**Hydrogen - a beacon of hope for the energy transition**

*As we move towards a climate-neutral future, great hopes are being pinned on hydrogen as a key element of the energy transition. The energy-rich molecule can be used for storage and can act as an ideal versatile chemical energy carrier. But how might the hydrogen economy of the future look like? What volumes are required and what infrastructure is suitable? This trend report provides answers to these questions.*

**Green Deal and Climate Change Act pave the way for the hydrogen economy**

The EU's Green Deal aims to avoid as many greenhouse gases as are emitted by 2050, making the EU greenhouse gas neutral. With the adoption of the 2021 Climate Change Act by the European Parliament and Council, climate targets have also been enshrined in law, with the EU's interim target for emissions reductions by 2030 raised from 40% to at least 55%. The legislative package known as 'Fit for 55' contains provisions to put Europe on this path. In the last two to three years, these political decisions have laid the foundations for medium to large-scale hydrogen projects in Europe and around the world.

The goal has been set, and it is clear that green electricity is certainly going to play a key role in a renewable energy system. Using it directly is undoubtedly the most efficient way to go. However, wind and solar power are intermittent sources of energy and therefore not always available. Electricity storage is also a problem. Another argument in favour is that a modern industrial society such as Germany requires very large amounts of renewable energy, which cannot be covered by the available national renewable generation capacities. This is where hydrogen comes into play: renewable energy can be stored as hydrogen in chemical form, which means it can be stored for long periods of time, is always available and can be transported over long distances. Hydrogen thus offers the possibility of using renewable energy independent of time and place.

As an energy-rich feedstock, hydrogen is not new. It is already used in large quantities in refineries, in the chemical and petrochemical industry and partly also in the steel industry. Until now, this hydrogen has mainly been produced from natural gas via steam reforming. The carbon contained in the natural gas is oxidised to CO2 and emitted into the atmosphere. This is precisely what is set to change in the future with the introduction of low-carbon hydrogen.

**Low-carbon hydrogen: green and blue are not mutually exclusive**

Low-carbon hydrogen has a significantly lower carbon footprint than hydrogen produced from fossil fuels using conventional processes. This includes, for example, green and blue hydrogen.

Green hydrogen is produced by the decomposition of water with renewable electricity, whereby the electrical energy is converted into chemical energy. The efficiency of this conversion is between 60 and 70 %. The fact that the hydrogen produced can be stored and is available at any time, unlike electricity, compensates for this loss of primary energy. However, the current production capacity for green hydrogen is nowhere near sufficient to meet the current and growing demand for hydrogen. This requires a massive scale-up. The advantage of green hydrogen is that it does not cause any emissions during production. At the same time, there are high costs involved, which are to a large extent determined by the cost of electricity from renewable energy sources.

Blue hydrogen is produced by the natural gas reforming process described above, the only difference being that the CO2 produced in the process is captured and permanently stored rather than released into the atmosphere. The advantage of this process over electrolysis is the significantly lower energy input, as the natural gas already has a high energy content. In addition, existing reforming processes can be used if they are supplemented with CO2 capture. Overall, blue hydrogen can be realised on the scale required much faster than green hydrogen, so that large amounts of greenhouse gas emissions can be saved on a shorter timescale. On the other hand, the separated CO2 must be stored permanently and safely sealed.

Green and blue hydrogen are therefore not mutually exclusive. Rather, they can complement each other: The faster, blue solution offers security of supply and timely emissions savings, while the green, fossil-free solution paves the way to a more sustainable future.

**Allrounder hydrogen**

In a renewable energy system, hydrogen power plants (gas turbines) and fuel cells can be used to bridge dark periods and balance out fluctuations. Hydrogen can also be used as a reducing agent in the steel production, as a feedstock for chemicals, or to provide heat or process heat.

In the mobility sector, with increasing distances and masses transported, the trend moves towards e-fuels produced from green hydrogen. In this case, the advantage of high volumetric energy density of e-fuels outweighs the disadvantages of conversion losses and, moreover, is without alternative for certain applications, particularly in intercontinental shipping and aviation.

The importance of hydrogen as a main pillar of the energy transition has become increasingly evident since 2020 at the latest, when it became widely recognised that green electricity and green or low-carbon molecules must complement each other. To date, more than 20 countries of the 56 globally strongest economies have published national hydrogen strategies. What they all have in common is the goal of reducing greenhouse gas emissions, usually combined with technological development and the creation of new economic growth as part of the transformation process. Further measures in the hydrogen strategies vary according to the needs and potential of the individual countries: While industrialised countries are focusing not only on domestic production, but also on importing and diversifying their energy suppliers, countries with high potentials for renewable energies are working on structures for the production and export of hydrogen in addition to their own supply. Adding up the quantities of hydrogen estimated in the strategies, the global hydrogen potential is in the high four-digit terawatt-hour range per year - an immense figure with correspondingly large opportunities. This requires significant investment in technology development, plant construction and infrastructure. New international hydrogen partnerships will emerge. Negotiations between importing and exporting countries are already underway and business models are being developed.

