Hydrogen Energy–The Terrestrial „Man-to-the Moon“-Project of the 21st Century

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ABSTRACT: The paper delivers an argumentation in favour of the installation and operation of the hydrogen energy economy.—Hydrogen joins electricity in the secondary energy realm, both environmentally and climatically clean, both switching the center-of-importance within the energy conversion chain towards its end, both facilitating so far dormant distributed energy conversion of high exergy efficiency. Hydrogen and its technologies are considered powerful economic growth engines of national economies and a countermeasure of the ongoing oligopolization of primary fuel sources. Financially and with respect to time the building-up of the hydrogen energy economy compares well to a "Man-to-the-Moon" project, this time including all nations of the world.

Keywords: Hydrogen energy, exergy, fuel cell, decarbonization, hydrogenation, dematerialization, distributed energy conversion.

1. INTRODUCTION

On November 13, 2006 the Centennial Memorandum on Hydrogen Energy (Annex) of the International Association for Hydrogen Energy (IAHE) and members of the world hydrogen energy engineering community was submitted to the G8 Heads-of-State and the UN Secretary General. The G8 President for 2007 and President of the EU Ministerial Council (first half of 2007), German Chancellor Angela Merkel, was asked to give the matter top priority in the agenda of her presidencies as well as at the G8 meeting June 2007 in Heiligendamm, Germany.

In one word, the Memorandum reads “Abundant clean energy for humankind as a means for mitigating anthropogenic climate change, avoiding environmental challenges, and decelerating the world’s ongoing conventional primary energy raw material’s oligopolization”.

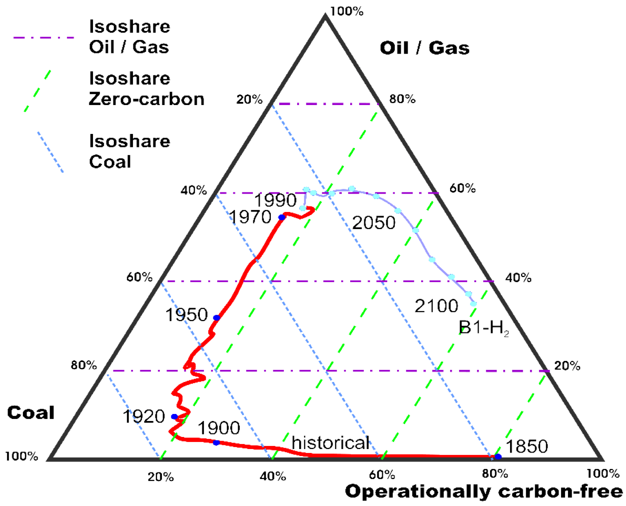

Figure 1: Shares of Primary Energies (source: L. Barreto et.al., The hydrogen economy in the 21st century: a sustainable development scenario, Int'l J. Hydrogen Energy 28)

Fig. 1 shows the expected non-avoidability of hydrogen energy in the energy scheme of the world: the red line is history.

At the turn of the 18th and 19th centuries renewable energies of the first solar civilisation were replaced by coal which then dominated the next 100 years and which around the turn of the 19th and 20th centuries was step-by-step replaced by oil and gas, and much later by nuclear fission. Now, at the turn of the 20th and 21st centuries, again renewable energies, now of the second solar civilisation, begin to replace oil and gas and also coal. Since, however, all sorts of renewable energies, because of their lacking storability and transportability in macroeconomic terms, need a chemical energy carrier in order to contribute limitlessly to the global energy trade, hydrogen energy is a necessity (blue dotted line).

For the broad and in-depth initiation and powerful furtherance of hydrogen energy technologies' introduction to market a project plan is needed: a project plan which names the technological challenges along all links of the hydrogen energy conversion chain from production via storage and transport to dissemination and finally utilization; a plan which suggests preferred nations or regions in the world where one or the other hydrogen technology has first rank chances for development, demonstration and pilot production; a plan which gives the financial arena an indication of the financial constraints of a solid, straightforward hydrogen technology market evolvement; and, finally, a plan which gives the necessary time frame: all in all, a plan for politicians and decision makers in industry to take pertinent action.

