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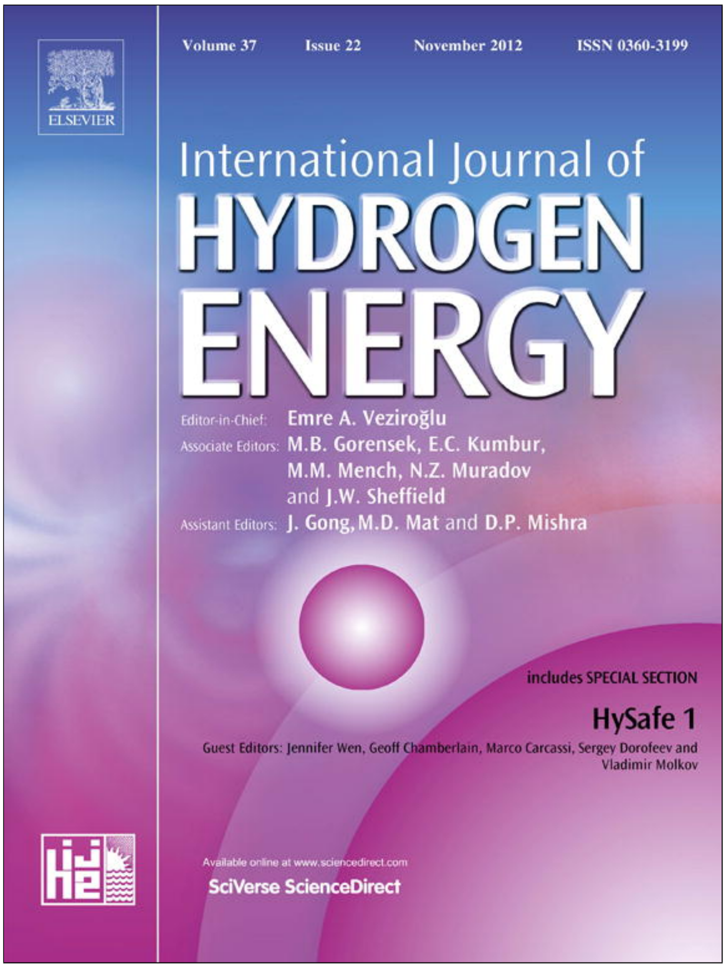

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The *Energiewende*: Not an energy turnaround, rather a customary energy system adaption☆

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ABSTRACT

Secondary energy hydrogen is on the verge of becoming – after or in parallel to coal, oil, natural gas, nuclear fission, electricity, energy efficiency gains, and all sorts of renewable energies — the eighth energy in the octagonal energy mix mankind utilizes, before — perhaps — nuclear fusion may become the ninth. Never in the 250 years of modern anthropogenic energy history was the mix in a steady state, never did a new energy addition fully replace its predecessors; the ever increasing demand needed them all; the relative importance of an individual energy changed, energy multiplicity and heterogeneity grew — and still grow.

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What we face is an intensified multidisciplinary debate: More arguments than before, with more areas of concern, are to be exchanged in order to result in an environmentally benign and anthropogenic climate-change-risk-abating hydrogen-supported supply in a secured and societally accepted future energy mix. Three parameters are in the foreground: (1) The demographic factor of a growing world population is the overruling factor; (2) the growing influence of efficient energy technologies reduces the influence of traditional primary energy raw materials and turns energy policy into technology politics. Efficient technologies become as good as energy, they are quasi-energies. Even energy-poor but technology-rich industrial nations get the chance to become – almost – energy self-sufficient; hydrogen-technology-supported energy supply services' security is not an illusion, particularly in times of increasing world oligopolization of primary energy sources; and (3) the ecological factor, almost inexistent in the past energy discussion, has become, together with the economic and social criteria, and the criterion of reversibility (as demonstrated by renewable and non-renewable hydrogen energies), an equally entitled criterion of energy sustainability.

