H Is for Hope

TEXT TOM RADEMACHER

A hot topic: Thyssenkrupp produces almost 12 million tons of crude steel in its plants every year. In the future, plans call for hydrogen instead of coal dust to generate the necessary operating temperature in the blast furnaces

When it burns it only produces water, its supply is inexhaustible, and its applications are manifold: Hydrogen has what it takes to fundamentally transform our economic system. Evonik is working in many areas to help make this vision a reality

In Duisburg-Bruckhausen, everything is gigantic. On an area that is 22 times as big as the Vatican, Thyssenkrupp Steel Europe generates around one fourth of Germany's total steel production—about 11.5 million tons a year. The plant's blast furnaces tower more than 100 meters into the sky. For decades, they have been spewing out hundreds of tons of glowing iron per hour.

However, the first tiny and as yet invisible steps in a transition that will completely change this seemingly immovable giant have already begun. With support from the federal state of North Rhine-Westphalia, Thyssenkrupp is taking the first tentative step toward climate-neutral steel production. Instead of coal dust, hydrogen will be blown into a blast furnace—initially as a test "in homeopathic quantities," as the company puts it. If all goes well, the first blast furnace will be converted by the end of 2021. Because hydrogen produces water vapor instead of carbon dioxide when it burns, Thyssenkrupp could reduce its emissions by more than three million tons of CO_2 per year—more than is caused by all domestic flights in Germany. And that's just the start.

The plan is that hydrogen will be the fuel of the future, in the steel sector and beyond. Business communities and policymakers all over the world are intensively driving this development forward. According to the European Union's "Hydrogen Roadmap," almost one fourth of the EU's energy needs could be covered by hydrogen by 2050. Plans call for 5.4 million jobs to be created in a hydrogen economy that uses this odorless gas, which is symbolized by the letter H in the periodic table, in every possible area. All kinds of systems, ranging from furnaces in cellars to regular-service buses, refineries, and steelworks, could be operated climate-neutrally with green hydrogen produced by means of renewable energy drawn from the wind and the sun. Most of the puzzle pieces for completing this vision of the future already →

Gray hydrogen: In steam reformers like this Evonik facility in Marl, hydrocarbons (mostly methane) are split into hydrogen and carbon dioxide

exist. It seems that they only need to be put together. However, many questions still remain unanswered. Evonik is one of those aiming to provide some of the answers.

"Water will be the coal of the future," wrote Jules Verne almost 150 years ago. He believed that the energy source of the future would be water decomposed into hydrogen and oxygen by means of electricity. This idea has never lost its fascination. In the late 1980s a cover story of the news magazine *Der Spiegel* called "The Energy of the Future" claimed that solar energy and hydrogen would provide the power that nuclear energy had promised but never delivered.

The hopes pinned on hydrogen are still running high today. "We have to forge ahead with the production and utilization of hydrogen as fast as possible," says Svenja Schulze, Germany's Minister of the Environment. "With regard to hydrogen, we can't afford to lose any more time," adds Anja Karliczek, the Minister of Education and Research. And her cabinet colleague Peter Altmaier, the Minister for Economic Affairs and Energy, insists that Germany must "become the Number One country for hydrogen."

There are good reasons for their enthusiasm. In light of our concern about the climate, hydrogen's qualities sound almost utopian. Its combustion produces only water. No soot, no carbon dioxide, and no oxides of nitrogen remain—thus, at least theoretically, hydrogen solves crucial problems of the petroleum age in one fell swoop. Besides, the supply of hydrogen is almost inexhaustible. Nine tenths of the atoms in the entire universe are hydrogen atoms. On the earth, hydrogen is mainly found in seawater. The rest of it is chemically bound within almost all fossil and biological raw materials. However, the economic potential of hydrogen is hardly being utilized.

> "With regard to hydrogen, we can't afford to lose any more time"
>
> ANJA KARLICZEK, GERMANY'S MINISTER OF EDUCATION AND RESEARCH

A MAJOR COMPONENT FOR THE CHEMICAL INDUSTRY

To date, the main user of hydrogen has been the chemical industry, which needs it to build molecules. More than half of the globally produced hydrogen is processed into ammonia, primarily for fertilizer. Refineries also need huge amounts of hydrogen, for example to crack and desulfurize petroleum products.

