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Into the hydrogen energy economy—milestones

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Abstract

Many roads lead to Rome; many roads lead toward the hydrogen energy economy. They are marked with milestones, those alongside the fully operational hydrogen economy, which was established long ago, and those marking the up and coming hydrogen *energy* economy, which is the subject of this paper.

Keywords: Hydrogen energy economy; Coal hydrogen; Structural changes

Hydrogen is nothing really new. It goes back to Antoine Lavoisier (1743–1794) and Henry Cavendish (1731–1810), who independently of each other described hydrogen for the first time in the late 18th century. One generation later, in 1839, Christian Friedrich Schönbein (1799–1868) and William Robert Grove (1811–1896) published their works on the fuel cell effect and the construction of the first-of-its-kind fuel cell which electrochemically recombines hydrogen and oxygen (from air), delivering electricity and heat efficiently and cleanly.

Here and there you read that the fuel cell is not a Carnotian (Sadi Carnot 1796–1832) energy converter; this is not correct. Correct is the fact that the fuel cell is not a heat engine and, thus, does not need ever higher temperatures and, as a consequence, expensive temperature-resistant materials for energy-efficient operation. This is only one, though one of its most important, decisive advantage!

In liberal market economies, innovations are the cooperative result of the triad of science and engineering, industry, and politics. For sure, this applies for hydrogen and fuel cells, too. Consequently, there will be technological, industrial, and political milestones to pass on our way toward the hydrogen energy economy. They are interdependent. Their relative importance changes over time. Now, after decades of successful R&D, the tide begins to turn—the time for entrepreneurs has come. They need to rely on technologically safe ground, as well as societal and political support. Particularly for a country like Germany, which depends on imports for three quarters of its energy supply, wise and far-sighted foreign politics is an indispensable framework condition for any energy-related innovation!

This paper brings five milestones:

- Hydrogen from coal
- Hydrogen as the transport fuel
- The exergetically efficient stationary fuel cell
- Hydrogen and fuel cell-induced industry structure change
- Political framework conditions for investment planning security.

All in all, energy needs time! Never did a new energy added to the mix in a first significant contribution make it earlier than after many decades, up to half a century. Hydrogen and fuel cells will be no different. Hydrogen energy is not a nine-day wonder. As a consequence, "it's HYtime!", it is absolutely time to start and never give up again, it seems

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that it is almost always too late. J.A. Schumpeter (1883–1950) wrote: "It's the innovations which support economic booms!"

Milestone 1: hydrogen production from coal

For the time being, 50 million tonnes of hydrogen are traded annually worldwide with a growth rate of ca. 10% per annum. By factors more than that it is regularly produced and utilized in refineries for de-sulphurization of diesel fuel or re-formulation of gasoline and the like. The bulk of hydrogen, traded or non-traded, stems from steam–methane reforming of fossil fuels (SMR), especially of natural gas, or partial oxidation of heavier oil fractions (POX), or gasification of coal. Only a few percent are electrolytically generated where inexpensive electricity is available, e.g., at big hydrodams around the world. Renewable hydrogen (made electrolytically from renewable wind, solar, etc. generated electricity) is the climatically ultimately desirable goal but not, however, the precondition for entry into the hydrogen energy economy. As long as the desirable goal is not yet reached, hydrogen from fossil fuels will prevail, although under the indispensable condition of capture, sequestration and final storage of co-produced carbon dioxide (CO_2). Avoidance of climate change requires avoidance of release of anthropogenic greenhouse gases into the atmosphere, with CO_2 of highest interest because of its concentration rate.

