Advances in solar-based thermochemical hydrogen production

TAKING HYDROGEN FURTHER

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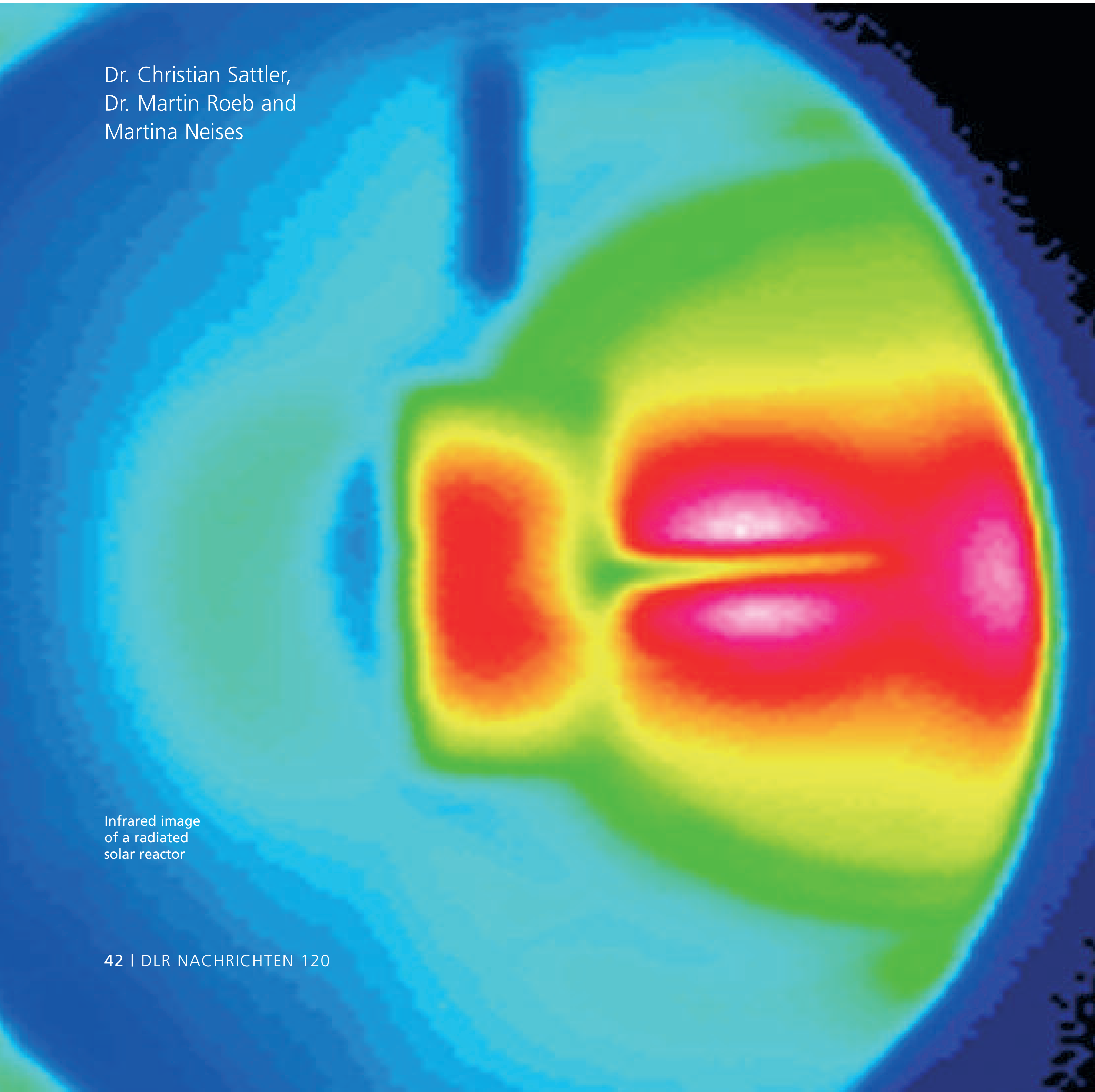


Infrared image of a radiated solar reactor

Lamark de Oliveira of the DLR Institute of Technical Thermodynamics assembles the HYDROSOL reactor (EU project HYDROSOL – Catalytic monolith reactor for hydrogen generation from solar water splitting)

Great hopes are pinned on hydrogen. As a clean-and-green energy resource, it has the potential to play an important part in fuel and power production worldwide. However, the propagated "hydrogen economy" only makes sense if it can offer a solution to the environmental problems inherent in the fossil-based energy economy, particularly the release of carbon dioxide. Also, hydrogen-based energy production can only be successful if it receives substantial political and economic support. If it is to cover the enormous global need for energy, the hydrogen economy will need to be implemented in huge technological dimensions. Let's not forget: hydrogen is only an energy carrier, not an energy source as such. Theoretically, it can provide as much energy as was put in during its production, but in practice only part of this energy can be exploited. This is one of the main challenges researchers have been facing.

