Electricity
from Bits of Wood

Clean, efficient and reliable – that's how the power of the future should be. An example of this is the electric current generated by fuel cells fed with biomass. Researchers from the **Max Planck Institute for Dynamics of Complex Technical Systems**, the **Fraunhofer Institute for Factory Operation and Automation IFF**, and the **Fraunhofer Institute for Ceramic Technologies and Systems IKTS** are smoothing the way from the farm to the electrical outlet.

TEXT **ALEXANDER STIRN**

One piece of the puzzle is rusty, dusty and stuck in an acid yellow plastic stand. The puzzle pieces are packed in three dozen little tubes filled with a reddish substance and adorned with chemical formulas, indications of size, and cryptic combinations of numbers. It takes an expert to decode the descriptions scribbled on the tubes in thick marker.

Peter Heidebrecht picks up one of the puzzle pieces. He holds the tube against the light and shakes it gently. The dirty red powder rises in a cloud of dust. “This substance is just one of many options we are currently investigating,” says the process engineer. “But it’s this variety that makes the project exciting.”

The project is called ProBio, and the only thing the researchers know so far is the kind of picture the completed puzzle should eventually produce. Heidebrecht and his fellow researchers from the Max Planck Institute for Dynamics of Complex Technical Systems in Magdeburg have been working on it for three years. They aim to demonstrate a method for generating electricity from biomass as efficiently as possible. However, determining how the individual pieces of the puzzle should look and, especially, how they fit together, remains something of a challenge for the researchers. The composition of the reddish powder that is set to become an important substance in bringing power to the electrical outlet is only a small part of a much larger puzzle.

There is no doubt that biomass will play a significant role in the future. In fact, biomass already accounts for 7 percent of Germany’s energy consumption – by far the largest share of all the renewable energies. The German government aims to meet 18 percent of the country’s energy demand with renewable sources by 2020. “The challenge of converting biomass to electricity is thus extremely relevant today, and significant for the future,” says Kai Sundmacher, Director at the Magdeburg-based institute and spokesman for ProBio, a joint project being carried out by the Max Planck Society and the Fraunhofer-Gesellschaft. “Even though biomass is not the only solution for the energy supply of the future, it can certainly make a substantial contribution.”

But there are many ways to get power to the electrical outlet. Biomass can be burned, fermented or gasified. The resulting products can be used to operate steam turbines, gas engines or fuel cells. Each variant has its advantages and drawbacks. Many of the methods are well studied, while others are still virgin territory, technologically speaking.

Like the fuel cell at the center of the ProBio project. Fuel cells are small power plants that directly convert the chemical energy stored in a gas to produce electrical energy. “Of all the energy converters at our disposal, fuel cells promise the highest level of efficiency,” says Peter Heidebrecht. To date, such cells are mostly fed with natural gas, methanol or pure hydrogen. In principle, however, there is no reason why they can’t be fed with clean gas from biomass – provided the right pieces of the puzzle can be fitted together.