A table (Table I) is added with the whole range of hydrogen energy technologies divided into three categories: (1) production of hydrogen, (2) its storage and transport, and (3) its dissemination and utilization in the end use sector. An attempt is made to assemble state-of-the-art technologies, and those technologies which need more, in cases much more research, development, demonstration (R, D&D), available within some 10 years' time from the present (midterm), or within 10 to 20 years or more (long term).The following results can be drawn from the table.

Table I: Hydrogen Energy Technologies

Hydrogen Production

State-of-the Art, *with incremental further development*	***Midterm,*** *c. 10 yrs from present*	***Longer term,*** *in 10 to 20 yrs*
• reformation of natural gas • gasification of coal • partial oxidation of heavy crude • electrolytic hydrogen from hydropower • hydrogen form nuclear electricity	• electrolytic renewable hydrogen from wind, PV, solarthermal power, and other renewable sources • hydrogen from biomass • hydrogen from high temperature nuclear reactors	• hydrogen from fossil fuels with carbon capture and storage (CCS) • hydrogen from coal with the help of high temperature nuclear heat CSS = Carbon Capture and Storage

Storage and Transport

State-of-the Art, *with incremental further development*	***Midterm,*** *c. 10 yrs from present*	***Longer term,*** *in 10 to 20 yrs*
• hydrogen liquefaction plants • hydrogen cartridges for portable electronics • metal hydride containers • continuous or badgewise GH_2 or LH_2 transport • hydrogen in refineries or the space business	• pickaback hydrogen in natural gas pipelines • 700 bar filament wound mobile hydrogen tanks • vacuum insulated liquefied hydrogen tanks with low boil-off	• "supergrid" – the LH_2 cooled superconducting high capacity cable and simultaneous hydrogen transport • LH_2 tankship transport • LH_2 loading and de-loading harbour equipment

Dissemination and Utilization

State-of-the Art, *with incremental further development*	***Midterm,*** *c. 10 yrs from present*	***Longer term,*** *in 10 to 20 yrs*
• hydrogen in space transportation • space borne fuel cells • fuel cells in submersibles • hydrogen fuelled low temperature fuel cells in portable, stationary, or mobile applications • hydrogen in gas turbines • the hydrogen fuelled mobile auxiliary power unit (APU)	• hydrogen/oxygen spinning reserve • hydrogen and the high efficiency internal combustion engine • hydrogen filling stations • hydrogen as the jet fuel in air transportation • hydrogen in the air borne APU • hydrogen as the laminarization agent in aerodynamics	• hydrogen jet fuel in air transportation • hydrogen as the laminarization agent in aerodynamics

2. STATE-OF-THE-ART HYDROGEN ENERGY TECHNOLOGIES

The operational hydrogen economy which deals with hydrogen as a commodity, not as an energy carrier, in parts operational for more than a century, provides most of the state-of-the-art technologies which offer an excellent ground base for switchover to the hydrogen energy economy. Production, storage and transport, as well as dissemination of hydrogen are day-to-day practice for the technical gases industry, the commercial gas traders, the refineries, and the natural gas or coal companies. Fig. 2 shows a "christmas tree" with the whole variety of operational hydrogen industry applications from methanol or ammonia production via fat hardening, metal treatment, glass manufacturing to diesel de-sulferization and many others. - Of course, there is always room for improvements and further development of detail technologies. That applies in particular to the hydrogen utilization areas where fuel cell R, D&D is by far not yet completed, both in vehicle transportation or in residential and commercial building central heating/electricity systems, although around one thousand demonstration units in both mobile and stationary applications are already in place worldwide (2006).