Evonik uses hydrogen to make numerous products, especially for the synthesis of hydrogen peroxide (H_2O_2). Hydrogen peroxide is used as an environmentally friendly bleaching agent in paper and cellulose production, as a means of sterilizing beverage containers, and as a fuel for space travel. Evonik is one of the biggest global producers of H_2O_2, with an annual capacity of more than one million tons. Hydrogen also plays an important role in the production of amino acids for animal feed and in the production processes for silanes, fumed silica, and specialty oxides—multifaceted products that are used in glues, plastics, and car batteries. Hydrogen is also frequently generated as a byproduct or a coproduct that is then used later on in other parts of a production network.

The company is currently represented in projects across all links of the value chain – from extraction to distribution to use – in order to better understand future customer needs and the associated potential for specialty chemicals. "Those who want to see the energy transition can't avoid coupling sectors by means of hydrogen," says Oliver Busch, the Head of Sustainable Businesses at Creavis, Evonik's strategic innovation unit, which is working to develop new and sustainable business areas. "And if we do things right, the transition won't pass us by either." Together with Axel Kobus, the Head of Evonik's Process Technology and Engineering Business Line, Busch wants to promote the hydrogen agenda. "As an industrial group, we have an especially large number of contact points," says Kobus. For example, Evonik produces hydrogen for numerous users and operates hydrogen pipelines that supply a variety of industrial companies. The Group also supplies innovative process technologies and products that could close gaps in the hydrogen economy. Kobus and Busch agree that "in this area we can provide substantial added value as a supplier of solutions."

GREEN IS THE COLOR OF HOPE

At the Marl Chemical Park, it's especially clear to see how multifaceted the uses of hydrogen already are today. "In this industrial park, which is home to almost 20 companies, hydrogen is used in nearly every laboratory and every plant—not always in large amounts, but almost always for crucial processes," says Swen Fritsch, the manager in charge of hydrogen operations at this location. The location's steam reformer delivers several tens of thousands of cubic meters of pure hydrogen per hour. Most of this production volume is used to cover the site's own needs; the rest is drawn off directly by industrial gas suppliers from the region at their own filling stations. Marl has the biggest hydrogen filling station in Europe.

Steam reformers like the one in Marl cover more than 95 percent of the worldwide demand for hydrogen. They use heat, pressure, and catalysts to produce hydrogen from fossil sources such as natural gas. This process generates about ten tons of carbon dioxide (CO_2) per ton of hydrogen. According to the International Energy Agency (IEA), in recent years hydrogen production has generated about 830 million tons of CO_2 emissions worldwide per year. That's more than the emissions of the UK, France, and the Czech Republic taken together. This is not a good balance sheet for hydrogen, the beacon of hope for advocates of an energy transition.

However, a different approach would also be possible. Hydrogen can be produced directly from water by means of electrolysis. The principle is simple and well known: A voltage applied between two electrodes splits water into its chemical components, oxygen and hydrogen. In a fuel cell, this process is reversed: Hydrogen and oxygen from the air react without combustion to form water. The reaction generates an electric current and some waste heat. Within this cycle, hydrogen is the storage medium for electrical energy. This potentially climate-neutral cycle, which is expected to spur the energy tran- →

> "Those who want the energy transition will need the sector coupling using hydrogen"
>
> OLIVER BUSCH, HEAD OF SUSTAINABLE BUSINESSES AT CREAVIS

Green hydrogen: In the future, more hydrogen should be produced using electricity from renewable resources

A basic material for industry: Hydrogen is the chemical basis of numerous products, including silanes for tire production, hydrogen peroxide for bleaching pulp, and ammoniac for the production of fertilizer

sition, is now attracting large amounts of attention and capital. The magic words here are "sector coupling" and "power-to-X." In other words, the aim is to store "green" energy, make it transportable, and use it in a variety of applications. Hydrogen makes this possible. It can be produced directly at the sites where renewable energy is inexpensive to produce. It's easy to store it and transport it to distant consumers via pipelines. And depending on the user's needs, it can be burned, used as a material or reconverted into electric current.