Hydrogen is already an important base material in the chemical industry. Of the more than 50 million metric tons of hydrogen produced around the world each year, almost half is used each for the production of fertilizer and the refinement of crude oil. Only four percent make it onto the open market, and only one percent is used as actual fuel – mainly in space transport.

More than 95 percent of today's hydrogen is produced from fossil resources, predominantly natural gas and coal. If this were the primary method for producing hydrogen as an energy carrier, more overall carbon dioxide would be released than if the fossil fuels were combusted directly. Only five percent of today's hydrogen is produced from the electrolytic splitting of water into hydrogen and oxygen. The world's leading country to pursue this method is Norway, where the electricity required for the electrolytic process is provided by hydropower.

Finding alternative ways to produce hydrogen has been a major research concern for many years. For example, hydrogen can be extracted from biomass. Plants convert CO_2, water and sunlight into organic matter, albeit at a very low efficiency level. With the help of an external energy source, the hydrogen can then be extracted from this matter. Very large areas would need to grow energy crops to produce significant volumes of hydrogen – an approach which would inevitably be in competition with food production. Although especially waste biomass can contribute to a sustainable energy economy, it cannot by any means constitute its main basis.

Basic research is also being conducted into the biological production of hydrogen through microorganisms, particularly algae. It remains to be seen whether this is a feasible path towards hydrogen production for energy generation.

Carbon-based transition processes

Currently, the most common way of producing hydrogen is steam methane reforming. Natural gas and steam are heated to 750 to 850 degrees Celsius, and under great pressure they are converted into hydrogen and carbon monoxide. This mixture is called synthesis gas, or syngas. The energy required for heating is generated by burning part of the natural gas. One approach that might make this process viable for the envisioned hydrogen economy is to lower emissions of CO_2. Instead of burning natural gas to provide the required heat, an alternative, CO_2-free heat source is used.

In principle, there are two suitable heat sources. The most sustainable heat source we know is sunlight. Concentrated solar energy can easily produce the high temperatures required for steam reforming. However, this only makes economic sense in the sunnier regions of the world. The chemical processes involved require constant conditions, and even in a desert the sun doesn't shine at night, so excess heat produced in the sunlight hours needs to be stored overnight to ensure the steam reformer remains powered at all times. Since the 1980s, DLR has been participating in several R&D projects for processing and storage concepts, ranging from laboratory experiments to real-world pilot plants. Reactor efficiency levels of 80 to 90 percent have been achieved. Feasibility studies have shown that even today, the cost difference between conventional and solar steam reforming is very small. The commercial break-even point for solar steam reforming is at a natural gas price of 30 euro cents per cubic metre; this is the same as the average natural gas price on the spot market in May 2008. At peak times, prices well in excess of 40 euro cents are being paid for natural gas. When energy is generated from hydrogen produced through solar steam reforming, significantly less CO_2 is released than when the gas itself is used for combustion. This is because around 30 percent of the solar energy ends up being stored in the hydrogen.

The second main heat source that can be used for steam reforming is nuclear heat. Countries that strongly advocate the use of nuclear energy, such as France and Japan, have been developing steam reformers that are driven by the waste heat from high-temperature nuclear reactors. This is not a new concept by any means, and was already demonstrated in the 1980s with Forschungszentrum Jülich's pebble-bed reactor. The problem is that even today there are no commercially operated high-temperature reactors. The first are now about to be erected in South Africa and China. Without even delving into the overall pros and cons of nuclear energy, this approach will simply not be implementable on a global scale, nor can a sufficient number of suitable reactors be built. This is not a feasible solution to the world's energy supply problems.