Milestone 1
Hydrogen from coal

- has tradition
- has a static range of centuries
- is indispensable because of its contribution to energy supply security
- is hardly "OPECizable" because of its ubiquity
- makes possible the CO_2-free coal fired power plant
- enables coal to enter booming gas markets

has to meet the condition of CO_2 sequestration

Hydrogen from coal has tradition. Under serious re-evaluation of the future energy mix, its environmental and climatic responsibility, and its foreign energy trade policy, coal was, still is, and will be indispensable. Coal's worldwide availability is unquestioned; there is no continent where coal is not mined. Coal is ubiquitous. Consequently, a coal "OPECization" is highly improbable. Hydrogen gives coal two more chances: it enables the CO_2-free coal fired power plant which, with today's average world coal power plant park efficiency of not much more than 30%, is absolutely necessary from a Kyoto Protocol point of view. And, the second chance, hydrogen as a future participant in booming gas markets opens up the re-participation of coal via hydrogen in the two energy end user sectors transport and households, from where it disappeared with the advent of oil and gas. Truly, a renaissance! For the time being, steel and electricity keep coal alive; in the future, hydrogen from coal will become a powerful partner keeping coal alive!

Principally, CO_2 capture and sequestration is a precondition, regardless of which fossil fuels are under consideration: coal, oil, or natural gas. However, the sequestration necessity varies, because the relative atomic hydrogen-to-carbon ratios are $\leqslant 1:2:4$ for coal:oil:natural gas. In the prospective hydrogen energy economy, this ratio will approach infinity (∞). Within the context of the development of the CO_2-free power plant, experiments are under way on CO_2 mineralization via re-carbonization and its storage in unminable coal seams, in emptied oil or gas wells, or even as a carbonate mineral on the earth's surface.

Let us recall that after a century of de-carbonization and hydrogenation by switching from coal to oil and further to natural gas, two-thirds of all fossil fuel atoms burnt are hydrogen atoms; the trend points to even higher hydrogen numbers.

Milestone 2: hydrogen—the automotive fuel

To date, material mobility of humans and goods is guaranteed by ca. 1 billion vehicles, ships and airplanes worldwide. Their annual reproduction rate is ca. 60–70 million. Hydrocarbons are the predominant fuel.

Environmental neutrality for earthborne vehicles meeting the EUR IV (2009 EUR V) certification requirements is given, down to the sub-ppm level; for airborne or seagoing vehicles it is technologically possible. Climatic neutrality, however, is an illusion even with drastic reductions of fuel burnt, because energy efficiencies near 100% are thermodynamically impossible, and the dislocation of hundreds of millions of emitters makes capture of emitted greenhouse gases hardly feasible. Here, hydrogen as a fuel comes into play, regardless of whether it is renewable hydrogen or hydrogen from CO_2 sequestered fossil fuels, or whether hydrogen serves as the fuel for an internal combustion engine (ICE) under the hood, or for a fuel cell in an electric drive train. In any case, the ultimate consequence needs to be climatic neutrality over the entire length of the energy conversion chain from cradle-to-grave, i.e. from well-to-wheel via hydrogen production, storage and transport, and finally on-board utilization.

Milestone 2
Hydrogen as transport fuel

- is the ultima ratio in fuel
- means reformerless vehicles
- guarantees environmental and climatic cleanness

requires the installation of a hydrogen infrastructure

It so happened that in the labs of academia or development shops of industry, experiments are pursued not only with hydrogen as the fuel cell's fuel, but with a whole variety of carbonaceous fuels. This has two significant consequences:

(1) Pure hydrogen on board results in the "simpler" vehicle, because there is no need for a reformer which is heavy and perhaps bulky and has to guarantee reliable temperature dynamics between −40 and +50 °C; only the decision to "fill her up" with high pressure gaseous or cryogenic liquefied hydrogen has to be made. The consequence is that a stationary hydrogen supply infrastructure, so far not in place, needs to be installed.

(2) For hydrocarbons as on-board fuels, exactly this is unnecessary, because natural gas, gasoline, or diesel fuel are in place anywhere and anyhow, and for methanol only insignificant adaptations are added. A reformer, however, is mandatory with its lifelong need to be accelerated, decelerated, accelerated, etc., and whose annual asset utilization hardly reaches more than 1%. For sure, hydrocarbons on board, even reformed, may become *environmentally* clean; from a *climate change* standpoint, however, because of the global dissemination of the emitters, they will never supply what is needed.

