FUEL FROM THE STEELWORKS

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With the steel industry accounting for some six percent of global CO_2 emissions, the Carbon2Chem project is taking an unusual approach to reducing the industry's climate footprint: scientists from organizations including the Max Planck Institute for Chemical Energy Conversion and the company thyssenkrupp AG are studying how this greenhouse gas can be used as a raw material for chemical products that – until now – have been produced from oil.

Almost everyone sees carbon dioxide as a problem, but it could actually provide a solution in certain situations. No matter which area of society or the economy you look at, most people are trying to find a way to get rid of the stuff – and few people have found the perfect way of doing so. The steel industry is one such example. Although it may one day be able to convert iron ore into iron using hydrogen or perhaps even electricity instead of by burning coal, this process is fraught with challenges, and the scale of these obstacles is often played down. Moreover, even if these challenges can be overcome, other steps in the steel production process still involve the emission of considerable quantities of CO_2. The problem is even worse when it comes to waste incineration plants or cement works, where it's almost impossible to reduce CO_2 emissions. To prevent the greenhouse gas from entering the atmosphere and further exacerbating climate change, these facilities have just two options: either to capture the carbon and compress it into underground reservoirs or find someone who can do something with it. One potential buyer is the chemical industry, which could use CO_2 as a raw material for the production of plastics, dyes or fuels. Until now, the industry's primary raw material has been oil – which not only exacerbates climate change, but is also only available in limited quantities.

As part of the Carbon2Chem project, scientists are researching how waste gas containing CO_2 can be used for chemical production via a process that specialists refer to as carbon capture and use (CCU). Given that the steel industry is one potential user, thyssenkrupp AG is one of the key partners in the project – after all, the company could not only apply the technology itself but could also offer it to other steel producers. The key participants also include teams from the Max Planck Institute for Chemical Energy Conversion in Muelheim and the Fraunhofer Institute for Environmental, Safety, and Energy Technology (UMSICHT) in Oberhausen. In addition, other industrial companies and research facilities have also joined the project, which since 2016 has received more than EUR 140 million in funding from the Federal Ministry of Education and Research. "With Carbon2Chem, we want to show that CO_2 is also suitable for synthesizing chemicals such as methanol under actual industrial conditions," explains Robert Schlögl, Director at the Max Planck Institute for Chemical Energy Conversion and one of the initiators of the Carbon2Chem project.

The project partners have set their sights on methanol, firstly because chemists have a great deal of experience when it comes to producing this alcohol from CO_2. Secondly, the chemical industry uses methanol as a precursor for a number of plastics and other products, consuming 70 million metric tons per year worldwide. That isn't all that much when you consider that steel companies around the world emit over two billion metric tons of CO_2 each year, which would be enough to produce around 1.4 billion metric tons of methanol. But 70 million metric tons is a start – and demand could potentially increase, including in areas other than chemical production. Methanol is also suitable for use as a fuel in parts of the transport sector that will continue to be reliant on liquid fuels for the foreseeable future, such as aviation. In addition to meth-

A smoking source of raw materials: at the thyssenkrupp plant in Duisburg, the Carbon2Chem team is researching how CO_2 emissions from steel production can be put to sensible use.

PHOTO: PICTURE ALLIANCE/JOCHEN TACK

anol, the Carbon2Chem partners use CO_2 to synthesize urea – another substance that is required in large quantities in the chemical industry.

As the project aims to adapt the processes for industrial applications, some of the researchers work at a "technical center" on the premises of thyssenkrupp in Duisburg. At first glance, the site looks very industrial. It is skirted by two pipelines, as thick as sewer pipes, that are supported on pillars. These pipelines carry gases released during steel production – and above all exhaust gas from the blast furnaces. Among other applications, thyssenkrupp uses the heat from these gases to generate electrical power. From the moment you peer through the gate of the Carbon2Chem site, one installation in particular catches your eye: standing as tall as a six-story building, a towering mass of steel pipes and boilers is encased in bright yellow scaffolding. It all looks more like a chemical production facility than chemical research, which is more commonly associated with flasks and test tubes.

Clearly, the research being conducted here has already outgrown its laboratory. Built in the first phase of the project, this system has a key role when it comes to using steelworks or other prolific emitters of CO_2 as a source of raw materials for chemical products. For example, it is responsible for purifying the steel mill gases that are channeled from the pipeline. This is necessary because the emissions that emerge from the chimneys during iron smelting, as well as those from cement production or waste incineration, contain a heady mixture of substances in varying proportions. Although this is a nightmare scenario for chemists who are keen to operate industrial processes in as controlled a manner as possible, steel mill process gases contain CO_2, carbon monoxide and hydrogen. In other words, they contain all the components of "syngas," which the chemical industry has so far produced from natural gas or coal, specifically for use in methanol production. At the same time, blast furnace gas does not contain a sufficient quantity of hydrogen, which must therefore be added. Where this hydrogen is going to come from is a question for Carbon2Chem.