The *Energiewende*[1] is not an energy turnaround: Rather, it is the customarily renewed octagonal energy mix which came down to us over time, parametrically adjusted now and then to policy decisions on supply security, environmental and climatic cleanness, and — most important from an energy science standpoint — decisions on ranking efficient energy technologies first and foremost. Raising the energy and, in particular, the exergy efficiencies to the utmost, makes more technical work available from energy! The traditional energy system produces much too much heat, of which, with a national energy conversion efficiency of an all too modest 30% (Germany) (the world's is not much more than a lamentable 10%!); more than two-thirds of the introduced energy is converted to losses of no further anthropogenic use, worth only emitting into space. Added to the prevailing energy thermodynamics, the more efficient electrochemistry of hydrogen-supported technologies such as electrolysers, ionic

☆ Germany's national effort to replace some 22% nuclear electricity effective 2022.

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[1] another "Germanism" that has entered the English language, such as Kindergarten, Zeitgeist, Realpolitik, Wunderkind, …

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compressors, liquefiers, and fuel cells deliver much more technical work: hydrogen exergizes energy. The exergy share grows, the anergy share shrinks: Energy = Exergy + Anergy, where exergy can be converted to any other form of energy, anergy cannot!

According to the decision taken by the German Bundestag, nuclear energy will no longer be produced in Germany as of 2022, i.e., at that time some 22% of the country's electricity production capacity will no more be available. The octagonal energy mix shrinks to a heptagonal one, with further-developed fossil energy technologies with remarkably high efficiency, renewable energies of all sorts, and electricity, and with forthcoming hydrogen energy as the latest component — so far. The following arguments present hydrogen characteristics and consequences.

1. Hydrogen arguments

1. Hydrogen (H) is the smallest element in the periodic table, its ordinal number is 1. Pure hydrogen is very rare on Earth, if there is any at all; predominantly, hydrogen is found in chemical compounds such as water H_2O, methane CH_4, ammonia NH_3, hydrocarbons CnHm, … Energy is needed for hydrogen's extraction.
2. Hydrogen is not really something new. It was discovered by Henry Cavendish (1731–1810) and almost at the same time by Antoine Lavoisier (1743–1794). Hydrogen in those days was named "flammable air". Industrial hydrogen chemistry began in the early 19th century. Prior to natural gas usage, so called town gas was used to heat homes, cook meals or light streets; it contained up to 70% hydrogen.
3. Of course, hydrogen is not primary energy. Like other secondary energies such as electricity, hydrogen is secondary energy; for its production primary energy is needed (see argument 1).
4. The two secondary energies, electricity and hydrogen, have much in common: Like electricity, to date the dominant secondary energy carrier, hydrogen can be produced from almost any primary energy raw material or primary energy. Presently, hydrogen is produced almost exclusively from fossil fuels, through steam reforming of natural gas, gasification of coal or partial oxidation of hydrocarbons. Only a few percent come from electrolysis of water, at nuclear stations or at big hydropower dams in order to allow them to idle. Low temperature electrolysers are state-of-the-art; high temperature/high efficiency electrolysers are still a subject for R&D.

For the time being, the bulk of hydrogen is produced and captively handled in refineries for hydro-treating of oil fractions, de-sulfurization of diesel, production of light distillates. In addition, 600–700 billion norm cubic metres of hydrogen are traded annually worldwide. That seems much, it represents energetically, however, only about half of the end energy demand of a country like Germany. Consequently, from a world energy economy standpoint, hydrogen energy is at its very beginning!

So far, there is only one industrial branch using hydrogen energetically, the space launch industry, and, furthermore, it is dependent on it, because, although hydrogen needs three to four times more volume per unit of energy, it has, however, only one third of the weight, compared with hydrocarbons. Non-energetically, hydrogen is used in the food industry for fat hardening, in methanol synthesis, in the electronics and glass industries, …

5. On principle, there is nowhere and at no time absolute safety; that is also true for energy technology safety. Each energy carrier has its specific safety risks dependent on its physical/chemical/technological nature. Hydrogen (H_2) has a high affinity to air or oxygen (O_2); the ignition range of an ignitable hydrogen/air (oxygen) mixture is wide, the ignition energy is very small. The diffusivity of hydrogen in air, however, is very high, so that possible hydrogen leakages or hydrogen reaction products tend to diffuse quickly vertically upwards.
6. On the other hand, the energy carrier hydrogen has two inherent safety advantages relative to all other energies:
   - per se, long time follow-up casualties of unknown extent are impossible, because (radio) toxicities and radioactivity are inexistent, and
   - hydrogen is not capable of contributing to the anthropogenic greenhouse effect (under the one condition that future hydrogen airlines operate below the tropopause where their water vapour exhausts meet abundant natural water vapour).