Experiments are fine, even experiments with negative results; generally, they will clarify the situation. Finally, however, it seems certain that only one fuel will make it—hydrogen—because vehicles are imported and exported and they are operated all over the world under dissimilar circumstances; different fuels in neighbouring countries seems unimaginable. Let us try to avoid red herrings!

Milestone 3: the exergetically efficient fuel cell

In Germany, 15 million central heating systems are operated in industry and households, fuelled with natural gas or light oil, in a few cases with heavy oil. The number of boilers also utilizing the energy of condensing constituents of the exhaust gases is increasing. The energy efficiencies reached are excellent: almost 100% of the chemical energy content of the fuel is converted to heat. The exergy efficiency (energy = exergy + anergy; exergy per definition being converted into any other energy form, thus proving the ability to do work) is, however, miserable; it offers only a few percent; it is exergetically absurd to produce a boiler temperature of 1000 °C only in order to guarantee a radiator temperature of some 70 °C!

Milestone 3
The exergetically efficient stationary fuel cell

- de-centralizes energy
- exergizes energy
- activates dormant virtual power

requires professionalization of the end of the energy conversion chain

Here, exergetically efficient fuel cells come into play: as combined heat and power (CHP) devices with exergy efficiencies of 35–40% they deliver first-hand electricity which is pure exergy, and the 80–100 °C heat provided in parallel is still sufficient to cover most heating requirements. The power is premium uninterrupted power (UPS) used on the spot, or fed into the grid. The fuel cell is quiet, and without moving parts it is without vibrations; if fuelled with hydrogen it is environmentally and climatically clean, its "waste" product is pure water, and it has a good chance with a production lot of a few hundred thousand per year to sail into the waters of competitiveness. If hydrocarbons (natural gas) rather than hydrogen is utilized, a stationary reformer needs to be installed; in this case, climatic cleanness cannot be achieved.

A thought experiment says that 15 million fuel cells at 5 kW each as replacements for the traditional boilers in the nation's cellars sum up to a virtual power plant of 75,000 MW, which comes close to the 100,000 MW now on-line.

Thought experiments seldom become a reality, but there is usually a true core in them. Here, we find two cores: (1) The fuel cells exergize the energy system; they make more technical work out of energy. We enjoy an efficiency gain which is as good as primary energy raw material demand reduction—an eminently important result for a country with three quarters imported energy in its energy portfolio, as mentioned above. (2) The longevity of the operating German power plant park and the political decision to phase out the 19 nuclear stations in some 20 years' time require new installations of some 40,000 MW within the next 20–25 years. It seems exergetically only wise to install a good portion of this capacity through fuel cells operated in CHP mode with total efficiencies of 80–90%. Certainly, in a first period the fuel cell will be fuelled with natural gas from the nationwide operational gas grid, in an interim time period with a mixture of natural gas and hydrogen, and finally, after shifting of the points, with pure hydrogen. Because of their distributed location, millions of natural gas-fuelled fuel cells will never become climatically clean, and millionfold capturing of greenhouse gases is not feasible.

Milestone 4: hydrogen- and fuel cell-induced industry structure change

There are already visible changes in the industrial structure of an industrialized nation:

- Like electricity, one secondary energy carrier, hydrogen, the other one, will be generated from all thinkable primary energy sources, from coal, oil and gas, to nuclear or biomass and other renewable sources, per se environmentally and climatically clean in all cases where renewable energies are the source, cleaned through CO_2 capture and sequestration in the case of fossil fuels.
- Again like electricity, hydrogen generated centrally and utilized de-centrally in distributed installations requires grid delivery; many hundred kilometres of operational gaseous or liquefied hydrogen pipeline systems are harbingers.