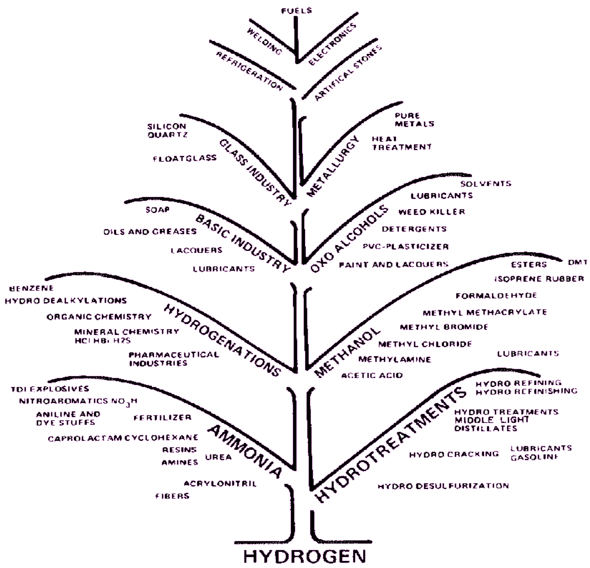

Figure 2: Hydrogen is no stranger

3. MIDTERM HYDROGEN ENERGY TECHNOLOGIES

In the midterm two items deserve particular attention: Electrolytic production of hydrogen from all sorts of renewable electricity converters (wind, PV, solar thermal, geothermal, ocean, etc), and hydrogen from nuclear stations, generated with the help of both nuclear electricity or high temperature nuclear heat.

- For the time being, marketed renewable energy technology booms worldwide, and is expected to continue into the next decade(s). However, clearly in the foreground of interest is the generation of electricity and/or heat and its utilization as such. Only in cases of temporarily limited electric overhead line capacities or difficulties with electricity transport, say, from off-shore wind parks (and in future possibly ocean energy parks), hydrogen as a storage and transport means does come into play. But so far nowhere is a commercial renewable hydrogen plant in operation, not even a demonstration plant, except some R&D units in the few hundred kilowatt range; the German-Saudi HYSOLAR project with a unit capacity of 350 kilowatt electric in the solar village in Riad, Saudi Arabia is one example.
- In many countries around the world, nuclear electricity suffers from lacking societal acceptance; as a consequence, no new plant was built in that countries after the 1980s. And commercial high temperature nuclear reactors are nowhere in the world still in operation; some were dismantled after completion of their demonstration phase.—Consequently, it is a matter of reality that for the time being and the near future of decades to come hydrogen from nuclear electricity or, more so, high temperature nuclear heat will only be produced in those countries of the world which go nuclear—if at all.

4. LONGER-TERM HYDROGEN ENERGY TECHNOLOGIES

On a longer term the dominant R, D&D efforts focus on carbon capture and storage (CCS). Climate change considerations allow fossil fuels' future utilization only when care is taken that carbon and its compounds

(CO_2, CH_4, …) are prevented from being released into the atmosphere. Many methods of realization are under development; none, however, has succeeded so far at macroeconomic commercial scales. That applies to electricity generation, hydrogen production, or the simultaneous production of both.

In some interesting high efficiency processes hydrogen is not only a product delivered from fossil fuels (like electricity, its mate in the secondary energy realm), but is mandatory from a process efficiency standpoint.

5. ANTHROPOGENIC CLIMATE CHANGE

Climatically, solar hydrogen, i.e. hydrogen delivered from all sorts of renewable energies, because it is clean over the full length of its conversion chain, is clearly the ultimate solution; it is, however, not at all the precondition for entry into the hydrogen energy economy. Many decades are still necessary to raise the energy efficiencies, decrease the material intensities and reduce the surface demand of renewable energy technologies and to bring down their cost prior to the point in time when solar hydrogen will be well prepared to enter the market. This will be particularly true for the transport sector, where people count each dime! —In the meantime, everything that has been learned during the decades' long operation of the hydrogen economy will be beneficially conveyed to the hydrogen energy economy. A "dual carriage way" is visible, where two lines run in parallel in the same direction, one heading for market readiness of renewable energy technologies, the other introducing hydrogen technologies link by link along their complete energy conversion chain, the two developed in tandem.