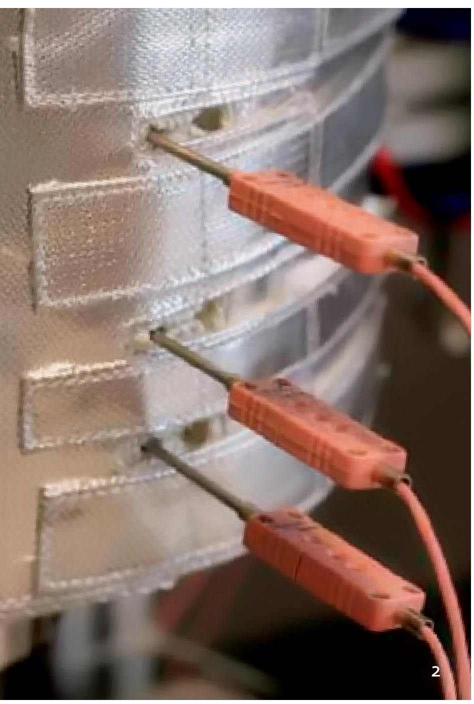
FUEL CELLS INCREASE THE ELECTRICITY YIELD

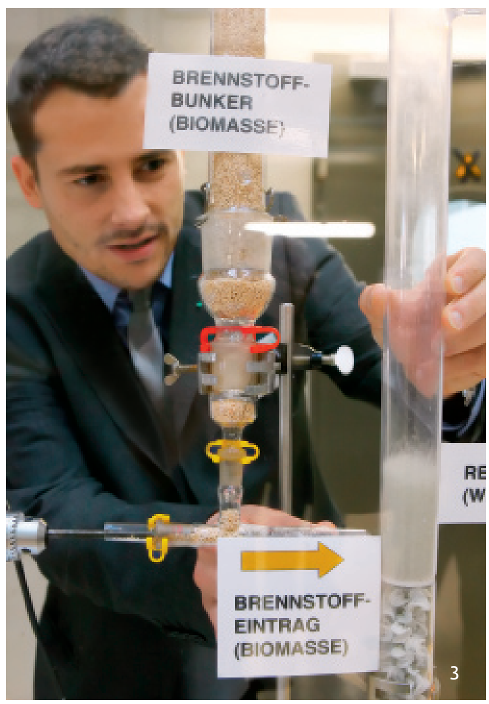
When it comes to handling the biomass, the Max Planck researchers are not exactly taking the easiest road, either: “The potential of simple combustion has been exhausted,” says Heidebrecht. Combustion burns biological raw materials and the heat released is used to generate electricity. “This process has upper limits set by the laws of thermodynamics. And no matter what engineering tricks you use, you just can’t change them,” says Peter Heidebrecht.

Fermentation – the process by which microorganisms decompose biomass in an oxygen-free environment and convert it into gas – has its drawbacks, too: the raw materials, such as wood and straw, contain a large proportion of a substance called lignocellulose. Bacteria aren’t quite sure what to do with it. It is hard to digest, so it doesn’t go down very well. Moreover, it is a slow process, and there is noth-

The Max Planck scientists are looking to generate electricity as efficiently as possible using wood chips or straw.

Photos: Bastian Ehl (bottom), iStockphoto (top)





ing that can be done about that: "Biology can't just be sped up to suit one's needs," says Heidebrecht.

Thus, gasification is the sole remaining option. This entails high-temperature conversion of biomass into a partially combusted gas. The gas contains many high-energy components, such as hydrogen, carbon monoxide and short-chain hydrocarbons. This makes it well suited for generating electricity – at least in theory.

Sascha Thomas opens a furnace with a circular metallic aperture that makes it look like the shiny exhaust on an American truck. Thomas, a process engineer, is the coordinator of the ProBio project at the Fraunhofer IFF located on the banks of the Elbe, just a stone's throw from the Max Planck Institute.

The exhaust-like furnace contains what is known as a fluidized bed gasifier – the beating heart of the gas generation for the ProBio project. The gasification agent, for instance steam, is fed into the apparatus from below. It meets a layer of sand whose particles are exactly the right size for the gas to keep them suspended and fluidizing in the air. "This guarantees us uniform temperatures and concentrations in the reaction zone," says Thomas. And that's where the biomass is introduced – by a spiral conveyor. The conveyor is water-cooled, as the fuel is intended to break down in the reaction zone – which is heated to 800-850 degrees Celsius – and not before it gets there.

BIOMASS DIVERSITY COMPLICATES MATTERS

Insulated pipelines with a silvery sheen conduct the fuel gas produced to the analysis equipment in the Fraunhofer lab. In a future ProBio power plant, the researchers want the gas to move directly into the fuel cells after it has passed through various cleaning stages. Then everything will be much bigger, too. A fluidized bed gasifier for a power plant with an output of several megawatts would have to be about one meter in diameter, whereas the pipe in the Magdeburg lab measures a mere five centimeters across. "This scale is sufficient to enable us to study the conversion of the biomass in the fluidized bed," says Thomas. "But the amount of fuel gas produced would be insufficient for a pilot plant."

