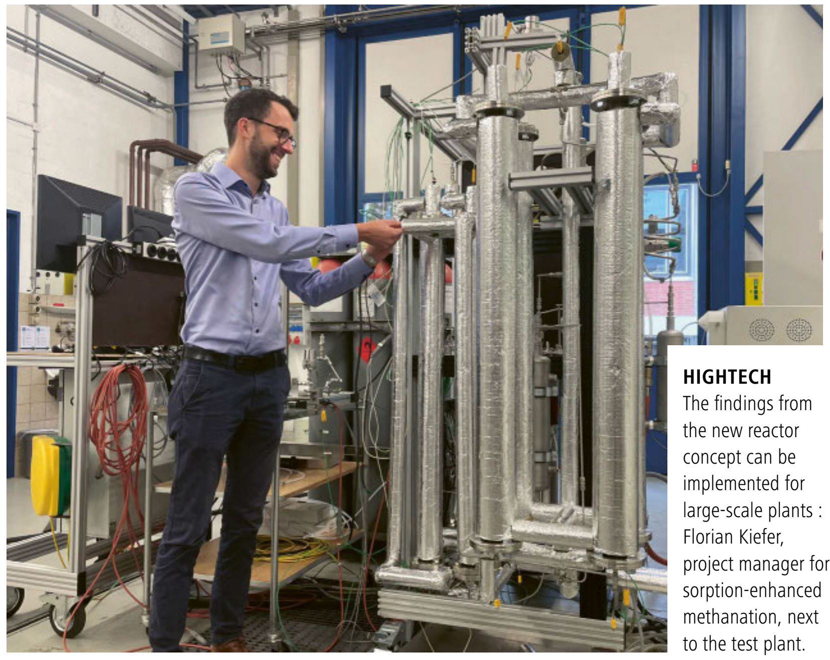
This is because methane produced by such a catalytic process still contains hydrogen, which prevents it from being fed directly into the gas grid. Empa researchers Florian Kiefer, Marin Nikolic, Andreas Borgschulte and Panayotis Dimopoulos Eggenschwiler have therefore developed a new reactor concept, in which the formation of hydrogen on the product side is prevented. This leads to a simpler process control and a better suitability for dynamic operation, e.g. for coupling with unsteadily available renewable energies. The project is supported by the Canton of Zurich, Avenergy Suisse, Migros, Lidl Switzerland, Armasuisse, Swisspower and the ETH Board.

DIRECT FEED INTO THE GAS GRID

At move, the hydrogen-free methane is produced by a process called sorption-enhanced methanation. ▸

THE METHANIZATION TEAM

The new reactor concept is part of an integrative concept for the production of methane gas at "move": Project team from the left: Brigitte Buchmann (Empa), Beat Lehmann (Canton of Zurich Construction Department), Karin Schröter (Empa), Tobias Geisser (Migros-Genossenschafts-Bund), Adrian Gonzalez (Empa), Daniel Stolz (Lidl Switzerland), Hanspeter Kaufmann (Armasuisse), Florian Kiefer (Empa), Christian Bach (Empa), Mauro Montella (Swisspower); not in the picture: Roland Bilang (Avenergy Suisse), Fabian Nager (Glattwerk AG)



HIGHTECH
The findings from the new reactor concept can be implemented for large-scale plants : Florian Kiefer, project manager for sorption-enhanced methanation, next to the test plant.

The idea: The water produced during the reaction is continuously adsorbed on a porous catalyst support during methanation. Continuous removal of water results in just methane as a product – in pure form – eliminating the need to purify the (previous) product mixture.

At the end of the reaction, the catalyst support material is dried again by lowering the pressure – and is ready for the next reaction cycle. "This process is more flexible and stable than previous processes, but it also has some potential for energy savings because we can run it at a lower pressure and do without hydrogen separation and recirculation. However, a precise assessment of the energy efficiency will only be possible once the demonstrator is in full operation," explains Florian Kiefer, project leader for sorption-enhanced methanation at move.