The enormous annual damage cost of the traditional energy conversion scheme gives a convincing and powerful incentive for a radical switch to the environmentally and climatically clean hydrogen energy scheme: the almost unimaginable sum of nearly 5 x 10^{12} US$(2005)/GJ has been calculated![1] Reducing these costs step by step frees financial resources for the introduction of the hydrogen energy economy.

6. TIME

Novel energy technologies need time, of course, this applies to hydrogen energy technologies, too! In the energy realm, it is not at all a special case that hydrogen, although mentioned in literature for the first time already in the later 18th century by Henry Cavendish and Antoine Lavoisier, or fuel cells, brought to the world's attention already in the early 19th century by William Grove and Christian Friedrich Schönbein, that we had to wait until the mid 20th century to be brought to market, i.e., to the space business where it fuelled space borne H_2/O_2 fuel cells or powered space launcher engines.

Consequently, more or less all the hydrogen energy technologies of the forth

Automobiles	Buses	Underwater vehicles, boats
Locomotives	Scooters	Distrib. Power generation
Golf Carts	Bicycles	Cogeneration
Airplanes	Space	Portable, back-up power

Figure 3: Demonstrated Fuel Cell Applications

[1] T. Nejat Veziroglu, Hydrogen Energy System: A Permanent Solution to Global Problems, http://isjaee.hydrogen.ru/?pid=273

coming hydrogen energy economy will need time, many decades, almost half centuries rather than years, to become inevitable—a not too comfortable insight for the impatient, though a reality! The consequence: starting early and see it through is imperative! Fig. 3[2] shows a compilation of fuel cell technologies, only two of which are currently marketed (the space shuttle and the submersible); all the others are in a pre-market stage.

7. COST

The annual energy market of the world stands at US$ 2000 billion, with a growth rate of some 3% p.a. (in 2000 figures). If we imagine a R&D percentage of 3% p.a., an amount of some US$ 60 billion will be available for further development of the energy economy; for 6% we end up at US$ 120 billion. Depending on the decisions taken in favour of hydrogen energy, the amount of hydrogen R&D money required can be derived from these figures.

The cost of hydrogen in US$/kg$H_2$ (1 kg H_2 is the energy equivalent of approx. 1 gallon of gasoline = 3.785 litres) from centralized or distributed sources, without tax and compared to the cost of gasoline in the US (2006), can be seen in Fig. 4[3] . Obviously, centralized hydrogen production plants (except biomass), even including CCS[4], have the lowest cost, even undercutting gasoline both in terms of current and future costs! Only potential future costs of distributed on-site productions come near the cost of present gasoline costs. Fig. 5[5] brings a European (German) example of the cost of hydrogen produced from natural gas or renewable sources on a 50:50% basis relative to the emissions of CO_2 equivalent in g/kilowatt-hour.