Fluidized bed gasification is actually not a new idea. It was devised back in the 1920s for the purpose of extracting synthesis gas (syngas) from coal. However, petroleum chemistry soon made the process superfluous. Yet coal has one important advantage over biological waste: its main component is always the same – carbon. "Nevertheless, one type of biomass is not the same as another," says Thomas.

Glass jars holding wood pellets, oilseed rape straw, biomass coke and jatropha, a member of the spurge family of plants and a popular source of biomass in Asia, stand next to the fluidized bed gasifier.

Photos: Dirk Mahler for Fraunhofer (top and bottom left), Peter Förster for Fraunhofer (bottom right)

1 Full control: André Herrmann from the Fraunhofer IFF controls the fluidized bed gasifier, the column wrapped in shiny metallic foil in the background.

2 Detail of the gasifier with temperature sensors.

3 Hands-on experiment: Sascha Thomas uses the model experiment to demonstrate the principle of gas production from biomass. The objective is to use the gas to operate a fuel cell.

4 Sample test: In this reactor, Liisa Rihko-Struckmann tests how efficiently various mixtures with an iron oxide basis render carbon monoxide harmless in the gasification products.

In the puzzle that is ProBio, each substance has been extensively tested – with various gasification agents, at different temperatures and for different residence times in the fluidized bed. The composition of the gas changed each time. Even the season, the age of the wood and the way it was stored affect the quality of the gas. “Biomass is simply not a pure substance; it’s a complex composite mixture,” says Kai Sundmacher. “That’s part of what makes our project so interesting.”

Ideally, the gas that escapes from Sascha Thomas’s furnace is colorless and therefore free of impurities. However, it usually has a yellowish tinge, indicating that it contains tar, dust, and halogen and sulfur compounds, all of which fuel cells dislike – they contaminate their electrodes and must therefore be removed from the gas.

This is normally done by scrubbing systems in which jets of water are sprayed into the gas, promptly cooling it to room temperature and flushing out the contaminants. What remains is cold gas and lukewarm water. “The problem with the cold gas is that it would first have to be reheated to 800 degrees Celsius for the subsequent steps,” says Peter Heidebrecht.

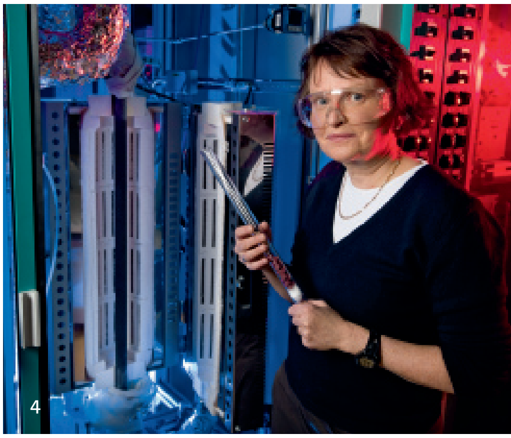
So the ProBio scientists thought up another method for their process: they pass the gas through a packed bed of ceramic beads to which any dirt particles adhere. “The way it works is similar to groundwater seeping through layers of sand and getting purified in the process,” explains Sascha Thomas. Catalytically active packed layers simultaneously convert the unwanted tar compounds into additional fuel gas, thus increasing the energy content of the gas. Finally, halogens and sulfur are removed with metal oxides. These react with the toxic components at fairly high temperatures.

What remains is a gas that contains clean hydrogen, but also large amounts of carbon monoxide. That can be good or bad, depending on the type of fuel cell the gas is feeding: high-temperature fuel cells, such as solid oxide fuel cells (SOFC), are robust energy converters that can take any fuel. They have a ceramic electrolyte, function at about 800 degrees Celsius and can even make electricity out of carbon monoxide. They run best at a constant load around the clock, and do not react well to sudden changes in the electricity demand.