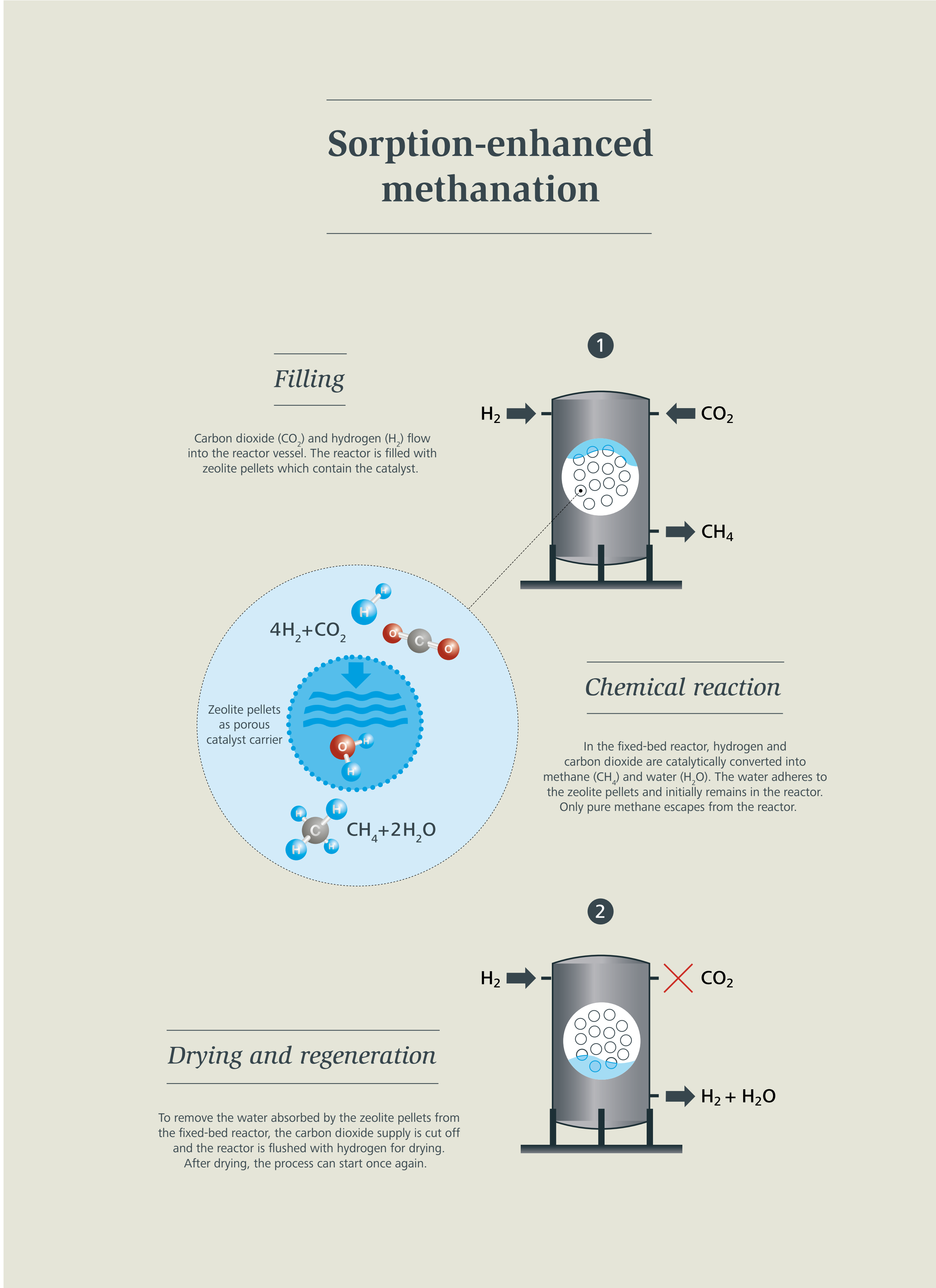
FROM LABORATORY TO INDUSTRIAL PLANT

Florian Kiefer and his team spent around three years developing a new reactor concept with zeolite pellets that act as a porous catalyst carrier and simultaneously adsorb the water produced during the methanation reaction. The focus was also on upscaling the process – in other words, a concept for how this process can be implemented for large-scale plants. To this end, Empa collaborated with various partners from industry. The regeneration time, i.e. the time needed to dry the reactor, is crucial for the reactor design and for process planning. To ensure continuous methane production, at least two reactors must operate alternately. Heat management is also crucial for the drying of the reactors, either by removing heat from the reactor or by storing heat internally in the catalyst bed. Kiefer's team has already filed a patent in this area. ■