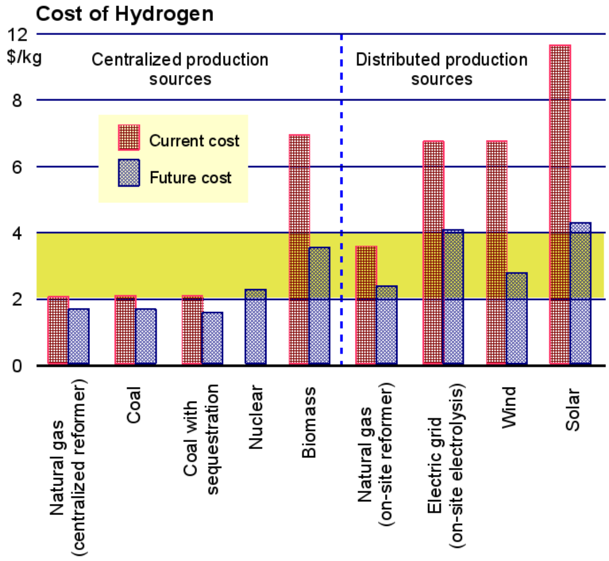

Figure 4: Hydrogen production cost

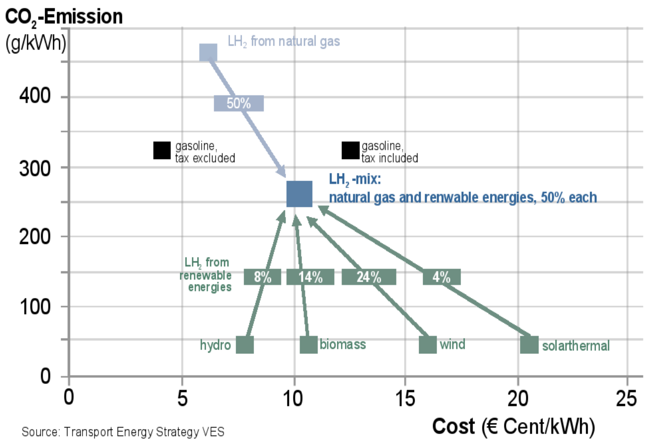

Figure 5: LH_2 costs and CO_2 emissions – dissimilar energy pathways compared

8. EARLY STARTERS

It so happens that there are countries in the world which within their industrial development scheme have accumulated certain preferred hydrogen technology development, manufacture and operation experience. Japan or the US, to take these examples, seem well prepared to be active in the large and versatile field of hydrogen supported portable electronics; the space faring nations have decades long experience in reforming, storing, transporting, handling, and combusting large amounts of hydrogen, particularly liquefied hydrogen; today, there is no auto making company in the world not

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[2] Courtesy Frano Barbir
[3] J. Ogden, High Hope for Hydrogen, Scientific American, September 2006, 70-77
[4] carbon capture and storage
[5] The Transport Energy Strategy (Verkehrswirtschaftliche Energiestrategie VES)

engaged in hydrogen fuelled mobile fuel cell or optimised ICE R&D; for more than a century heavy industry centres have well known how to produce hydrogen from fossil fuels (hydrogen chemistry, the natural gas industry, oil refineries, the coal industry); traditional industrial branches accustomed to using hydrogen as a commodity are well experienced to play their part also in sectors of the hydrogen energy economy. As a result we can say that the hydrogen energy economy doesn't need to start from scratch; there are lots of lots of active "hydrogen islands" in the world economy which have to be connected. What we face is not too dissimilar to what happened at the turn of the 19^{th} and 20^{th} centuries when the electricity market began to evolve; after more than a complete century it has not yet come to saturation. On the contrary, electricity and hydrogen, are the two major constituencies of a vital secondary energy economy of ever more importance.

8. THE TERRESTRIAL "MAN-TO-THE-MOON" PROJECT

The "Man-to-the-Moon" Project gives us an indication of what we are facing: Other than the historical Man-to-the-Moon project which was the endeavour of one nation, the USA, the project of the 21^{st} century has to be a worldwide endeavour, no nation excluded, either with its hydrogen production skills, or its hydrogen storage and transport experiences, or its will for an early engagement in hydrogen dissemination and utilization. To name only a few examples: all nations active in the space business are predestined to take over market sectors of handling, storing, transporting, or combusting hydrogen; nations involved in portable electronics will be (and already are) going over to hydrogen supplied fuel cells replacing low longevity battery devices; or nations with a long tradition in coal production now face the urgent efforts of hydrogen supported de-carbonization and carbon capture and storage for the benefit of the environment and climate; and finally, those regions in the world blessed with high capacity renewable energy potentials (hydro, wind, solar, others) sooner or later face the necessity to add the chemical hydrogen energy carrier to their renewable energy facilities in order to facilitate their contribution to the global energy trade; since renewable energy lacks storability and transportability in macroeconomic terms, so far renewable energy utilization is restricted to local, at most regional utilization.