Nina Kolbe is in charge of the Carbon2Chem subproject "CO_2 Sources and Infrastructure" at thyssenkrupp. She helps us get to grips with this complex maze of pipework, showing us where the individual components of the gas mixture are extracted and where they are subsequently mixed again in the required ratio. There are modules whose purpose is to remove sulfur-containing substances or ammonia, for example, as well as modules that can scrub out CO_2 if required. All of this technology allows the researchers to control how thoroughly a component is removed from the waste gas. "We purify the gas as thoroughly as necessary and as inexpensively as possible," says Kolbe. In a laboratory next door, staff working under Holger Ruland, head of the Carbon2Chem working group in Robert Schlögl's Department, carry out checks to determine whether the gas is pure enough. The lab is packed with instrumentation and electronics used to analyze the properties of the gas, but the key piece of equipment is a proton-transfer-reaction mass spectrometer. This instrument is able to analyze complex gas mixtures during operation and can detect a specific gas at a concentration of just a few particles per million.

SUMMARY

Using CO_2 from waste gases from the steel industry – as well as from waste incineration plants and cement works – to produce methanol and other essential chemicals could reduce the carbon footprint of these sectors.

In the Carbon2Chem project, researchers have found that the established process for methanol synthesis can also be carried out using industrial waste gases.

Whether the concept enjoys widespread use will depend on factors such as whether enough affordable hydrogen can be generated using renewable energies.

Ruland's team also address questions such as how methanol can be synthesized as efficiently as possible using steel mill top gases and why this process sometimes falters. This work is being carried out at the project's second location, the Carbon2Chem laboratory at Fraunhofer UMSICHT, about half an hour's drive from the technical center in Duisburg. In the facility, which is big enough to house a basketball court, Ruland points to a box that wouldn't quite fill half of a small freight container. "That's Schmusy." This tailor-made apparatus is connected to the ceiling by finger-thick steel pipes and appears to contain a large number of valves, pipes, regulators and other electronic control elements. "Schmusy allows us to produce dirty syngas," he says, explaining that the device's name is a portmanteau of the German words for "dirty" and "synthesis gas."

Unlike in steel mill gases or other waste gases from industrial plants, Schmusy allows the researchers to accurately control the addition of contaminants. Accordingly, they can determine which components of the top gases, for example, interfere with the established industrial process for methanol synthesis – and in which quantities. "Most problems are caused by the usual suspects," says Ruland. These include for example, all of the sulfur-containing substances and large quantities of oxygen, which are already known to cause problems because they poison the catalyst. This catalyst, which is made of copper, zinc and aluminum oxide, is responsible for activating the highly inert CO_2 and the hydrogen so that they can combine to form methanol and water.

All in all, methanol synthesis has so far proven to be relatively impervious to most of the contaminants found in the waste gases in question. "Many doubted that the standard catalyst would work with CO_2 from the waste gases, because it should be deactivated by the large quantities of water that are produced in the process," says Ruland. The fact that this does not happen is good news when it comes to implementing the Carbon2Chem concept in industry, because searching for a new catalyst can be quite a laborious process. Nevertheless, the chemists' work is still not done. Indeed, the researchers working with Holger Ruland and Robert Schlögl not only want to understand the process in detail, but also to improve upon it if possible and to adapt it to other waste gases from iron smelting. In this context, the chemists have spotted a problem that has practical implications. "In experiments conducted over a period of several thousand hours, the catalyst's activity sometimes peters out and then at some point comes back," says Schlögl. The researchers already have their suspicions as to what might be causing this phenomenon: too much oxygen. "It may be that the measures we've taken to remove the varying levels of oxygen are insufficient," Schlögl says. However, it's still unclear whether these uncontrolled interruptions would even be noticeable in an industrial facility. "In a system that contains 25 metric tons of catalyst, it's not a problem if one kilogram doesn't behave exactly as it should," says Schlögl.

Researchers from Fraunhofer UMSICHT are keen to establish whether this temperamental behavior is also relevant on an industrial scale – and whether other challenges may emerge under these conditions. The team is attempting to answer these questions with the help of a small demo system that produces two liters of methanol per hour. Their next step will involve a demo system at the Duisburg technical center that produces several thousand metric tons per year. "With this, we hope to prove that the process is also stable on a large scale and over a long period of time," says Holger Ruland.