Water-based processes

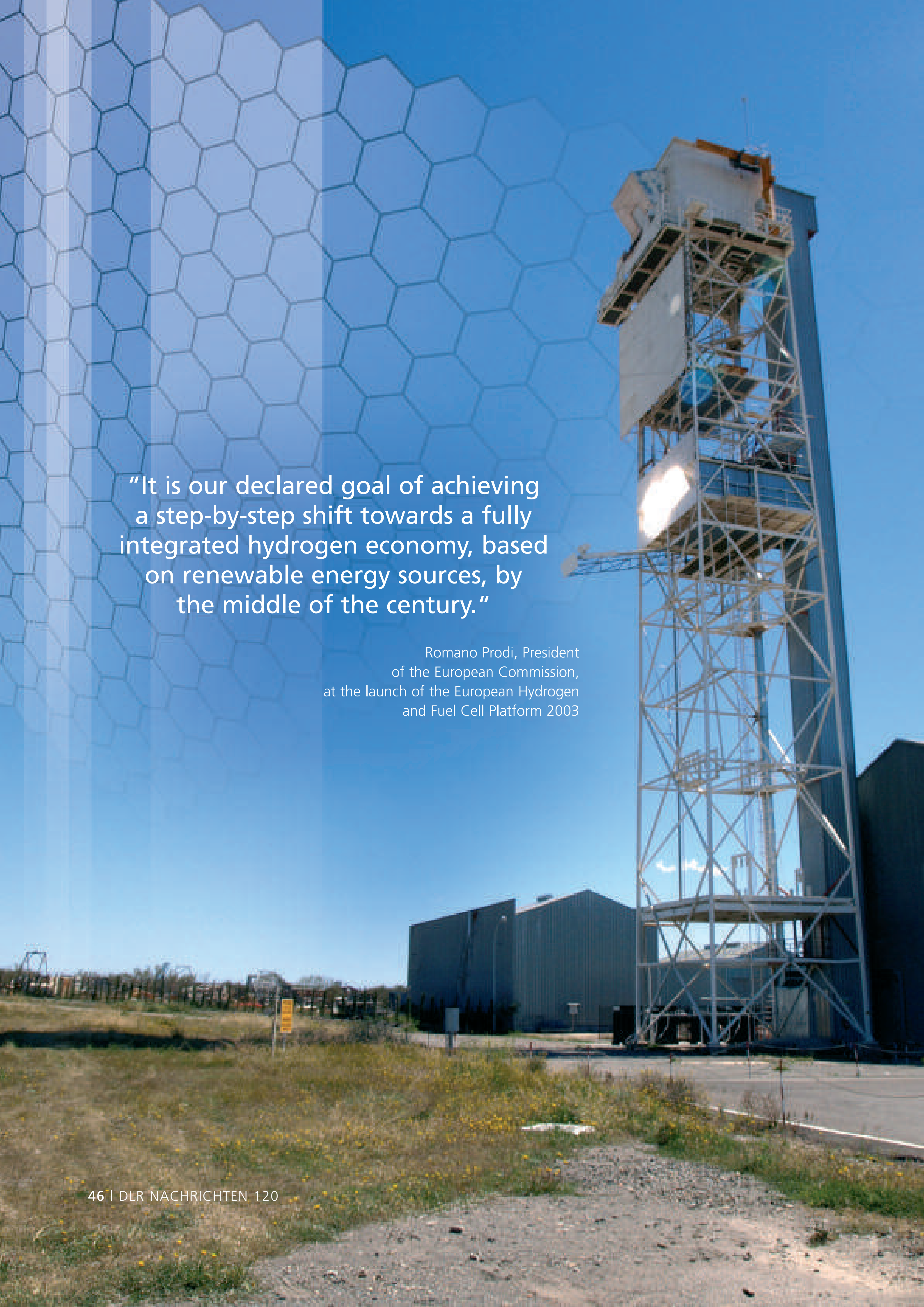
In the long term, we need to be able to produce hydrogen from natural resources that do not release carbon dioxide, pose no risks to our climate and health, and are not expected to run out in the foreseeable future. Two such resources are water and sunshine. Unfortunately, water is typically very scarce in regions with lots of sunshine, unless it is extracted from the ocean. There are two solutions: Either the solar energy can be transported to where the water is (for example, in the form of electricity), so the water can be split through electrolysis, or sea-water treatment can be coupled with solar-thermal processes.

Thermal processes have the advantage over electrolysis that they eliminate the electricity conversion stage and may be more efficient. A study at the US research centre SANDIA National Laboratory has determined

Launch of the HYDROSOL 2 project, with Prof. Johann-Dietrich Wörner (centre), Chairman of DLR, and Prof. Caetano Lopez (right), Deputy Director of the Spanish energy research centre CIEMAT that the efficiency of converting solar energy into hydrogen through solar thermal power and electrolysis is currently 14 percent. In comparable conditions, thermochemical cycles can achieve efficiencies of 20-25 percent. In addition to the increased efficiency, combined water-desalination and water-splitting plants could also provide drinking water – which would be a great bonus in the world's arid regions.