9. MARKET CONDITIONS

Market economics ask for competitive costs of novel goods and services entering the market place compared with traditional goods and services of the same market sector. Costs are always investive and consumptive costs along the complete life cycle, including infrastructure costs. For example: it gives the wrong signal to only compare hydrogen costs with gasoline or diesel costs! For a number of reasons: because the gasoline or diesel market has long been fully developed, and the hydrogen market is just starting. Or, although the production of hydrogen at the front end of its energy conversion chain may be more costly than the production of hydrocarbon fuels, the much higher efficiencies in cases of hydrogen energy end use, for instance in optimised ICEs or fuel cells in the transport sector, sometimes more than outweigh the front end cost. And a final argument, gasoline or diesel fuels have to face climate change costs, since even the best ICEs emit greenhouse gases, and hydrogen fuelled converters don't!

The term "well-to-wheel" cost clearly says what is meant: All costs have to be taken into consideration, from the mine mouth to the wheels of the vehicle, from production of hydrogen via transport and storage to dissemination and dispensing, and finally to usage along the complete drive train of the vehicle.

Similarly, the terms "well-to-radiator" or "well-to-electricity socket" mark the hydrogen energy pathways, all the way from production to home heating or electricity services.

10. EXERGY THERMODYNAMICS

One particular thermodynamic argument is worth mentioning: hydrogen energy exergizes the energy system! What does that mean? Whenever energy is handled (produced, stored, transported, used), it is split off into exergy and anergy: energy = exergy + anergy. Exergy is the ability to deliver technical work; it can be transformed into any other form of energy, anergy cannot. For example: the central heating system of a building is energetically superb, almost 100% of the energy content of the light oil or gas is converted into heat; exergetically, however, it is miserable, it is thermodynamically simply absurd to produce a flame temperature in a boiler of 1,000°C in order to provide only 70°C radiator temperature for room heating services.—If the boiler is replaced by a hydrogen fuelled low temperature fuel cell, it delivers electricity (= exergy) firsthand with an efficiency of 30 to 40% and the remaining heat from the fuel cell still suffices to heat the home over almost the entire year.—Or another example: the automobile with a hydrocarbon fuelled ICE under the hood is exergetically only 20% efficient, at most 30%, the rest is waste heat. The vehicle is, so to speak, a mobile stove, also delivering a small amount of tractional motion (= exergy). Again, the hydrocarbon fuelled ICE replaced by a hydrogen energy optimised ICE or a low temperature fuel cell raises the exergy efficiency up to 50%.

11. CONCLUSION

1 The build-up of the hydrogen energy economy is the 21st century's energy venture, not too dissimilar to the build-up of the electricity economy in the 20th century. Hydrogen energy is energy groundwork and farsightedness, not tackling day-to-day inconveniencies.

2 Hydrogen energy is secondary energy. It joins electricity in the secondary energy market which, thus, becomes much more important than the primary energy (raw materials') market: More hydrogen and electricity from less primary sources is the credo.

3 Hydrogen energy is going to become the powerful countermeasure to growing oligopolization of primary supplies.

4 Hydrogen energy influences positively the energy parameters worldwide: centralized <u>and</u> distributed sources; active <u>and</u> (so far) dormant sources of the world energy scheme; no world region excluded.

5 Hydrogen exergizes. It adds to the principally available three energies—coal, oil and gas, and operationally carbon-free renewables and nuclear energy—a fourth leg to stand on: the skill of scientists and engineers to gain more technical work (= exergy) from less primary sources. Energy policy increasingly becomes energy technology politics!