At that point, the process of methanol synthesis from steel mill gases will also be fed with hydrogen produced at the technical center. After all, the process is only beneficial in terms of climate protection if the hydrogen is green – in other words, if it was obtained from water using electricity from renewable sources. The problem is that, at present, wind and solar power rarely produce more power than is needed. Producing green hydrogen on a large scale would require a massive expansion of renewable energy sources, especially since many areas of the economy and industry – not least iron smelting – are pinning

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Searching for causes of disruption: in the Carbon2Chem laboratory at the Fraunhofer UMSICHT research institute, a team of Max Planck researchers are analyzing, among other things, which constituents of blast furnace gas have an adverse impact on methanol synthesis. For this, the researchers use a specially designed system to mix up dirty syngas from various components, which are supplied from gas cylinders in the yellow cabinet (right).

PHOTO: THOMAS HOBIRK/MPI FOR CHEMICAL ENERGY CONVERSION

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Synthesizing methanol: Christian Froese, a researcher from the Max Planck Institute for Chemical Energy Conversion, monitors a methanol synthesis process in the Carbon2Chem lab in Oberhausen. The vacuum tubes in the foreground are part of a mass spectrometer.

their hopes on hydrogen as part of their efforts to transition to climate-friendly practices. And even if there are theoretically enough facilities to meet demand, there will always be fluctuations in supply. This means that the electrolysis process, which is used to split water into hydrogen and oxygen, must be able to operate flexibly and may even have to be stopped altogether on windless nights. So far, these unpredictable conditions have been a source of concern for the operators of electrolyzers, who fear that the systems will not be able to cope and will quickly fail. Whether their concerns are justified has also been the subject of research by scientists from thyssenkrupp AG and the hydrogen and fuel cell center ZBT in Duisburg.

This research is being conducted on back at the technical center in Duisburg – in a facility that stands about as high as the gas-purification installation and just a few steps away from it. Special safety measures are required in order to enter the facility because it operates at high voltage and uses a caustic alkaline solution – but we're at least allowed to peep through the door. Enclosed by scaffolding, the electrolyzer takes up relatively little space inside the vast facility. Inside the device, you can see a series of chest-high plates lined up behind one another, and it's between these plates that the hydrogen is produced. The electrolyzer was developed by a thyssenkrupp subsidiary, which is already distributing it commercially, and has proven to be more flexible than initially assumed. Indeed, the system operates flawlessly even with an unsteady power supply. This is another outcome that paves the way for applications of the Carbon2Chem concept.

From a technical perspective, there is little standing in the way of the CCU project and its aim of using waste gases from the steel industry as a source of raw materials for areas of chemical production. Nevertheless, it remains to be seen whether the two sectors will ultimately put the concept into practice. This is a question of long-term security of investment – and, of course, of the cost. “Are customers ready to pay a surcharge for green steel or green methanol?” asks Nina Kolbe. For those buying a car, for example, the climate protection contribution would perhaps come to a few hundred euros. Given the correct political and economic framework, these goods could still be competitive despite their higher production costs. Although the future price of CO_2 is a factor, it's not the most important thing to consider: “One key question is whether we have enough affordable hydrogen – and enough electricity from renewable sources to produce it,” emphasizes Holger Ruland. And this sentiment is echoed by other specialists working with CCU technologies.

A global market for renewable energies

Robert Schlögl believes that hydrogen would be significantly cheaper if electrolyzers were no longer manufactured in a workshop but rather using modern production technology. Still, this does nothing to change the fact that Germany is likely to face a shortage of green electricity in the future. This shortfall could be remedied by countries with a greater supply of sunshine and wind, such as Namibia. Indeed, the German government has just signed a hydrogen partnership with the southern African country, where a feasibility study and pilot project will be carried out to determine whether Namibia is capable of becoming a hydrogen exporter.

This would also constitute an important step toward establishing a global market for renewable energies, such as that which currently exists for fossil fuels. Schlögl helped to develop the German government's hydrogen strategy, and he believes that global trade in hydrogen, for example, is the best way to ensure that products from Germany remain competitive on the world stage – a better way, in fact, than EU tariffs on climate-damaging imports: "That would mean everyone has to pay higher prices." Of course, this assumes that a global demand exists, because the world is turning away from fossil fuels. Schlögl is very optimistic in this regard: "No one can continue to ignore the reports of the Intergovernmental Panel on Climate Change and the obvious signs of climate change."