FOOD FOR MANY DIFFERENT FUEL CELLS

“The temperatures inside the cells must remain within a certain window,” explains Peter Heidebrecht. “Any change in load alters the temperature profile and can damage the cells.” Moreover, the high-temperature fuel cells being studied by the Fraunhofer IKTS in Dresden take several hours to days to reach operating temperature, depending on their size.

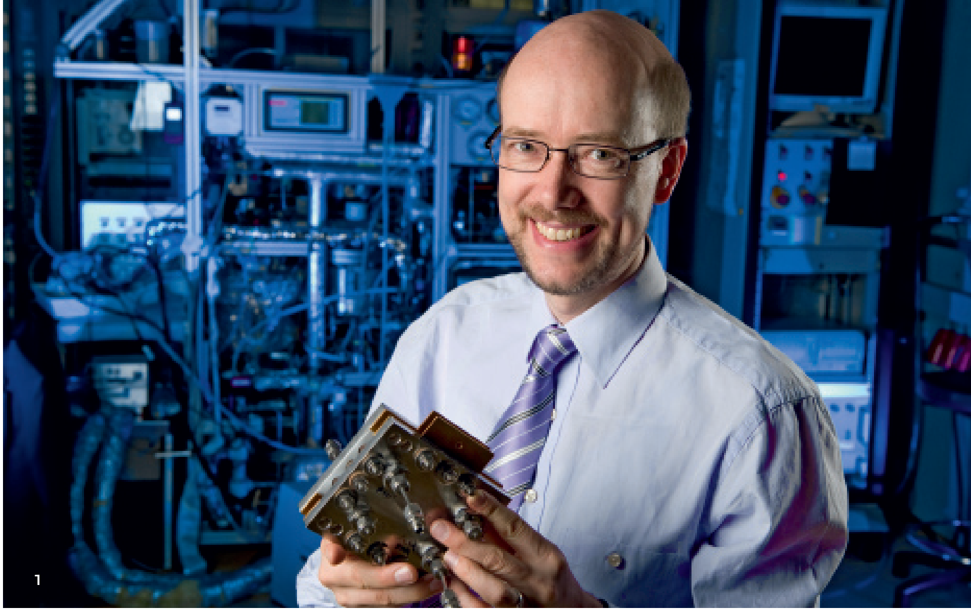
Things are different with low-temperature cells, known as PEM (polymer electrolyte membrane) cells. These cells are flexible but sensitive. Their electrolyte consists of a polymer membrane, which means it can’t withstand temperatures above about 80 degrees Celsius. However, the cell’s power output can be adapted to changing electricity demand at an hour’s or even a minute’s notice, if need be. This flexibility comes at a price, though: low-temperature fuel cells are almost completely incapable of handling carbon monoxide. Any concentration of more than


4

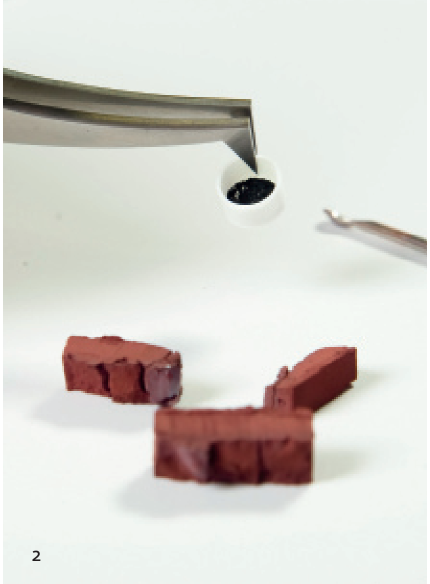
0.01 parts per thousand is highly detrimental to the cell, causing the electrical power output to plummet.