A HUNGRY MARKET

Hydrogen has a wide variety of possible applications. For example, cars powered by fuel cells can already drive further on one tank filling than most battery-powered cars and—unlike plug-in vehicles—they can be completely refueled in a few minutes. However, they have not been commercially successful so far. At last count, only 6,558 hydrogen-powered cars were on the road in the USA; in Germany, there were fewer than 400. There still is no network of filling stations, and the technology is still too expensive and too bulky for the mass market. State-of-the-art materials could help to change this situation. For example, thanks to specialized cross-linkers from Evonik, fiber-reinforced plastics can be used to make safe hydrogen storage tanks for vehicles and filling stations that are significantly lighter and cheaper than the gas containers available today. This technology could become established for commercial vehicles sooner than for cars. Regular-service buses, for example, always use the same filling station, weigh about 20 tons with a full load of passengers, and have a purchase price of more than €200,000. So the present-day disadvantages of fuel cells play a lesser role. The situation of trains is similar: According to a study conducted by the German Aerospace Center, hydrogen-powered trains are the best option for replacing diesel-powered locomotives, especially on long branch lines without overhead wires. Germany's first hydrogen-powered train is already making regular runs in the region around Cuxhaven. Shipyards are also trying out this technology. Norway aims to convert its many ferryboats to fuel-cell operation. And even the aviation industry hopes that hydrogen will one day be driving normal turbines by means of fuel cells or after being processed to form methanol and then kerosene.

Meanwhile, large fuel cells for reconversion are currently attracting interest as buffers for the power grid, and several producers of heating systems are offering small devices that supply households with both electricity and heat.

But the greatest hunger for hydrogen can be found in industrial companies—especially among steel producers. According to its sector association, Germany's steel industry could be operating completely CO_2-neutrally by 2050. What's more, it probably needs to do so if it doesn't want increasing penalties for CO_2 emissions to force it off the global market altogether. Thyssenkrupp plans to use hydrogen to re-

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Global Pioneers

Some countries make use of hydrogen only sporadically, while others are developing ambitious master plans. Six countries, six strategies:

JAPAN

Japan has long been known as one of the most ambitious advocates of a hydrogen-fueled future, especially in the mobility sector. The country's government aims to lower the price of hydrogen by 90 percent by 2050, thus making it cheaper than natural gas. A crucial part of this plan will be a project in which hydrogen is extracted from lignite in Australia, the resulting CO_2 is sequestered underground, and the hydrogen is then shipped to Japan. Japan, which has few fossil raw materials, already imports more than 90 percent of its energy supply from abroad.

NETHERLANDS

The Netherlands decided to end its extraction of natural gas in 2022. Since then, the country has been preparing its northern region around the city of Groningen to become Europe's future "Hydrogen Valley." The plans call for green power from offshore wind parks in the North Sea to generate enough hydrogen for industry, the region, and the export trade. The Netherlands, formerly the EU's biggest natural gas supplier, could in the future use its freed-up pipelines to also supply its neighbors with hydrogen.

NORWAY

In Norway, plans call for trucks and ferryboats to soon be fueled with hydrogen. Norway may also play a significant international role in the use of blue hydrogen, because the government in Oslo is forging ahead with the large-scale construction of CO_2 storage sites. After decades of extracting and exporting oil and natural gas, Norway has huge underground capacities that are ideally suited to storing large volumes of greenhouse gases from all over Europe.

SAUDI ARABIA

In countries that extract oil and natural gas, such as Saudi Arabia, the production of gray hydrogen from natural gas is particularly economical. According to the IEA, the production of blue hydrogen, in which carbon dioxide arises and is sequestered underground, is also cheaper here than anywhere else. The multinational oil corporation Saudi Aramco opened the country's first hydrogen filling station in mid-2019.

USA

In the United States, California in particular is setting stringent goals regarding climate protection and energy standards. That's why it also has the most ambitious plans for a future hydrogen economy. California's government aims to open at least 1,000 in-state hydrogen filling stations by 2030 and register a million hydrogen-powered vehicles by that date—figures that the Chinese aspire to for their country as a whole. Thanks to the USA's local shale gas production, gray hydrogen is cheaper there than it is in many other countries. That makes the shift to green hydrogen less attractive, unless there is state intervention in pricing.

SOUTH KOREA

Last year Seoul published particularly ambitious goals, especially for the mobility sector. South Korea aims to become a leading producer of fuel cells and hydrogen-powered vehicles by 2030. According to the Ministry of Transportation, all of the country's commercial vehicles will have been converted to hydrogen drive systems by 2035. The hydrogen supply will be secured by the construction of the world's biggest liquid hydrogen plant in the harbor city of Ulsan.