The Hindenburg zeppelin incident of 1937 in Lakehurst, New Jersey, USA, was not causally related to hydrogen!

Complete hydrogen safety sensorics are on the market.

7. Never in the history of energy supply was only one energy form in use, never did an additional energy completely replace its predecessors; the energy demand of a growing human population needed them all:
   - Up until far into the 18th century, exclusively renewable energies of the 1st solar civilization were in use
   - The 19th century was coal's century, with complementary mineral oil towards the century's end
   - The 20th century saw the emergence of natural gas and nuclear fission
   - Many plausible arguments indicate that the 21st century is on the verge of becoming the century of energy sustainability, energy and, above all, exergy (energy = exergy + anergy, with exergy converted into any other energy form) efficiency, conservation of energy, all sorts of renewable energies (solar, wind, biomass, hydro, geothermal, …) of the 2nd solar civilization, and — in parallel to electricity — the second secondary energy carrier hydrogen.
8. The history of anthropogenic energy of the 19th and 20th centuries was clearly dominated by the primary energy raw materials coal, oil, natural gas, and uranium: The energy supply system was – and as before still is – energy raw material-oriented. The 21st century, on the other hand, is expected to be different: It will be technology-oriented, because energy efficiency and conservative energy use limit the amount of primary energy necessary;

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they help to provide more energy services with less energy raw materials. For renewable energies, operational primary energy raw materials are even inexistent, and the secondary energy carrier hydrogen is the lightest element in the periodic table: It is lightweight, it lightens efforts in handling, transport and storage, it lightens the burden on environment and climate, and sheds light on an environmentally and climatically clean energy future.

9. In principle, energy utilization means proceeding simultaneously through the energy conversion chains and the chains of energy material conversion: From primary energy raw materials to primary energy, and further to secondary energy, to end energy, to useful energy, and finally to energy services; environmentally responsible energy services supply at acceptable cost and in time is the exclusive reason for proceeding through the chains; all preceding and follow-up chain links have no meaning in themselves; they are means to an end. In parallel, the energy material chain is run through: It begins with the primary energy raw materials taken out of Earth's crust and ends – after a number of physical or chemical conversions – with the residues and their release into the biogeosphere. It is not really the energy conversion which is of environmental and climatic relevance; it is the material conversion chain with its numerous openings to environment and climate which causes conflicts.

Here is the great advantage of renewables, their operational conversion chains have no operational material conversion chains at all (except biomass); consequently, all potential operational material influences on environment and climate are inexistent! What is left is the investive material for the plant construction, its lifelong maintenance, its demolition, recycling and final disposition, which altogether are comparatively of minor influence.

10. Coal, mineral oil, and natural gas are hydrocarbons whose atomic hydrogen/carbon ratio H/C are

Coal:Oil:Natural Gas = <1:2:4

For a prospective hydrogen energy economy, it tends to become infinite. The switch from coal to oil, and further to natural gas and hydrogen goes along with the decrease of the carbon content finally to zero, and an increase of the hydrogen content to a maximum.