Further information on the topic is available at: www.empa.ch/web/move

Photos: Annina Schneider / Empa

Graphic: Empa



HOW TO SAVE HEATING ENERGY

With energy prices soaring, heating costs will also inevitably rise in this winter. In order to mitigate this, solutions for operating buildings more efficiently are needed. The Empa spin-off Viboo has developed an algorithm that makes it possible to operate even older buildings with around 25 percent less energy – while user comfort remains the same or even improves.

Text: Loris Pandiani

A thermostat that predictively controls the indoor climate and thereby improves energy efficiency and comfort – Empa researchers Felix Bünning and Benjamin Huber came up with this idea while working in Empa's Urban Energy Systems lab. They developed a control algorithm that can calculate a building's ideal energy use several hours in advance based on weather forecasts and building data. The first experiments at NEST, Empa's and Eawag's research and innovation building, showed that this approach can save around 25 percent of the energy. In March 2022, the two researchers, together with Matthias Sulzer, Senior Researcher at Empa, founded a spin-off company, Viboo, to bring the solution to the market. In order to facilitate market entry, however, the algorithm still has to undergo more field tests.

PILOT PROJECT IN AN OFFICE

"We aim to integrate our solution into older buildings with no integrated building management system," explains Benjamin Huber. For this reason, the two neo-entrepreneurs decided to further test their algorithm in older buildings after the successful experiments in NEST. For that, they needed a suitable test object and a partner company that has smart thermostats in its portfolio.

Empa's directorate provided the former: an office building, built in the 1960s and renovated in 2009. The Viboo team also found a suitable partner company. "With Danfoss, we were able to win an international manufacturer for the project whose smart radiator thermostats already had a suitable interface. The control values calculated by the Viboo algorithm can be transmitted from the cloud to the hardware via this interface," explains Huber.

SMART HEAT
The cost of heating is rising and it is becoming increasingly important to reduce the amount of heating energy required. The Empa spin-off Viboo has developed a solution that makes this saving possible.

Photos: Empa, Adobe Stock

In a first step, the team replaced 150 existing analog thermostats in the Empa building with a smart solution from Danfoss, the Danfoss Ally. Next, they connected the hardware to the Danfoss cloud. To obtain the control values for the smart thermostats, the Danfoss cloud communicated with the Viboo cloud, which ran the self-learning algorithm. The setup was thus ready for field tests.

The new thermostats controlled the indoor climate from Christmas 2021 to the end of March 2022. In order to be able to draw a comparison, the operating modes were changed regularly, i.e. from the Viboo controller to the standard Danfoss Ally mode and back again. At the end of the trial, the team surveyed the users in order to understand how they perceived the room comfort and whether users accept such new solutions in general.

WIN-WIN: LESS ENERGY, MORE COMFORT

The results of this pilot project were very positive. Overall, energy consumption was reduced by about 23 percent compared to the same heating period of the previous year – with the same or even better user comfort. In comparison, Danfoss Ally alone saved only about twelve percent. "In our surveys, very few users expressed skepticism about the new technology. This makes us confident that the market will eventually accept our solution," says Felix Bünning.

The partner company is also impressed by the initial results. "We see great potential in the collaboration with Viboo and think that solutions like this are the future – not only for the control of a single building, but for entire energy systems," states Andrea Cannarozzo, Managing Director of Danfoss AG. From a visionary perspective, the Viboo algorithm could in future optimize various smart home integrations such as heat pumps or solar systems, but also help operating the electrical grid or heating networks more sustainably.