"Our customers want concrete answers regarding the CO_2 backpack that our products are dragging around with them"

AXEL KOBUS, HEAD OF THE PROCESS TECHNOLOGY AND ENGINEERING BUSINESS LINE AT EVONIK

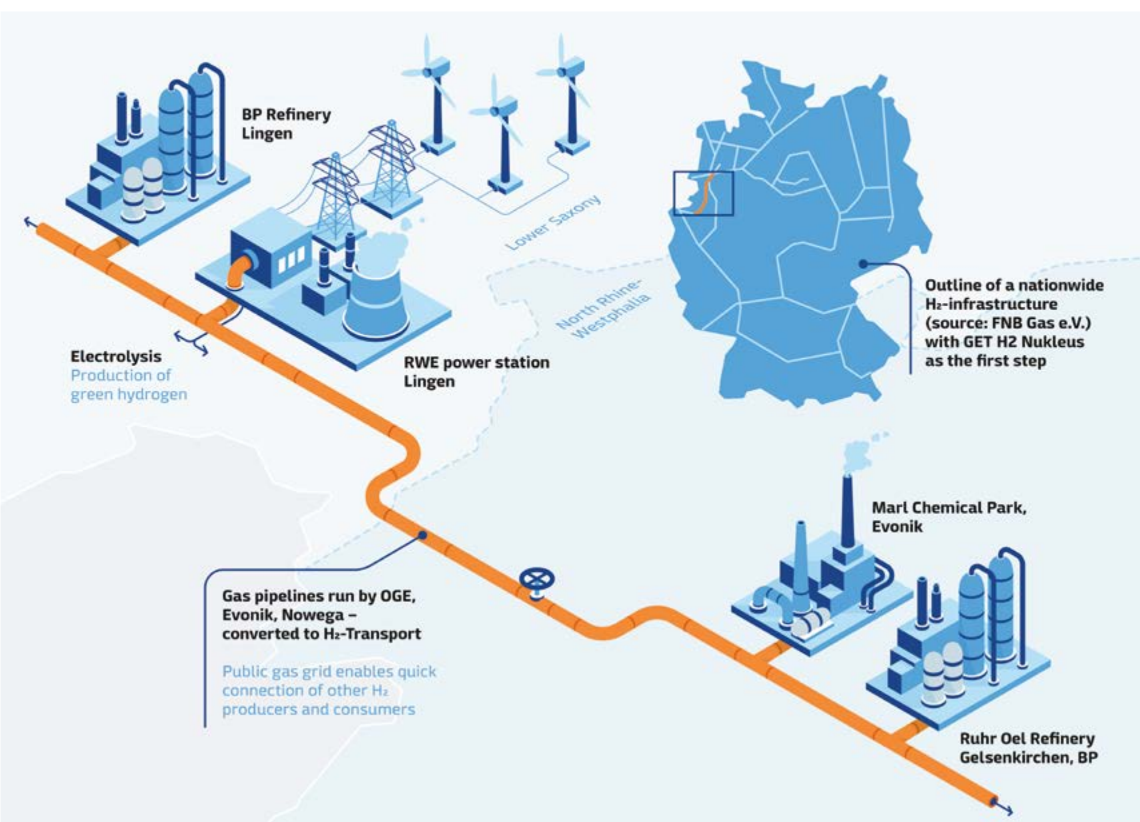
duce the emissions from its blast furnaces and make the remaining waste gases usable for chemical products. Carbon2Chem, a development project in which Evonik is participating, is searching for ways to manufacture chemical precursor products from burned carbon. For the long term, however, almost all steel producers are focusing on the direct reduction process, which thanks to hydrogen operates completely without carbon and coke.

This technological transition will cost Thyssenkrupp about €10 billion in the coming decades, according to the experts at the group's headquarters in Duisburg. And the volumes of hydrogen that will be needed for this transition are gigantic. "Around 2050, we will need about eight billion cubic meters of hydrogen per year," says Jens Reichel, who heads the Sustainable Production unit at Thyssenkrupp. According to Reichel, in order to produce this volume of hydrogen via electrolysis, 40 terawatthours of energy are needed. That's the approximate output of eight of the biggest Irsching 5 natural-gas power plants or about 3,800 offshore wind turbines in the three-megawatt class.