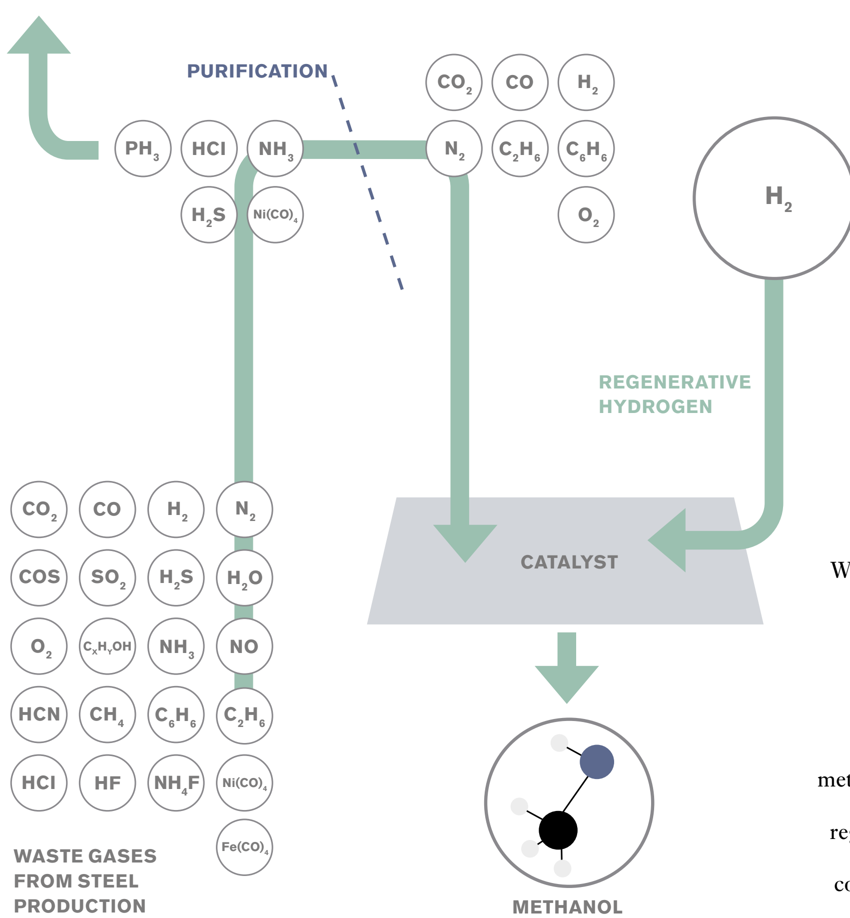
But these insights alone are not enough. It's also vital that emerging economies in particular are able to afford the measures needed to transform their industries in an environmentally friendly manner. Moreover, Carbon2Chem and other CCU technologies may not yet be effective enough, especially in terms of climate protection. "Any system that begins by using fossil resources and ultimately releases CO_2 is problematic if we want to achieve climate-neutrality," says Stefan Lechtenböhmer, who is carrying out research at the Wuppertal Institute into how industrial and energy systems can be redesigned in a climate-friendly manner. In the short and medium term, CCU could certainly aid the transition to a climate-neutral economy, particularly if the CO_2 is converted into durable products. "In any case, you've then used the CO_2 twice, as it were. Depending on the product, you've also stored it for a number of decades." However, the economist points out that, in the long term, carbon should only be used in locations where no alternatives exist. Still, hydrogen can be used to produce steel almost entirely without carbon. "Because the investment cycles in the steel industry are long, we should start embracing this solution as well. Otherwise, we might run into problems if we want to achieve net zero by 2045."

Nevertheless, Lechtenböhmer believes that a project like Carbon2Chem is vital, so that we have various courses of action to choose from in the future. Of course, this is a position that Nina Kolbe shares – including with regard to whether the steel industry should produce iron using hydrogen instead of coal, thereby avoiding CO_2, or whether it should opt to make use of the greenhouse gas instead: "There's a lot going on in industry around the world in terms of climate protection," she says. "We should pursue both approaches in order to reduce CO_2 emissions as quickly and cost-effectively as possible."

GLOSSARY

CARBON CAPTURE AND USE (CCU)
uses CO_2 from industrial waste gases for chemical production.

BLAST FURNACE GAS
is produced in the blast furnace process, where coke is used to reduce iron ore to pig iron, and makes up the greater part of the CO_2-containing waste gases at the steelworks. In addition, coke oven gas is produced during the conversion of coal into coke, and converter gas is produced during the conversion of iron into steel.



Waste gases from steel production contain many different substances (bottom left). The gases are purified in order to remove components that interfere with methanol synthesis (top left). A catalyst uses regenerative hydrogen to convert the CO_2 contained in the gases into methanol.

GRAPHIC: GCO BASED ON THE ORIGINAL BY HOLGER RULAND/MPI FOR CHEMICAL ENERGY CONVERSION