- De-centrally operated virtual fuel cell power grows into a competitive position with traditionally centrally organized power; from an energy economy standpoint we can expect a fascinating development: which one will be the most inexpensive, or the cleanest competitor?
- The clearly foreseeable replacement of stationary or mobile combustion engines through fuel cells shrinks the markets of the forging industry (crankshafts, camshafts, connecting rods, etc.) and the casting industry (engine housings, gear housings, etc.), and expands the industries of membrane technologies (fuel cell stacks), reformer technologies and the like.

Milestone 4
Hydrogen- and fuel cell-induced industrial structure change

- initiates competition between de-central virtual power plants and central power plants now in use
- replaces thermal energy conversion with heat engines by electrochemical conversion with fuel cells
- replaces combustion engines and batteries with fuel cells

requires early preparation

- We distinguish three industrial revolutions over the last two and a half centuries: the first revolution was introduced in the later 18th century by James Watt's steam engine; the second one, a good hundred years later at the turn of the 19th to the 20th century, was induced by electrification; now, at the beginning of the 21st century, it is a whole bunch of developments of "punctuated equilibria" (Stephen Jay Gold) whose names are de-centralization, decarbonization and hydrogenation, de-materialization, micro-miniaturization, electronification, etc. More or less all of them have something in common: they are lightweight, and the products are lightweight. High-temperature ceramics weigh less than steel, biotechnology weighs less than bulk chemicals, fast electrons are of much lighter weight than bulky letters or parcels, solar energy weighs nothing, hydrogen is the lightest element in the periodic table of elements, etc. In whatever industrial branch we take a look, low weight down to weightlessness prevails. In extenso, this is particularly obvious where the downslope development of "old industries" has come to the point where the transfer to service industries has been completed.
- When electricity became common one hundred years ago, the General Electric (GE) company was founded in the USA, and in Germany the Allgemeine Elecctricitätsgesellschaft (AEG). Now, a good century later, when the other secondary energy, hydrogen, is on the verge of being added to the energy schemes, the General Hydrogen company (GH) is already established in the USA. Who will be founding the Allgemeine Wasserstoffgesellschaft (AWG), and when, in Germany?
- Hydrogen and fuel cells will be continuously shifting the centre-of-gravity in a nation's energy conversion chain toward its end where millions of lay persons try to handle energy efficiently, cleanly, and securely safe—almost generally in vain. What hydrogen and fuel cells ask for is professionalization also at the end of the conversion chain, just like the successful professional handling at the front end of the chain. The reasoning is clear: people live and work downstream. Here, at the end, is the key, each kilowatt hour of energy services at the chain's end not asked for on the market avoids 3 kW h of primary energy raw material being introduced into the national energy economy at the front end of the chain (Germany's national energy efficiency is approx. 30%). In the world at large, with its overall anxious-making low energy efficiency of not much more than 10%, the situation is even worse: with each kilowatt hour of energy services not asked for on the market, up to 10 kW h of primary energy raw materials can be avoided being introduced into the world's economy! In exergy terms the situation is even worse: Germany's national exergy efficiency is a little more than 15%, and the world's only a few percent!

Milestone 5: political framework conditions

- Hydrogen is not simply another energy carrier in an otherwise unaltered energy scheme. On the contrary, the introduction of the hydrogen energy economy into the overall energy scheme alters it fundamentally, like electrification did a good one hundred years earlier. The essential arguments are as follows: hydrogen stores and transports renewable energies and, thus, is key to facilitating their participation in the customary global energy trade system; hydrogen de-carbonizes fossil fuels and makes them Kyoto conformable; hydrogen and fuel cells de-centralize the energy scheme, they activate so far dormant virtual power of an enormous capacity at the end of the value adding chain. Traditionally, the operational energy system is more or less governed by the primary energy raw materials; the hydrogen energy system, on the contrary, is clearly technology governed: technology is physically not an energy, but it is as good as energy, and it is available in industrialized countries: energy politics become technology politics! All this requires the hydrogen energy economy to be put onto the agenda of the political class. Two or more human generations will be engaged in the installation of the hydrogen energy economy. Consequently, what hydrogen asks for is continuity, not only nationally but internationally, because, truly, energy is something universal!