MORE PROJECTS ALREADY IN THE PIPELINE

However, back to the near future. To further pave the way for market entry, Viboo is conducting additional pilot projects in the upcoming heating period – together with Danfoss, but also other manufacturers such as ABB and Schneider Electric. The aim is to collect additional data and put the solution to the test in other environments. At the same time, there is already interest from the public sector in integrating the algorithm into existing buildings, for example from the Federal Office for Buildings and Logistics (BBL) and the municipality of Männedorf. The work at Empa is not yet finished for Viboo and Danfoss either. In the future, the partners will equip further buildings on the Empa campus with their smart solution. ■

VERY PRACTICAL
Switching from conventional radiator thermostat sensors to "Danfoss Ally" smart thermostats is simple and can be done in a few seconds.

AWARD-WINNING WORK

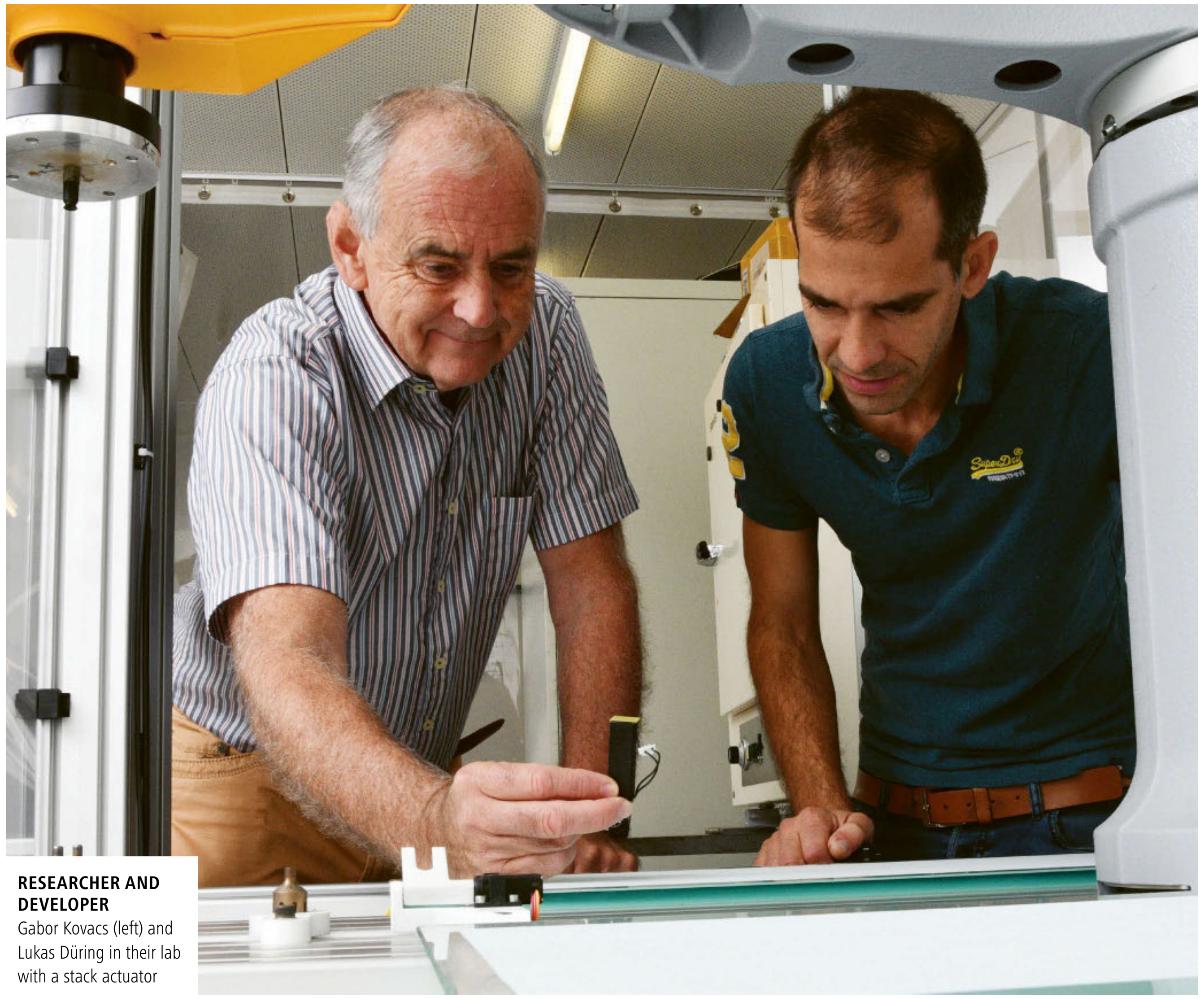
Various expert juries and committees were also convinced of the potential of the Viboo solution. The young entrepreneurs therefore received various awards and funding in 2022 to further advance their solution. For example, Viboo won the Venture Kick finals, received an "InnoBooster" from the Gebert Rüf Foundation and was named the winner of digitalswitzerland's GreenTech Start-Up Battle. But the spin-off was also recognized internally this year by being awarded the "Empa Innovation Award".