Since the 1970s, then, research has been focusing on so called thermochemical cycles for water splitting. These processes require one or more reactants that are recycled quasi infinitely within the process. One advantage of thermochemical cycles is that hydrogen and oxygen are not produced within the same reaction, which means that no explosive oxyhydrogen is produced. Hundreds of such cycles have been described in research publications, and the most efficient ones have been developed for real-world implementation. There are two main groups of thermochemical cycles: those that use metals or metal oxides – particularly iron – and those that use inorganic sulphur compounds, such as sulphuric acid. Of the sulphur-based processes, the sulphur-iodine cycle and the hybrid sulphur cycle are the most common. These are also known as the "General Atomics Process" and the "Westinghouse Process", named after the companies that developed them. In both cycles, the energy demanding stage is the splitting of sulphuric acid in the presence of catalysts. This happens at a temperature of around 850 °C. Both of the cycles can potentially achieve very high efficiency levels. A major problem that still needs to be resolved is the

Preparing the solar furnace concentrator for HYDROSOL testing: Jan Peter Säck and Daniela Graf from the DLR Institute of Technical Thermodynamics assemble the mirrors



> “It is our declared goal of achieving a step-by-step shift towards a fully integrated hydrogen economy, based on renewable energy sources, by the middle of the century.“

Romano Prodi, President
of the European Commission,
at the launch of the European Hydrogen
and Fuel Cell Platform 2003

corrosive nature of the chemicals; this necessitates highly resistant component materials.

As part of the EU-funded projects HYTHEC (2004-2007) and HyCycleS (2008-2010), DLR has contributed significantly to research into the development of sulphur-based thermochemical cycles. The research activities at the DLR Institute of Technical Thermodynamics have been focused around the high-temperature processes of sulphuric acid splitting using solar energy. This was successfully demonstrated as part of the HYTHEC project. In order to speed up development on a worldwide level, the HyCycleS project now also includes partners from the US, Japan and Australia. The goal is to demonstrate the new technology with a pilot system very soon after the project is completed.

DLR is also working on iron-based thermochemical cycles. This process, which has been researched extensively by the EU project HYDROSOL, consists of two stages. The iron-oxide-based reactive material is alternately oxidised and reduced. The reactive matter is coated on a ceramic structure, and the two process stages occur sequentially in the same reactor. The coated ceramic structure is heated inside a solar receiver reactor using concentrated solar energy. For the water-splitting stage, steam is fed into the heated reactor. The steam reacts with the coating at a temperature of 800 to 900 °C; the hydrogen is released, and the oxygen is bound by the material. Once the material is saturated with oxygen, the flow of steam is shut off and the reactor's temperature is increased to around 1,200 °C. This releases the bound oxygen from the reactive coating, and the cycle begins afresh. A solar thermochemical cycle like this was first demonstrated by the HYDROSOL project in 2004; the two process stages were successfully repeated in one reactor several times. The project received a number of prestigious awards: the EcoTech Award of Expo 2005 in Aichi, Japan, the Technical Achievement Award 2006 of the International Partnership for the Hydrogen Economy (IPHE), and the Descartes Research Prize 2006 of the European Union.

To further develop the HYDROSOL process, a HYDROSOL 2 pilot system has been installed on a solar tower at Plataforma Solar de Almería in southern Spain. To make this possible, the Spanish research centre CIEMAT has joined the HYDROSOL consortium, which also counts as its members the Aerosol and Particle Technology Laboratory (APTL) of the CPERI research centre (Thessaloniki/Greece), Johnson Matthey Fuel Cells (UK), Stobbetech (Denmark), and DLR (Germany). The pilot reactor, which can convert 2 x 100 kilowatts solar heat, was inaugurated on 31 March 2008. After successful thermal test campaigns the hydrogen production tests started in November 2008.


Jan Peter Säck and Mirko Meyer-Grünefeld on the testing platform of the solar tower at Plataforma Solar de Almería, Spain, where the HYDROSOL pilot system is being run

Conceptually, solar-based hydrogen production is well underway. However, in order to make hydrogen available as an economically viable energy carrier on a global scale, two major steps are still lacking: the technical demonstration of thermochemical cycles, and the development of efficient storage mediums that enable simple, safe and economical hydrogen use. DLR is participating in a number of German, European and worldwide research consortia that are working on these issues and on the energetic conversion of hydrogen (e.g. in fuel cells). With all these activities, DLR's stated goal is to make a significant contribution to safe, economical and sustainable energy production.

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