The process engineers in Magdeburg were assisted in their search for the matching piece of the fuel cell puzzle by happenstance – and a dusty red powder: “We really only wanted to remove the carbon monoxide from the combustion gas,” recalls Peter Heidebrecht. The stream of gas can contain up to 20 percent of the substance that is either toxic or useful depending on the type of fuel cell. The researchers attempted to bring it under control with dirty, reddish iron oxide – rust, basically: when the gas, heated to 800 degrees, flows over an oxide powder of this kind, the powder liberates some of the oxygen atoms the powder lattice contains and passes them on to the carbon monoxide. Carbon dioxide is formed, which is harmless to even a low-temperature fuel cell. The problem is that, whatever the scientists do, the gas still retains large quantities of carbon monoxide. Too much for a PEM fuel cell. Moreover, the iron oxide also converts the badly needed hydrogen into useless water. >

Photo: Bastian Ehl



1



2

3

However, the powder turned out to be very useful, thanks to a different kind of strength: once the powder lattice has shed its oxygen atoms, it greedily tries to replace them. Steam is one of the things that can provide them. When the steam comes into contact with the depleted iron oxide, the powder reclaims oxygen from the water molecules. What is left over is pure hydrogen – ideal for a low-temperature fuel cell.

WANTED: A DURABLE SUBSTANCE FOR GAS SCRUBBING

"When we saw that, we knew this kind of method would be wonderfully suited for gas separation," recalls Peter Heidebrecht. In the first round, when the combustion gas flows over the iron oxide, the mixture that is left over is something with which high-temperature fuel cells can live very happily indeed. The second step, when it is flooded with steam, produces the virtually pure hydrogen for the low temperature cells.

There is still a great deal to be done: "If we use iron oxide alone, the oxygen exchange takes a heavy toll on the material, and the amount of hydrogen we get out of it quickly diminishes," says Liisa Rihko-Struckmann, who is coordinating the ProBio project at the Max Planck Institute together with Peter Heidebrecht. That is one of the reasons for the many different powder samples in the acid yellow stands in the lab rooms in Magdeburg. Many contain nothing other than the red iron oxide particles measuring between one-tenth and five-tenths of a millimeter, while others have had aluminum oxide or silicon oxide added, though the most common additive is cerium-zirconium oxide. The researchers heat each sample to 800 degrees Celsius in one of the lab furnaces and then test it with a carefully mixed gas. "Right now we are taking particular care to ensure that the materials are stable and can be used for a lengthy period," says Rihko-Struckmann. The powders should be able to withstand a thousand gas and steam cycles.

Samples that produce a positive result in the lab are given a chance to prove their worth in the pilot plant lab, a gray cube at the northern end of the Max Planck Institute. This is where the engineers have built a test apparatus – a heatable steel pipe that they fill with roughly 20 centimeters of the iron oxide mixture. Instead of the 250 milligrams used in the lab, the researchers here need 100 grams of the substance.

"We are currently working on making larger particles out of our pretty fine powder, so that the gas can stream around them," says Liisa Rihko-Struckmann. Afterward, the process engineers intend to study how the gas diffuses within the powder, how to make optimum use of the oxygen in the oxide powder, and how the timings for switching between fuel gas and steam ought to be arranged. "These kinds of dynamically operated processes are some of the things our institute has been working on for years now," says Kai Sundmacher.

Gas purifiers in the Max Planck pilot plant lab, fluidized beds and packed beds at the Fraunhofer Institute, fuel cells in Dresden and Magdeburg – the pieces of the puzzle that comprise a potential ProBio power plant are still widely scattered. The only place they come together at the moment is in a computer's circuits, where the components – based on the values measured in the lab – can be simulated, combined and appropriately altered.

Photos: Bastian Ehl (3)

1 Biofuel cell: Kai Sundmacher with a low-temperature fuel cell. The fact that it can be fed with fuel gas even after gas from the biomass has already been fed into a high-temperature fuel cell is what makes the conversion into electricity particularly efficient.