Further information on the topic is available at: https://viboo.io

CTSYSTEMS: A MARATHON TO THE MARKET

Developing a product from an innovative technology takes years, sometimes decades. Gabor Kovacs has lived through this process with his spin-off CTsystems AG and electroactive polymers at Empa. From the idea, to creative tinkering, setbacks, progress and the right comrade-in-arms, to the acquisition by a large company: experiences and a conclusion.

Text: Norbert Raabe



RESEARCHER AND DEVELOPER
Gabor Kovacs (left) and Lukas Düring in their lab with a stack actuator

Photo: Urs Bünter / Empa

The beacons of hope are inconspicuous, tiny, dark gray: wafer-thin square silicone platelets measuring 15 by 15 millimeters on a table in Room 024 of a large hall at Empa in Dübendorf. In a box next to it lies the finished product of hundreds of them stacked into "turrets," with filigree electrode layers in between. When an electrical voltage is applied to such components, the silicone disks are pressed together; the actuator shrinks a little – and can also, vice versa, register electronically when it is pressed together. What for?

Such stack actuators are simpler and cheaper than conventional technology and could be used in a variety of ways: to drive pumps, as switches in steering wheels, control buttons with haptic feedback, and much more. This is a potential that Gabor Kovacs has brought to maturity, first at Empa and later at the Empa spin-off CTsystems, which he founded in August 2012 – from initial tinkering with various materials to the announcement of success four months ago: acquisition by the industrial group Datwyler, with which the team has already been cooperating since 2018. At the latter's site in Schattdorf in the canton of Uri, an automated production plant is currently being built and is due to go into operation soon. In short, the step into the market is imminent.

A NEW START WITH GREAT CURIOSITY

It took a while to get there: Around 22 years since mechanical engineer Kovacs, then responsible for ropeway technology at Empa, was inspired by the idea of electroactive polymers (EAP) – among others, by articles in the magazine Science. And because Empa was changing from a traditional testing institution to a modern research institute at the turn of the millennium, he decided to make a fresh start in this field. In retrospect, the beginnings seem adventurous: from the first components, whose layers were created from commercially available acrylic adhesive tape, to artificial EAP muscles for a robot that competed in an arm wrestling competition at NASA's Jet Propulsion Laboratory in San Diego. The result: runner-up. "That was our first highlight!" says Kovacs with a laugh.

The second was the Blimp airship developed by an Empa team led by Silvain Michel: a gas-filled hovering vehicle whose elevator and rudder were moved by EAPs. This ultimately resulted in an eight-meter-long demonstrator that, thanks to EAP stretches on sides and tail, moved in the air with fuselage bends and a flick of the fin – just like a fish in water.

FAILURES, PROGRESS, REFINEMENTS

Instructive experiences, from which the technology itself greatly benefited. The initial acrylic adhesive tape was replaced after a few years by silicone, which has many advantages after crosslinking by vulcanization: easy to process, stable over countless movement cycles and durable even at high and low temperatures. "That's the key, especially when used in automotive applications," says Kovacs, "only few elastic materials have such properties."

A special formulation is now used after commercially available silicone – one of many developments that also involved mechanical engineer Lukas Düring, 40, who came to Empa in 2008 for a masters thesis and stayed on as a researcher: a talented helper with valuable input who eventually became partner at CTsystems. "He did a lot of tinkering and testing – with great success," says Kovacs, "it's such a real 'Gyro Gearloose'!" Nevertheless, the developers were not spared setbacks. Materials that were suddenly no longer available, a lack of spare parts or defects in the high-precision wet-stacking machine for the finished silicone layers: Empa's patented system, which also serves as a model for future production at Datwyler.