**Hyperscaling: industrialising low-carbon hydrogen technologies**

The quantities in question indicate it: The term up-scaling doesn’t do it justice. What is needed is hyperscaling, an increase in capacity and structure in the order of a factor of 100. Germany's hydrogen strategy, for example, aims to realise 10 GW of electrolysis capacity for the production of green hydrogen in the domestic market alone. And the National Hydrogen Council now expects to see this demand revised upwards to 22-37 GW. Especially in heavily industrialised countries with chemical industries or steel production, the demand for hydrogen is high if these sectors are to become fossil-free.

These targets for green hydrogen can only be achieved if electrolysis technologies are massively scaled up. The number of electrolyser manufacturers on the international stage is growing steadily, and established suppliers are also developing their systems at full speed, investing in plant and automation to maintain and extend their technological lead and compete internationally.

However, such a scale-up cannot simply be realised by multiplying currently existing production units. Instead, entirely new processes and production technologies are needed. Large assemblies need to be mass-produced on fully automated assembly lines to increase throughput and minimise defects. Not only the performance of an electrolyser, but also the suitability of the components for automatic assembly, maintenance, and repair, and above all, operational safety and durability are now important target parameters. To produce large quantities of green hydrogen, renewable energy generation in particular will have to be expanded to provide the green electricity needed.

Many electrolyser manufacturers are currently working on scaling up their technologies. They are investing heavily and experiencing corresponding growth. One example is H-TEC SYSTEMS, which at the end of April 2023 held the official groundbreaking ceremony for a new factory in Hamburg's Rahlstedt district, together with representatives from the worlds of politics and business. In the future, the H-TEC SYSTEMS Stack Manufacturing & Development Center will combine development, production, testing and service at a single site and will eventually employ several hundred people. From as early as 2024, PEM electrolysis stacks with a potential total electrolysis capacity of up to 5 gigawatts are to be produced there automatically.

A similar scale-up would be required for blue hydrogen. Natural gas reforming is already being carried out on an industrial scale, although there is still a scale-up factor of about 10 between the quantities of hydrogen for today's common industrial applications and its envisaged role in the energy system. Large-scale processes are also already in place. The uncharted territory lies in combining the two technologies and integrating interfaces such as natural gas production or supply on the one hand and CO2 storage on the other. An example of this is the Norwegian-German cooperation between Equinor and RWE, where both natural gas and blue hydrogen will be supplied from Norway to Germany to contribute to security of supply and, in the future, to support the renewable energy system through hydrogen-ready gas-fired power plants. Another recent example is the CCS First project, launched by INEOS and Wintershall in March 2023, which involves injecting CO2 into a depleted oil field. The aim is to achieve 40% of Denmark's CO2 reduction target by storing 8 million tonnes of CO2 per year.

**Transporting and storing hydrogen**

A hydrogen economy can only come into being if the necessary infrastructure is put in place at the same time. Transport and storage technologies will be needed, and these need to be developed and scaled up, both for hydrogen itself and for some of its derived products. The challenge for infrastructure is the low volumetric energy density of hydrogen, as well as its high diffusivity and ability to corrode and embrittle certain steels. Typically, gaseous hydrogen is compressed for storage, e.g. to 350 or 700 bar, or even liquefied to increase the volumetric energy density. Both require energy and expensive tanks. Another way to make hydrogen more transportable is to bind it to liquid organic hydrogen carriers (LOHCs), where it is later released and recovered. This means that, as is already the case with fossil fuels, they can be transported in liquid tanks at ambient conditions.

When converted to derivatives such as ammonia or methanol, hydrogen can also be transported. Once transported, hydrogen can be recovered by means of reformation. Alternatively, in the production of fertilisers, for example, ammonia can be used directly as an essential chemical.

**Power-to-X and the carbon cycle**

Power-to-X (also "PtX") refers to the production of materials with renewable electrical energy. This is primarily about electrolysis, where X is hydrogen. But this is only the starting point. Hydrogen can be used to make organic molecules: The best-known candidates are methanol and its derivatives (e.g. methanol-to-gasoline), methane and liquid hydrocarbons from the Fischer-Tropsch synthesis. They can be used as platform molecules in the chemical and process industries or as carbon-neutral fuels, especially in applications that cannot be defossilised by direct electrification (e.g. maritime transport, aviation).

To produce organic feedstocks via PtX, i.e. with green hydrogen, carbon is needed. Today, most of the carbon comes from fossil fuels. This must be replaced by carbon from other sources. The perfect solution would be to extract CO2 from the air using Direct Air Capture (DAC). However, the concentration of CO2 in the air is low. As a result, DAC is complex and expensive. Another feasible option is to capture CO2 from point sources in 'must run' plants, such as cement production and waste incineration, so that emissions are avoided. CO2 for PtX synthesis can also be obtained from biogenic carbon sources or by recycling used plastics.

All in all, the transition to a hydrogen economy will require major changes and the development and implementation of new processes. The industry's transition to climate neutrality will be costly. For the development of new business models and value chains, the legal and policy frameworks for hydrogen and PtX products are therefore also crucial. And last but not least, the acceptance of the public is also important. A successful energy transition requires a holistic and integrated approach that combines technological, economic, social, and environmental considerations.

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