Milestone 5

Political framework conditions for investment planning security

- add energy technology politics to the usual energy supply politics
- enhance exergy politics
- support the Kyoto process
- perpetuate wise external economic affairs policies with the objective of opening up new supply regions and CO_2 sequestration by suppliers
- further continuity over decades up to half centuries
- offer hydrogen energy temporarily free-of-taxes

require the introduction of hydrogen energy into the political agenda and makes it an indispensable international societal goal

- The Kyoto process is part of the international politics for sustainability. Accordingly, fossil fuels releasing greenhouse gases need to be reduced, hydrocarbons de-carbonized and hydrogenated. Energy sustainability without hydrogen is irrational.
- Historically, it so happens that the energy raw material importing nations not only import energy, but also their associated pollutants! It is the obligation of the energy import nations to remove the pollutants and store them away securely and safely without risking release into the environment and the atmosphere.
- The hydrogen energy economy offers the chance to reconsider whether it might not be wiser to capture and sequester potential greenhouse constituents or environmental pollutants already at the well head in the energy exporting countries and trade pure hydrogen. After many decades of global energy trade experience the other way round, of course, this is an extraordinary challenge for world trade politics!
- Once again, the HYway into the hydrogen energy economy confirms that energy politics shifts to energy-technology politics. A few illustrations are given below: highly efficient, hydrogen-supported fuel cells deliver efficiency gains which compare well with an equivalent primary energy raw materials supply reduction; clean hydrogen made from coal requires the technologies of capture, sequestration, and disposal of carbon dioxide; renewable hydrogen made electrolytically from renewable electricity asks for economically viable renewable energy converters which so far are still deeply in an early development or demonstration stage; there are many more examples. In all these cases, energy technology knowledge is as good as energy; engineering skills become much more important than anything else. The hydrogen energy economy will eventually become a significant result of the knowledge-based industrialization which has just begun. The 21st century is considered to be the century of knowledge-based industries, and the hydrogen energy industry is a part of it.
- As is the case with renewable energies, biomass, or small size CHP, the introduction of hydrogen and its technologies needs to rely on a temporary tax reduction in order to compensate for the early market disadvantages, such as small and inefficient market capacities or production lots. Let us be aware that hydrogen is in a not too favourable position as long as the tax load of conventional fuels is as high as it is: for example, in Germany three-quarters of the fuel price at the filling station's dispenser is taxes! One thing is clear: taxpayers' money is welcome, in the early stages of a market introduction sometimes indispensable, however, not decisive. What is much more important is investment security for entrepreneurs and the internationally clearly visible societal and political will to take up the HYway into the hydrogen energy economy whose milestones we have tried to describe above: energy needs planning security over decades and, thus, continuity over more than one period of legislation. In general, delay is the enemy of success!

Annex: European Hydrogen and Fuel Cell Technology Platform

The European Commission, Community Research "Sustainable Development, Global Change and Ecosystems", through its President Prodi, its Vice President and Commissioner for Energy, de Palacio, and its Commissioner for Research, Busquin, has introduced a "European Hydrogen and Fuel Cell Technology Partnership", referred to as the "Technology Platform" with the objective of contributing to an integrated strategy for a sustainable hydrogen economy in Europe.

The objectives are

- to spread awareness of hydrogen and fuel cells, their concept and structures,
- to align ongoing and new activities, and
- to draw conclusions and formulate recommendations.

The Platform summarizes three fields of interest:

- hydrogen infrastructure,
- transport applications,
- stationary applications.

Infrastructure comprises hydrogen production, storage, transportation and dissemination.

An Advisory Council is to give guidance on initiating, structuring, implementing and monitoring the Platform's process. The Advisory Council consists of 36 high-level members from European academia and industry.

Details can be found at http://europa.eu.int/comm/research/energy/nn/nn_rt_htp1_en.html.