But now the chances of marketable products are good, says Kovacs: The technology is easy to use, robust and – unlike comparable electric motors – totally silent. But any guarantees of success? No, there are none. Even with the step into mass production, details are still open; for instance, the electrode material between the silicone discs. So ideas and passion are still needed – in the future more from Lukas Düring, who is already employed at Datwyler, than from Gabor Kovacs, now retired.

DEVELOPER VIRTUES? OF COURSE!

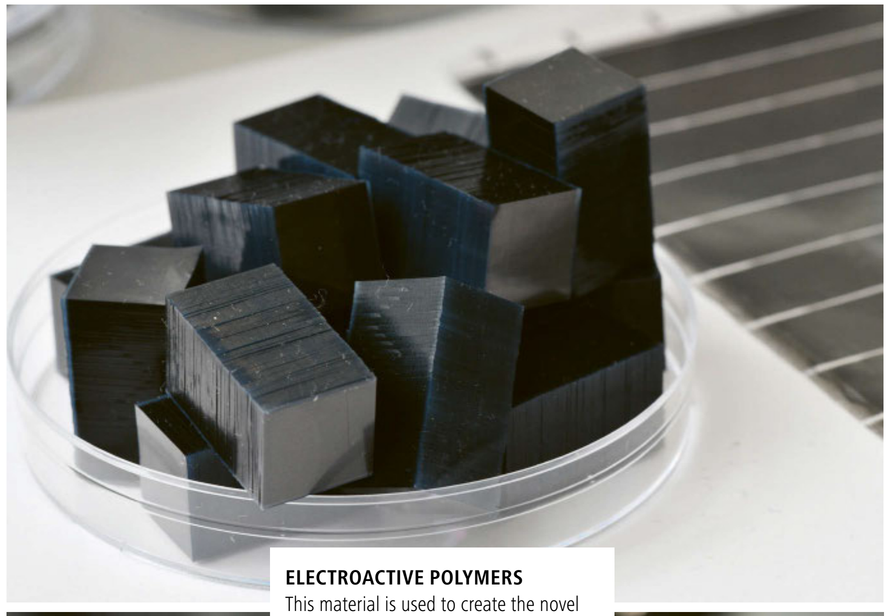
What is the senior's advice to young researchers who want to follow a similar path? A basic optimistic attitude? "Ooooh yes!" says Kovacs, nodding. Perseverance? "Ooooh yes!" he says, "it takes that relentless perseverance." And in addition to ideas for solutions, also the necessary sense of reality to weigh up which ones are feasible ▶

START-UP INCUBATION AT EMPA

The founding of a spin-off company is a proven tool for promoting promising technologies. In the case of CTsystems, the company was founded in August 2012 as Compliant Transducer Systems GmbH and an Empa spin-off by Gabor Kovacs and Lukas Düring to drive market development. In addition to the already acquired know-how and favorable licensing fees for two patents, the spin-off was given access to Empa's lab infrastructure and a small-scale manufacturing facility as well as other support.

with a view to the market. It's a marathon and at the same time a boxing match between vision and reality that lasts many rounds – and has been lost even by competent experts. For example, in Germany: "Many institutions have been working for years on how to produce such stack actuators," Kovacs recounts, "so far without success."

What made the difference? That things turned out better for CTsystems was also due to a simple circumstance, but one that Kovacs considers crucial. The last few percent on the road to success, "is personally sharing the risk," he says, "that it just has to work!" ■



ELECTROACTIVE POLYMERS
This material is used to create the novel actuators for a variety of purposes.

APPLICATION
A stacking actuator in the drive of a pumping device

Photos: Dätwyler Holding Inc., Urs Bünter / Empa

Further information on the topic is available at:
https://ct-systems.ch

SOLDERING AND WELDING IN MINIATURE

Electronic components are becoming smaller, more complex and more powerful – this calls for new solutions for joining them. An Empa team is developing nanostructured joining materials for the next generation of microelectronics and other demanding applications.