A BOOST FOR ELECTROLYSIS

This has been a tremendous spur for the developers of efficient electrolytic processes. The oldest, and so far the most frequently used, technology for hydrogen production by means of electricity is alkaline electrolysis. A newer technology called Proton Exchange Membrane (PEM) electrolysis has been gaining ground for about two decades. Other processes, such as solid oxide electrolysis, promise to be even more efficient but are still objects of research. Evonik too is working on key materials for new processes (see the article starting on page 28).

According to the IEA, currently less than 0.1 percent of the hydrogen produced around the world comes from electrolysis. The expansion of these capacities has begun. Since 2000, the IEA's database has registered more than 300 hydrogen projects that are either under construction or in the planning stage. Most of them are in Germany. Recently, however, new electrolysis facilities have on average had a capacity of just one megawatt. In the town of Wesseling near Cologne, Shell is building the world's biggest electrolysis facility, which will have a capacity of ten megawatts. The IEA estimates that the next generation of such facilities will deliver 100 megawatts or more. However, ten of these facilities would be needed in order to supply a single steel mill with hydrogen. A number of experts are therefore skeptical as to whether Germany can cover its predicted hydrogen requirements soon enough by means of electrolysis.



A CORE BUSINESS
The GET H2 initiative, in which Evonik is participating, is forging ahead with the Nukleus project, which aims to transport hydrogen produced using wind energy to various industrial users through a 130-kilometer-long existing pipeline.

A desert dream: In the future, large volumes of hydrogen could be produced in sunny regions such as North Africa and then transported to consumers via pipelines or tank containers

Added to these technical hurdles are economic ones: "Green" hydrogen is currently about three times as expensive in central Europe as "gray" hydrogen derived from natural gas. Because modern steam reformers like the one in Marl supply hydrogen efficiently and reliably, and because hydrogen is essential to the creation of the network, many experts in the sector believe that these steam reformers will have to play a crucial role in the medium term. The carbon dioxide generated in the process could be captured and stored. Hydrogen produced in this way is referred to as "blue" hydrogen. On a large industrial scale, this storage might take place in the underground reservoirs that remain after the extraction of natural gas. However, such caverns exist in only a few regions, and the technology itself is controversial (see the debate on page 22).

Another possibility is to capture and process the CO_2 that is emitted. For example, instead of hydrogen and carbon dioxide the steam reformer in Marl could also produce synthesis gas, which is a mixture of hydrogen and carbon monoxide—a common precursor product for the chemical industry. Evonik itself is working on a whole series of research projects that aim to use industrial waste gases to produce valuable intermediate and special products for the chemical industry in small modular plants. For example, Evonik is cooperating with the power plant operator STEAG and the University of Duisburg-Essen on the Vulcanus project, which is developing a new process chain that uses carbon dioxide and methane to produce higher alcohols for the production of high performance polymers.

COLD-PRESSED

In the future, industrialized countries may also be able to import more and cheaper hydrogen from renewable sources, for example from North Africa. The Desertec project was launched there more than a decade ago. The original aim was to transport solar and wind energy from the Sahara via direct-current lines through the Mediterranean to Europe. This aim was not achieved. The new hope is that the energy from the Sahara, in the form of green hydrogen, could be delivered to consumers by ship or by pipeline.

On principle, it's easy to transport hydrogen, but not every means of transportation is efficient. Because of →

the extremely low density of this gas, even 40-ton trucks with their impressive white high-pressure tanks can carry only about 300 kilograms of hydrogen. That's only a little more than the permissible load of a smart. Even the largest available tank trucks can transport a maximum of 1.1 tons of hydrogen at a pressure of 500 bar.

The low density of hydrogen also creates problems related to storage. In chemical parks such as the one in Marl you can find lots of gasometers and big pressurized containers full of oxygen, nitrogen, methane or ethylene, but you would look in vain for big tanks of hydrogen. Hydrogen can be compressed into cost-effective tank volumes only under tremendous pressure. It's true that hydrogen can be stored in the underground cavities that are left behind after the extraction of salt or natural gas. However, just like natural CO_2 storage facilities, they can be found in only a few regions. Hydrogen can be stored in a liquid, and thus especially compact, form only at a temperature of -253°C. That requires a great deal of cooling energy and elaborate insulation.