11. In the last 120 years energy has been decarbonised; the carbon tonnage relative to the unit of energy in the anthropogenic energy supply decreased by 35%; the decrease continues. The decarbonisation (relatively lesser carbon) process is still under way, along with hydrogenation (more hydrogen), and, since the atomic weights of carbon and hydrogen are 12 and 1, respectively, dematerialisation (less weight) processes. With the transition from coal to oil to natural gas and – in a prospective hydrogen energy economy – further to hydrogen, energy gets lighter and lighter, and cleaner and cleaner.
12. Gaseous or liquefied hydrogen transport via pipelines, in tanker ships, in railcars or tanker trucks is state-of-the-art; likewise with hydrogen storage in high pressure flasks or in containers, in metal hydride or gaseous or liquefied hydrogen storage on or under the ground; the same applies to filling or emptying the devices. A robot LH_2 filling station has been put into operation, and a continuously growing number of GH_2 filling stations are installed. For illustration, in 1922 the first gasoline filling station was opened to the public in Germany; since the 1960s, with some 15,000 stations, saturation may have been reached. One gets a feeling for the time necessary for hydrogen stations to cover a nation's need.
13. Hydrogen liquefaction follows the traditional Claude process. Magnetocaloric liquefaction offers higher efficiencies; it needs, however, still much more R&D.
14. Catalytic burners are well understood and can be purchased on the market.
15. The H_2/O_2 steam generator for spinning reserve applications in the 100 MW_e range is readily developed, and so is the H_2/air internal combustion engine for stationary applications.
16. The utilization of hydrogen and air or hydrogen and oxygen in aircraft engines or engines of space launchers is well understood. Legendary are the numerous space launchers using liquefied hydrogen LH_2 and liquefied oxygen LOX as oxidizer. In the 1980s a TUPOLEW 155 was operated successfully with one hydrogen engine at the rear. In the meantime, on-board hydrogen/fuel cell operated electrical front wheel motors are in development, enabling autonomous aircraft taxiing without the need for towing trucks.
17. The greatest challenge of today (and tomorrow) is the fuel cell, which was published for the first time by William Grove (1811–1896) and Christian Friedrich Schönbein (1799–1868). It is a chemo-electrical energy converter; the low-temperature PEM – proton exchange membrane – fuel cell is not dependent on the high-temperature material restrictions of the heat engine, which for higher thermal efficiencies needs ever higher temperatures and, thereby, better and more expensive materials. The fuel cell is a modularised energy converter with a unit capacity of watts to megawatts over a total range of 7 orders of magnitude; it operates without noise, is compact and – without moving parts – free of vibrations. It utilizes – with or without reformer – a multiplicity of chemical energy carriers such as hydrogen, natural gas, coal gas, methanol, biogas, sewage gas, even gasoline or diesel. The fuel cell is highly efficient with a total energy utilization of up to 90%, with comparatively high electricity yield. The fuel cell exergizes the energy system; it delivers more technical work from energy. Its emissions are low or even almost zero, with literally no pollutants when operated on hydrogen and oxygen, only water vapour is exhausted.

Fields of application are

- Combined heat and power cogeneration in the range of a few kilowatts up to a few megawatts,
- as the chemo-electrical energy converter on board electric busses and automobiles, either as a replacement of the

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rather inefficient engine driven electrical generator for the supply of onboard electricity, or of the prime mover itself,

- as topping cycles of gas turbine/steam turbine combined cycles with expected overall electrical efficiencies of 70%, and
- as mini power plants in portable electronic devices.

Worldwide, no automotive company, no electricity industry or utility company, no home heating systems provider, no one is not interested or not engaged in fuel cell R,D&D. It may be expected that in a decade or so the process of replacing home heating boilers or batteries in portable electronics or internal combustion engines under the hood by fuel cells will have resulted in a veritable new cleaner energy industry. The development is fascinating, the "race", however, between the "old" internal combustion engine (ICE) and the fuel cell in the auto drive train is not yet finally decided. The ICE still has potential, truly it doesn't wait for its final blow — not yet.