Text: Rainer Klose

SAFETY IN RESEARCH
Bastian Rheingans and Jolanta Janczak-Rusch work with a glove box that operates at underpressure. This prevents particles from escaping into the environment when preparing the nanopastes.

Photo: Gian Vaitl / Empa

Gordon Moore was right. In April 1965, the US engineer and later co-founder of Intel predicted that the number of transistors on a chip would double about every two years. To this day, this development continues with nearly the same speed – also because chip manufacturers worldwide use Moore's Law as the basis for their strategic planning. Thus, the prophecy is self-fulfilling. But the doubling of the number of circuits every two to three years sometimes reaches the limits of what is technically feasible. This also holds for the joining technologies, which have to keep up with the increased demands. After all, the ever smaller and more powerful electronic components still have to be integrated into larger systems, and the joints connecting the components to heat sinks or circuit boards should not fall apart during temperature changes or vibrations, or overheat during operation. A team led by Jolanta Janczak-Rusch and Bastian Rheingans from Empa's Laboratory for Joining Technologies and Corrosion is tackling this problem.

INDUSTRY IN NEED

"Our partners and customers, for whom we develop customized solutions, always want more, and preferably everything at the same time," says Janczak-Rusch. A joint for a new high-performance electronic component, for example, should be made at the lowest and gentlest possible temperature – and yet survive the highest possible temperatures when the component is in operation, and efficiently dissipate waste heat from the components. This is the only way to combine miniaturization with increased performance.

New materials and processes are therefore needed to meet the increasingly complex demands placed on joining. In this situation, joining with nanomaterials, so-called nanojoining, offers great potential. Industry is already using silver nanopastes, i.e. joining materials consisting of silver nanoparticles. The advantage: While the melting point for pure silver is 962 degrees Celsius, silver nanopastes can be applied to produce electrically and thermally highly conductive joints at temperatures as low as 250 degrees Celsius. And even better: Once produced, these joints can even withstand an operating temperature above their production temperature.

UTILIZING NANOEFFECTS

There's a lot of materials science know-how behind this innovative solution. "Here we are replacing a classic soldering process with a sintering process," explains Rheingans. This means that the particles in the joining zone are not melted, but grow together into larger particles and grains by diffusion, thereby reducing their surface energy. Diffusion, i.e. the movement of individual atoms, is very rapid at surfaces and interfaces. Since nanoparticles have an extremely large surface area in relation to their volume, sintering is particularly pronounced on the nanoscale and can be exploited even at comparatively low temperatures. In the case of very small nanoparticles or thin nanolayers, the amount of easily moving, "liquid" surface atoms becomes so large that the melting point can drop several hundred degrees below the melting point of the solid material. The researchers call this effect MPD (Melting Point Depression) – and use it to develop innovative and efficient joining processes.

THE RACE CONTINUES

"We are working on nanopastes with multiple components to optimize the properties of the joining compound and to open up new areas of application," Rheingans says. "For example, we are investigating combinations of copper and nickel nanopastes." These metals are less expensive than silver and exhibit very interesting electrical and thermal properties – but because they are less noble metals, they oxidize much more easily. That has to be prevented in the joining process. "So we put the nanoparticles in a paste of organic adjuvants that evaporate during the joining process and reduce the oxide on the particle surface. Or we coat the particles with a protective coating," explains the Empa researcher. Using special analytical methods such as X-ray diffraction (XRD) or X-ray photoelectron spectroscopy (XPS), the researchers can verify whether the postulated method of protecting the nanoparticles works as intended.

AN OVEN ON THE NANOSCALE

For particularly temperature-sensitive components, the researchers have another nanojoining method that they are continuously developing further: so-called reactive joining. In this process, reactive foils replace the soldering oven as a local source of heat. The foils consist of a large number of individual nanolayers, for example of nickel or aluminum. When these nano-multilayers are ignited, the nickel and aluminum react and form a new chemical compound – and release a great deal of heat that drives the process and makes it travel at speeds of up to 50 meters per second over the entire foil. Only layer thicknesses in the nano-range enable such a fast and self-perpetuating reaction. Locally, temperatures of up to 1000 degrees Celsius can be reached, but because of the low thickness of the reactive foil, the total amount of heat remains small and limited to the adjacent solder layers. In this way, sensitive electronic elements can be gently and firmly attached to copper heat sinks. ■