On the move: In northern Germany, hydrogen trains are already running regularly. The HY4 test aircraft with a fuel-cell motor made its maiden flight in 2016

"The only really efficient way to distribute hydrogen is via pipeline," says Thomas Basten, who heads Evonik's logistics business involving pipelines for all kinds of industrial gases and liquids. The Group operates more than 2,000 kilometers of pipelines all over Germany, three quarters of them under contract for other companies. In this function, Evonik is a participant of an initiative called GET H2, which is planning a public hydrogen network for Germany. The plans call for the network's "core" to initially be a 100-megawatt electrolysis facility that is being planned by the RWE power company in the town of Lingen—that's why the project is called Nukleus. Here in the Emsland region, not far from numerous wind farms in the countryside and in the North Sea, plans call for generating hydrogen by means of wind power.

RWE aims to transport this wind energy in the form of green hydrogen to industrial consumers by means of pipelines. One of these consumers is the BP oil refinery on the site; others are located in the Marl Chemical Park in North Rhine-Westphalia (see the graphic on page 16). A 130-kilometer-long steel pipeline could easily deliver up to 100,000 cubic meters of hydrogen per hour and help to supply consumers in the region. Best of all, a connection of this kind already exists, and it's partly operated by Evonik. These are pipelines that in some cases have become available because the Netherlands has discontinued its natural-gas business; these pipelines can be converted for carrying hydrogen.

HYDROGEN ON PIGGYBACK

"The pipeline business is not for poor people," says Basten. Laying pipelines has always been an expensive enterprise. In particular, fulfilling the bureaucratic requirements consumes a great deal of resources. That makes the use of existing pipelines an attractive option. Germany currently has approximately 50,000 kilometers of high-pressure pipelines for natural gas. If green electricity in the form of hydrogen is flowing through parts of this infrastructure, it might be unnecessary to build additional power lines.

At Evonik, this idea is being developed even further: Thanks to a Group-owned membrane technology, some parts of Germany's many-branched natural-gas distribution network, which is 500,000 kilometers long, could be repurposed. Commercially available natural gas already contains a low percentage of hydrogen today. However, more hydrogen could also flow through these pipelines in piggyback fashion without any problems. At various points in the network, SEPURAN® membranes from Evonik could be used to divert hydrogen for supplying filling stations or other consumers, for example.

In order to finally make the vision of a hydrogen economy a reality after 150 years, many factors have to come together: The network, the supply system, the demand, and the technology—all of these factors must develop in parallel while the price of green hydrogen decreases. This is where national governments must step in. "Everyone's waiting to see the German government's national hydrogen strategy," says Basten. "It would have to exempt hydrogen electrolysis facilities from the EEG-surcharge, change the energy industry law to permit the transportation of hydrogen in public networks, and create incentives for consumers to use green hydrogen." It's important to coordinate national planning and international partnerships. Evonik too wants to combine its numerous activities related to hydrogen within a comprehensive strategy. The Group's experts are feeling the growing pressure of the market. "Our customers want concrete answers regarding the CO_2 backpack that our products are dragging around with them," says Axel Kobus, the process technology engineer who is responsible for Life Cycle Management, among other things.

That's why the Group's hydrogen peroxide department in particular is considering when and how it can procure green hydrogen at market-appropriate prices—and how it can capture and process its own steam reformers' carbon dioxide emissions until then.

Unlike the steel industry and the energy business, the chemical industry is not aiming to exclude carbon from these processes. Carbon is a basic component of chemical products, and for that reason alone it's much too valuable to be burned and blown into the sky, says the Creavis manager Oliver Busch. "The ideal we are working on in the chemical industry is closed material cycles. Hydrogen offers us the unique opportunity to close material and energy cycles simultaneously." Now it's only a matter of putting together all the pieces of the puzzle.

For home use: The Daimler automotive group is further developing fuel-cell technology for stationary power plants

"The pipeline business is not for poor people"

THOMAS BASTEN, HEAD OF EVONIK'S LOGISTICS BUSINESS INVOLVING PIPELINES

THE COLORS OF HYDROGEN

GREEN HYDROGEN
If hydrogen is produced via electrolysis using renewable energy, no CO_2 is generated.

GRAY HYDROGEN
About ten tons of carbon dioxide are generated for each ton of hydrogen produced in steam reformers using fossil energy carriers such as natural gas.

BLUE HYDROGEN
The carbon dioxide from steam reformers can be captured and compressed in underground cavities, usually former storage facilities for natural gas. This process is controversial.

TURQUOISE HYDROGEN
In methane pyrolysis, biogas or natural gas is cracked in a reactor with liquid metal. This generates only hydrogen and solid carbon, which can be stored or used. This method is the object of research.