2,3 Rust for gas purification: The researchers removed carbon monoxide from the fuel gas in the lab by using finer iron oxide (3); in the pilot plant lab, they executed the process on a larger scale with the coarser granulate (2).

4 Looking for the right powder: Peter Heidebrecht and Liisa Rihko-Struckmann test which of the different materials is the most effective at splitting the fuel gas for high- and low-temperature fuel cells.

With the possible improvements they have identified on the computer, the researchers return to the reactor, "hoping that everything goes as we expect it to," says Peter Heidebrecht with a chuckle. "Of course, that's usually not the case on the first try." They feed the mathematical model with the new findings from the lab in an effort to optimize the experiment even further. It is a constant back-and-forth that gradually brings them closer to producing a real power plant.

MODEL POWER PLANT OF INCREDIBLE EFFICIENCY

The process engineers have simulated more than one hundred different variants over the course of ProBio. What they discovered is something no one would have expected at the start of the three-year project: in the optimum power plant, both types of fuel cells work in parallel – in practice, providing the red powder can split fuel gas into one highly pure and one less pure stream of gas. "That's a kind of combined power plant," says Peter Heidebrecht. "It delivers a broad range of products spanning electric base load, dynamic peak load and usable waste heat."

Above all, it works with almost unbeatable efficiency. For their simulation, the engineers selected a model power plant designed for biomass with a calorific value of just under 19 megawatts, equivalent to slightly more than one kilogram of wood per second. The fluidized bed gasifier, purification in packed beds, hydrogen splitting and parallel operation of high- and low-temperature fuel cells boost the final output to almost 9 megawatts of electric power – an electrical efficiency of nearly 50 percent. Traditional biogas plants with an internal combustion engine attain just 35 percent. "These days, an improvement of even a few percent is cause for celebration because it helps save an awful lot of energy in the long run," says Liisa Rihko-Struckmann.

Even though the ProBio project, which the two research organizations funded with 4.2 million euros, officially ended early this year, the researchers plan to continue on their own. A pilot power plant is currently being built at the Fraunhofer Institute in Magdeburg and is scheduled to go into operation in the summer. "Then the individual components we've gathered experience on to date can finally be studied together and on a larger scale," says Sascha Thomas.

The researchers at the Max Planck Institute, already dedicated to the study of complex chemical processes and related basic research, will also continue working on the individual pieces of the puzzle, including the fuel cell and the

dusty red powder. "Even the highest efficiency is useless if the equipment lasts only a matter of hours or days," says Kai Sundmacher. Therefore, they will primarily be fine-tuning the operating conditions and the materials in an effort to engineer in a significant prolongation of the lifespan. The researchers still have a couple of pieces to fit together in the big puzzle called ProBio. ◂

GLOSSARY

Lignocellulose
Cellulose that is stabilized by lignin. It makes up the walls of wood cells, which gives wood its mechanical strength.

Fluidized bed gasification
This process creates fuel gas from coal or biomass. The solid components are usually fluidized and heated with a substrate. Hydrogen and carbon monoxide are two of the gases produced during chemical reaction with steam or another gasification agent.

Syngas
A gas rich in hydrogen and carbon monoxide that is produced during the gasification of coal with steam and is suitable as a source material for chemical synthesis.

Solid oxide fuel cell, SOFC
The solid oxide or high-temperature fuel cell owes its name to the ceramic material that makes up its electrolytes and that is permeable to oxygen ions but not electrons. At temperatures of up to 1,000 degrees Celsius, it generates electricity highly efficiently and is not sensitive to carbon monoxide.

Polymer electrolyte membrane fuel cell, PEMFC
The two poles of this low-temperature fuel cell are separated by a membrane that only protons can cross. The PEM fuel cell provides flexible power output. However, it tolerates carbon monoxide very badly because this gas blocks the surface of the electrodes, making them inaccessible to the reactants responsible for the cell reaction.

Photo: Bastian Ehl