Further information on the topic is available at:
www.empa.ch/web/s202

PROMINENT VISIT TO THE DIGITAL TWINS

GREAT INTEREST
Empa researcher René Rossi, St. Gallen Government Council member Beat Tinner, Roland Ledergerber, President of the Board of Directors of Innovationspark Ost, President of the Swiss Confederation Ignazio Cassis, St. Gallen Government Council member Marc Mächler, St. Gallen Mayor Maria Pappa, Paola Cassis, Empa Director Tanja Zimmermann, Hans Ebinger, CEO Innovationspark Ost

Big crowd at the OLMA in St. Gallen: Federal President Ignazio Cassis visited the joint stand of Empa and Innovationspark Ost with a large entourage to find out about ongoing research. In one project, researchers from the participating institutions showed how food waste can be reduced with sensors and computer simulations – using digital fruit twins. In addition, the scientists demonstrated a chest strap for long-term monitoring of cardiovascular patients. It was validated with physicians in the sleep laboratory of the Cantonal Hospital in St. Gallen; the Empa spin-off Nahtlos AG will market it in future. In addition to the Federal President and his wife, the members of the St. Gallen Government Council Beat Tinner and Marc Mächler, St. Gallen Mayor Maria Pappa and other political players were present, as well as Empa Director Tanja Zimmermann and Roland Ledergerber, Chairman of the Board of Directors of Innovationspark Ost.

www.empa.ch/web/s604/olma

OLMA: MOBILITY ON NEW PATHS

How will we be refueling our cars in 20 years from now? And what kind of cars will it be? In times when the secure supply of crude oil, gas and fuels is in question, the joint stand of Empa, the Avenergy Suisse association, representing importers of liquid fuels, and the company Osterwalder St. Gallen AG was the focus of the public's interest. Fully electric cars and vehicles with a fuel cell drive attracted curious glances – and descriptive information about the production and environmental benefits of hydrogen as a fuel encouraged visitors to ask numerous questions of the experts present.

www.empa.ch/web/s504

THE RIGHT ANSWER
Many questions, many answers – and a chance to win: Curious guests could test their knowledge with a quiz with attractive prizes.

Photos: Empa

IN THE POLITICAL ARENA

EXCHANGE
Peter Richner in conversation with outgoing Energy Minister and Federal Councilor Simonetta Sommaruga

Photo: Empa

In late September, the parliamentary groups of the Federal Parliament went on their annual excursions and visited various corners of Switzerland. Together with party president Gerhard Pfister and parliamentary group president Philipp Matthias Bregy, the "Mitte" parliamentarians were shown the latest innovations in materials research and advanced manufacturing by Empa Director Tanja Zimmermann in Thun. Meanwhile, the Social Democratic parliamentary group excursion took the members of the National Council and the Council of States, accompanied by outgoing Federal Councilor Simonetta Sommaruga, to the Innovation Park in Dübendorf. At the invitation of ETH Zurich, they discussed the challenges of energy supply there – with them: Empa Deputy Director Peter Richner and the teams from move, the Empa spin-off Viboo and Empa's Materials and Technology Center of Robotics.

EVENTS
(IN GERMAN AND ENGLISH)

19. JANUAR 2023
NABEL Tagung: Luftqualität und Gesundheit
Zielpublikum: Industrie und Wirtschaft
www.empa-akademie.ch/Nabeltagung
Empa, Dübendorf

15. MÄRZ 2023
Kurs: Additive Fertigung von Metallen
Zielpublikum: Industrie und Wirtschaft
www.empa-akademie.ch/addfert
Empa, Dübendorf

23. MÄRZ 2023
13th VERT Forum
Zielpublikum: Industrie und Wirtschaft
www.empa-akademie.ch/vert23
Empa, Dübendorf

4. APRIL 2023
Kurs: Polymerwerkstoffe für technische Anwendungen
Zielpublikum: Industrie, Wirtschaft und Wissenschaft
www.empa-akademie.ch/polymerwerkstoffe

Details and further events at: www.empa-akademie.ch

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