18. The hydrogen energy conversion chain is environmentally and climatically clean over its entire length as long as the primary energies used are clean. An exemplary chain is the solar hydrogen chain with electricity production in hydropower plants, solar power or wind power plants or biomass converters with follow-up electrolysis of water, transport and storage of hydrogen and, finally, recombination of hydrogen and oxygen or air for the simultaneous production of heat and electricity.
19. Clean hydrogen energy chains are also possible when hydrogen is produced from fossil fuels, under the condition that the carbon is captured and the unavoidably co-produced carbon dioxide sequestered and stored away without risking of entering the atmospheric greenhouse. A typical process is under experiment in Norway: Natural gas from underneath the sea floor is reformed on the platform, and the carbon dioxide is immediately re-injected underground into the emptied natural gas field. So far, 1 million cubic metres of carbon dioxide have been re-injected. Another highly interesting project is pursued by ZECA – The Zero Emission Coal Alliance: Coal, water and lime react to hydrogen and calcium carbonate; the hydrogen is efficiently converted to electricity in a high-temperature fuel cell, the calcium carbonate is, with the help of the high temperature exhaust heat of the fuel cell, recycled to lime for the entry process and to carbon dioxide, which is mineralised and deposited on ground or in emptied mines. Literally, a zero-CO_2 coal plant seems possible! Hydrogen is key.
20. The solar-hydrogen residential home is an – almost – Zero-Energy-Home (zero = no commercial energy from the market over its entire lifetime) which converts solar summer photovoltaic electricity electrolytically into hydrogen and oxygen and recombines them in fuel cells in winter time to electricity and heat. Even a "Negative"-Energy-Home seems not too far-fetched, one which takes more energy from the sun than is needed for its own supply.
21. Energy needs time! Many decades up to half centuries are the reasonable time estimate for the irreversibly significant contribution of a new energy or a new energy converter. For example, nuclear fission is more than half a century old and stands worldwide for 7% primary energy equivalent, and the first plants are already demolished with no replacements foreseen; or, the gas turbine was for the first time mentioned in literature in the middle of the 19th century; initially it was used as a power plant in fighter aircraft in the 1940s, and today, more than 150 years after its first mentioning, it contributes to convincingly efficient and reliable combined cycle installations. Is there any reason why hydrogen will be any faster?

The consequence is that **"it's HYtime!"**, it is high time to start the establishment of the hydrogen energy economy and see the process through!

22. Hydrogen technologies on the market:
    - Steam reforming of natural gas
    - Partial oxidation of hydrocarbons
    - Low temperature water electrolysis
    - Alkaline fuel cell
    - Phosphoric acid fuel cell
    - Hydrogen engines in space launchers
    - Hydrogen compressors and pumps, including ionic compressors
    - All sorts of storage, stationary and mobile, on and under the ground
    - All sorts of transportation means
    - Hydrogen catalysis
    - Hydrogen sensors

Hydrogen technologies on the verge of entering the market
- High temperature/high efficiency electrolysers
- Hydrogen internal combustion engines with external and internal mixture formation for stationary applications
- Robot filling stations
- Fuel cells as a replacement for on-board electrical generators
- Mini-fuel cells for portable electronics
- Proton exchange membrane fuel cells for busses and automobiles
- Solid oxide fuel cells for residential applications
- H_2/O_2-spinning reserve

Pre-market demonstration necessary
- No-pollution city bus fleets
- Fuel cell supported district heating systems
- Molten carbonate fuel cells for industrial application
- Hydrogen production from fossil fuels and supply options
- Transatlantic pilot transport
- Hydrogen pilot airline and appropriate on-ground hydrogen infrastructure

Research and Development
- The high temperature fuel cell as topping cycle of combined cycles
- Photochemical hydrogen production
- Material research on membranes
- Reaction kinetics on surfaces
- Low-NOX combustion chambers
- Mechano-catalytic water splitting

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2. Summing up

If all preceding detailed arguments are put aside for a moment in order to unveil the argumentation's core, one item becomes very clear: The *Energiewende needs* hydrogen, it exergizes energy, it enables the advent of the most efficient and clean chemo-electric energy converters, in particular the fuel cells, which simultaneously provides electricity and heat; electrochemistry complements the so far prevailing thermodynamics of the massive heat system in place almost since the start of the anthropogenic energy system.

Home energy systems and transport are the two areas with two thirds of the end energy demand of the country (Germany); here the hydrogen fuelled stationary and mobile fuel cell has its domain! The *Energiewende* without inclusion of hydrogen and notably renewable-hydrogen-energy-supported fuel cells, stationary and mobile, forgoes technology-driven decentralised remarkably efficient energy conversion in two areas of nation's supply, transportation and energy for homes and buildings, which make up two thirds of the nation's end energy demand (i.e. Germany)!