6 Hydrogen is the key to de-carbonizing fossil fuels; it cleans-up the environment and is not a contributor to anthropogenic climate change. Hydrogen is the core of the triangulation from high carbon to low carbon to no carbon. It helps reduce the trillions of cost of damages provoked by the established traditional energy scheme.

7 Hydrogen decelerates oligopolization of primary supply, it helps avoid irrational shortages and counterproductive price dictates.

8 Hydrogen is considered one of a number of powerful economic growth engines of industrialized countries.

9 The hydrogen energy economy build-up is a marathon, not a sprint (Joan Ogden). It aims high, though its goal is within reach.

10 All in all: hydrogen energy is the "Man-to-the-Moon" energy project of the 21st century. Let us start and see it through. Actions speak louder than words. **It's HYtime**!

ANNEX

The Centennial Memorandum on Hydrogen Energy—the mitigation means of the forthcoming energy/climate change catastrophe

CENTENNIAL MEMORANDUM

13 November 2006

To: The Heads of G8 Countries:

Canada: Prime Minister Stephen Harper
France: President Jacques Chirac
Germany: Chancellor Angela Merkel
Italy: Prime Minister Romano Prodi
Japan: Prime Minister Shinzo Abe
Russian Federation: President Vladimir Putin
U.K.: Prime Minister Tony Blair
U.S.A.: President George W. Bush

Copy:
U.N. Secretary General: Kofi A. Annan
UNIDO Director-General: Kandeh K. Yumkella
UNDP Administrator: Kemal Dervis
UNEP Executive Director: Achim Steiner

Subject: Upcoming Energy/Climate Catastrophe and Permanent Solution of Hydrogen Economy.

We, the undersigned, herewith ask the heads-of-state of the Heads of G8 Countries to put Hydrogen Energy on top of the agenda of their respective states, individually or in common, and commit to Hydrogen Energy Technologies as a permanent solution to the upcoming energy/climate catastrophe. The following are the two major problems facing the humankind at the dawn of the twenty-first century:

- The anthropogenic climate change is real. The United Nations' Intergovernmental Panel on Climate Change expects a considerable temperature rise by the century's end. Catastrophic consequences for humans, fauna and flora, and the cultural heritage of humankind are expected, and
- The oligopolization of traditional fossil or nuclear primary fuel is exacerbated by being possessed by a few—not a comfortable situation for the majority of energy using nations.

"Energy policy is technology politics" is exemplified by huge energy efficiency gains, by the cleaning-up of fossil fuels, by safe and non-proliferating secured nuclear energy, and by renewable energies. On top of the progress in all these areas is "Hydrogen Energy Technologies" for the following reasons:

- Hydrogen Energy is an environmentally and climatically clean transport fuel,
    - Hydrogen Energy is the storage and transportation agent of so far dormant renewable sources which, thus, will become a powerful contributor to the global energy trade, and
- Hydrogen Energy from renewable energies is the ultimate solution; it is, however, not the precondition for entering the Hydrogen Energy Economy; environmentally compatible hydrogen could also be produced using nuclear energy, and even fossil fuels with carbon capture and storage.

We, as members of the International Association for Hydrogen Energy and members of the Hydrogen Energy Community are willing without hesitation to devote our further professional life to the furtherance of Hydrogen Energy and its technologies through advising policy makers, serving as Advisory Board Members, and collaborating with industry in implementing the necessary Hydrogen Energy infrastructure, because we share the conviction that

- Hydrogen Energy, once generated, is environmentally and climatically clean over the entire length of the energy conversion chain, "from cradle-to-grave",
- Hydrogen fuel cells activate dormant distributed virtual power,
- Hydrogen Energy eliminates land, sea, air and space transportation pollution,
- Hydrogen Energy facilitates the contribution of huge renewable sources to the global energy trade, and
- In one word: Hydrogen Energy Technologies provide abundant clean energy for humankind.

Respectfully Yours

Signed by: