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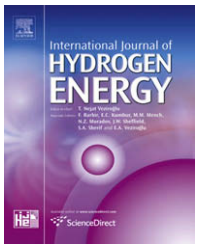

# Hydrogen energy — Abundant, efficient, clean: A debate over the energy-system-of-change☆

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A B S T R A C T

Both secondary energies, electricity and hydrogen, have much in common: they are technology driven; both are produced from any available primary energy; once produced both are environmentally and climatically clean over the entire length of their respective conversion chains, from production to utilization; they are electrochemically interchangeable via electrolyses and fuel cells; both rely on each other, e.g., when electrolyzers and liquefiers need electricity or when electricity-providing low temperature fuel cells need hydrogen; in cases of secondary energy transport over longer distances they compete with each other; in combined fossil fuel cycles both hydrogen and electricity are produced in parallel exergetically highly efficiently; hydrogen in addition to electricity helps exergizing the energy system and, thus, maximizing the available technical work.

There are dissimilarities, too: electricity transports information, hydrogen does not; hydrogen stores and transports energy, electricity does not (in macroeconomic terms). The most obvious dissimilarity is their market presence, both in capacities and in availability: Electricity is globally ubiquitous (almost), whilst hydrogen energy is still used in only selected industrial areas and in much smaller capacities.

The article describes in 15 chapters, 33 figures, 3 tables, and 2 Annexes the up-and-coming hydrogen energy economy, its environmental and climatic relevance, its exergizing influence on the energy system, its effect on decarbonizing fossil fueled power plants, the introduction of the novel non-heat-engine-related electrochemical energy converter fuel cell in portable electronics, in stationary and mobile applications. Hydrogen guarantees environmentally and climatically clean transportation on land, in air and space, and at sea. Hydrogen facilitates the electrification of vehicles with practically no range limits.



☆ Dedication: This article has two dedications: it is meant to honor both T. Nejat Veziroglu, and the thousands of hydrogen scientists, engineers, entrepreneurs, and policy makers all over the world in whose heads and hands lies the transition to the hydrogen energy economy. It is dedicated…….to T. Nejat Veziroglu who 36 years ago together with a handful of »hydrogen romantics« started the International Association for Hydrogen Energy (IAHE) with its so far 17 well esteemed World Hydrogen Energy Conferences (WHECs) with now up to 1000–2000 attendees each, taking place every two years on another continent, with the 18th WHEC in preparation for 2010 in Essen, Germany. How admirable is Nejat's reputation as scholar, his sense for continuity, his tireless attitude about never giving up, his inventive skill in establishing the World Hydrogen Energy Conventions scheduled for the odd years in between WHECs, his engagement as editor-in-chief of Elsevier's distinguished periodical »International Journal of Hydrogen Energy,« and, not least, his recent launch of the T. Nejat Veziroglu Hydrogen Energy Trust promoting hydrogen energy science and technology and furthering their societal acceptance….and to the thousands of hydrogen engineers, entrepreneurs and policy makers around the world who never lose their convictions, their vigor and their resilience, bringing to market abundant, exergetically efficient and environmentally and climatically clean hydrogen energy and its technologies. It is up to you, colleagues, to make this happen! What you face is truly a long way to Tipperary. More than one generation will be occupied: Novel energy needs time!

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## 1. Preface

Under the auspices of the International Association for Hydrogen Energy (IAHE) the 18th World Hydrogen Energy Conference (http://www.WHEC2010.com) will be held 16–21 May 2010 in Essen, Germany, organized by the EnergieAgentur.NRW. Essen was selected on purpose as the conference location: it is the capital of Germany's historic industrial heart, the Ruhr area, and was designated by UNESCO as the European Capital of Culture for 2010; hydrogen energy and its technologies are part of that culture!

The submitted text reflects the thinking and experience of scientists and engineers particularly in the hydrogen energy arena. It tries to amalgamate the immutable laws of energy science and thermodynamics, especially exergo-thermodynamics, the present status and future prospects of the world's energy, environment and climate change scene, and the specific national energy conditions of an industrialized country—Germany.

Essen as the location for the 18th WHEC2010 is a convincing selection. Here, in Germany's traditional centre of coal, steel and heavy industry (but not only there) a system change is due and already afoot. Related to the world coal market Ruhr coal has become much too expensive, and carbon capture, sequestration and securely safe storage (CCS), which climate change asks for, is still not yet fully understood, much less in day-to-day operational practice, nor is it yet environmentally and climatically responsible, securely safe, long-lasting, and commercially viable. The situation in the Ruhr region is by no means singular; it is characteristic of many old industry centres around the world!

The question arises, where to go from here. The response in the following text is threefold: (1) an argument for a changeover from the established heat-engine-related energy system of high irreversibilities to exergetically efficient, combined cycles; (2) the aggressive, minimally subsidized or possibly nonsubsidized addition of all sorts of renewable energies; and (3) the introduction of the secondary energy hydrogen as an exergizing agent, a chemical storage and transport means for globally traded renewable energies, and, by far not least, also as an abundant and clean fuel to powering fuel cells, particularly in transportation, but also in portable and stationary applications.

Many nations of the world are indigenously energy poor, and so is Germany. But many of them, again including Germany, are rich in scientific knowledge and engineering skills which, truly, compare well with »national energies«. Making more clean energy services from less primary energy raw materials is the credo! All three of the aforementioned up-and-coming additions to the world energy scene follow that line.

Energy utilization evolves over centuries: coal dominated the 19th century; oil, gas, and nuclear fission the 20th century; and the 21st century? It will see renewable energies, now of the second solar civilization; the hydrogen energy economy; and the maximum of technical work extracted from energy (=exergy), including hydrogen energy and its technologies into the mix lets energy heterogeneity grow, and, thus, the anthropogenic energy system approaches completion.

Novel energies need time. What we face, suggested by the subtitle of this piece, is another »man to the moon« project, this time including as many nations of the world as possible. It seems to be almost always too late to start.

Germany invites friends and opponents of hydrogen energy and its technologies to a challenging debate over energy. May the 18th WHEC2010 in Essen, Germany be truly international, spreading the word to the world of technologists, entrepreneurs, and policy makers: hydrogen energy is not merely a means for tackling day-to-day inconveniences; hydrogen energy is invention and innovation, is delivering the cornerstone of the clean and abundant and exergetically efficient future anthropogenic energy market. The journey is the end!

…and be aware: it's HYtime!

## 2. The summary instead of an introduction: Inevitably… it's Hytime!

> »It takes about 50 years for a new idea to break through and become vogue; no one likes an intruder, particularly when he is upsetting the commonplace« [25]

## 3. Hydrogen

… is the lightest element in the periodic table of elements; its ordinal number is 1.

… is the most abundant element in the universe.

… is available on earth only in compounds; freeing hydrogen from these compounds needs energy. That, very briefly, is the root of hydrogen production within the hydrogen energy economy.

… is considered the »forever fuel«, since, like electricity, its secondary energy »running mate,« it can be produced from any primary energy fuel: coal, oil, natural gas, nuclear, all sorts of renewable energies, and from grid electricity. Certainly, because of its environmental and climatic cleanness, »solar hydrogen« (hydrogen made from renewable energies) is the ultimate ratio. It is, however, not the precondition for building up the hydrogen energy economy. Hydrogen energy is the so far last missing addition to the continuously further developing energy mix—»until something better comes along« [52].

… and electricity are interrelated, since they compete for the same primary energies, since they may be produced simultaneously with elevated exergetic efficiencies in combined cycles, since they are electrochemically interchangeable via electrolysis and fuel cell, and since hydrogen electrolysis and liquefaction rely on electricity, and electricity depends on hydrogen in low temperature fuel cells.

… is environmentally and climatically clean at its point-of-use, and clean over its entire energy conversion chain when produced from renewable electricity or from fossil fuels when carbon capture and storage (CCS) is included. Clean hydrogen energy is Kyoto-compatible. Hydrogen energy and its technologies contribute to balancing the environmental and climatic off-balance utilization of the energy system in place.

… is not oligopolizable, since a ''hydrogen energy OPEC'' is highly improbable, because hydrogen's various primary fuels are obviously much more widely disseminated than OPEC's oil. They are spread over the entire globe, in contrast to the reservoirs of crude oil or natural gas which are concentrated in the »energy strategic ellipse« spreading from the Persian Gulf via Iran, Iraq, and central Asian states to as far as Siberia where the bulk of known fluid fossil fuels is located.

… is technology driven, because along its complete conversion chain hydrogen production, storage, transport, dissemination, and utilization technologies are well understood and marketed or on the verge of being marketed. Electrolytic production of hydrogen and its production from natural gas or coal or heavy fractions of oil are day-to-day practice. Hydrogen-fueled fuel cells are compact, quiet, clean, and, as chemo-electric converters and not Carnotian (Sadi Carnot 1796–1832) heat engines, highly efficient. Modularized, their unit capacity ranges from less than watts up to megawatts over more than six orders of magnitude with well-marketable temperature variations, depending on the cell type from some 80 up to c. 900 °C. They serve as long-life power packages in portable electronics, as stationary combined heat and power (CHP) facilities, as high-temperature topping modules in combined cycles, and onboard automobiles as prime movers in the electric drive train and as a replacement for today's miserably inefficient mobile electrical generators. Storage is provided through high pressure gas tanks, metal hydrides, or dewars containing energy dense cryogenic liquefied hydrogen.

Obviously, hydrogen energy policy is technology politics! With hydrogen technologies, particularly energy import intensive industrialized nations get a welcome quasi-indigenous energy from the knowledge of their scientists and the skills of their engineers and craftsmen. More energy services from less primary energy are the creed!

… is inherently securely safe, because long term and unforeseeable risks are inexistent, since hydrogen energy is without radiotoxicities or radioactivity, and its contribution to the anthropogenic greenhouse effect is very small, if any. Since on principle, however, absolutely safe conditions in technical systems are impossible, anywhere and under any condition, hydrogen's specific safety risks need to be thoroughly addressed. Safety related incidents have been experienced; for instance in the space launch industry, for the time being the only industrial branch utilizing hydrogen energetically in large quantities, now for more than half a century. But it has never had an accident which was *causally* introduced by hydrogen. No less experienced are refineries, and the merchant gas and hydrogen chemistry industries which are familiar with handling securely and safely very large amounts of hydrogen in their day-to-day practice. There is no arguing with experience and success: addressing hydrogen safety concerns will help hydrogen succeed!

… is produced worldwide in an amount of some 50 million tons p.a., worth some US-$ 280 billion (2006) with an annual addition of approximately 10%, in steam methane reformers (SMR), in partial oxidation of heavy hydrocarbon fractions, and through coal or biomass gasification, or in large electrolyzers. Major hydrogen users are the space flight business and the electronics industry, glass and food manufacturers and electrical equipment companies. By far the largest amounts of hydrogen are produced and utilized captively for methanol or ammonia syntheses, and in the refining industry for hydrogen treatment of heavy crude and the production of reformulated gasoline and the de-sulphurization of middle distillate diesel fuel. Worldwide, the amount of captive hydrogen is about seven times that of merchant hydrogen; merchant hydrogen consists of gaseous and liquid hydrogen where the amount of gaseous hydrogen is about six times that of liquid hydrogen.

… is ubiquitous, since hydrogen energy perpetuates continuously, cleanly, safely and securely the established world energy trade system; no continent and no nation are excluded as either hydrogen producer, hydrogen trader, or hydrogen user. New hydrogen producers and traders will join the club in those areas of the world where so far huge amounts of renewable sources are lying fallow because they cannot be stored or transported. Here hydrogen as a chemical energy carrier makes both possible. Other new hydrogen producers will emerge among the fossil fuel producers of the world when they start decarbonizing and, thus, hydrogenizing their products and start shipping hydrogen instead of fossil fuels. Herewith a switch is predicted from the energy buyer's obligation to clean up the fuels he purchases to the energy seller's cleaning up the fuels prior to selling them. So far, the energy sellers have been freed from any such obligations; traditionally they simply ship energy raw materials, including their pollutants and potential greenhouse gases.

… as a clean secondary energy carrier enables the ''old'' energies coal, oil, gas, and nuclear fission to join the per se clean renewable energies and electricity, and to continue playing their role in a future environmentally and climatically clean sustainable energy world. Today, electricity and steel keep coal alive; tomorrow hydrogen will help keep clean coal alive. The conversion of coal into hydrogen energy enables coal's return to the transport and household sectors which it had to leave with the advent of light oil and gas: truly, a renaissance!

… is sustainable economically, environmentally and climatically, as well as societally, and from a reversibility standpoint: economically, because of the global ubiquity of the primary renewable fuels from which hydrogen is produced; environmentally and climatically, since electrolytic hydrogen from renewable or nuclear electricity comes from water and is recombined to water again, water from the earth's inventory, water after recombination of hydrogen and oxygen given back to that inventory; and for hydrogen from fossil fuels the inclusion of securely safe handling, sequestering and storing away of carbon is an inevitable necessity. Finally, on principle, energy irreversibilities are not sustainable. Here, striving for much higher exergy efficiencies comes into play; they are all the higher, the lower the conversional irreversibilities are. Turning off the Carnotian heat-engine-related energy system is due; it produces much too much heat of the false temperature at the wrong location where no user asks for it.

… is on track, because energy sustainability without hydrogen energy is irrational, although there are still many milestones ahead. Energy sustainability is not a momentary value; rather, the road is the destination! Many hydrogen milestones along the road lead to the hydrogen energy economy, and, no doubt, similar to any of the past novel

energies, many stumbling blocks will have to be removed. Paving the HYway means more clean energy services from less polluting and climatically harmful primary fuel! When weighed on the energy sustainability scale, light weight hydrogen is a heavyweight!

… is urgent, because we have learned that novel energies need long, sometimes very long periods of time; typically many decades up to half centuries for the irrevocable establishment of a novel energy on the market are the appropriate estimates, and hydrogen energy is not different. Consequently, it's HYtime, it is high time to start the implementation of the hydrogen energy economy and see it through. For the innovation of a novel addition to the global energy system, it so appears that it is almost always too late; humans tend to ignore squeaking wheels, they stay with what they are accustomed to and seldom abandon this attitude without being compelled to do so. Three of these compulsions are clearly foreseeable: (1) the production peaking of the fluid fossil fuels oil and gas in a few decades to come, and as consequences, (2) increasing oligopolization of suppliers and skyrocketing prices; and (3) harsh environmental and in particular climate change challenges.

… decentralizes the energy system: historically, national energy conversion chains start with energy production at their front end, i.e., the conversion of primary energy raw materials into primary and secondary energies which, after transport, storage and distribution, are utilized at the back end of the chain. Potentially, through hydrogen energy and fuel cells in stationary or mobile applications, another production link is added to the national chain also at its back end. Both ends get the chance to become production ends and to start welcome competition. The so far untapped production potential at the back end is immense: in Germany some two-thirds of the national end energy is required for transportation and buildings!

According to United Nations predictions half of the world's population will be living in urban areas by 2008/2009; by 2050 some 70% will be dwelling in megacities that have more (in cases much more) than 10 million inhabitants: Urbanization proceeds, and hydrogen and its technologies help to free these agglomerations of fumes, smog, noise, pollutants and greenhouse gases.

… exergizes the energy system: whenever energy is converted (produced, handled, stored, transported, disseminated, utilized, …) it is split into two parts: energy = exergy + anergy. Exergy is the maximum of available technical work extracted from energy. Per definition exergy can be converted into any other form of energy, anergy cannot. The classical Carnotian energy system, built up over 200 years now, produces very high conversional irreversibilities and, thus, much too much heat of the false temperature at the wrong place where no potential user asks for it, in power plants, in residential or industrial heating systems, in automobile engines. On the other hand, hydrogen-supplied fuel cells are exergetically highly efficient, always generating firsthand electricity (= pure exergy), and the exergy content of the remaining heat at the fuel cell's specific temperature is in many cases exactly what meets the requirements of industrial or residential heat demands. It is the irreversibilities of combustion, of heat transfer and energy flow through the installation which cause exergy destruction and exergy losses. Bringing them down to lower levels in Carnotian systems is welcome, but is becoming increasingly difficult, because only tiny development increments in high-temperature materials, in the physical chemistry of combustion, and in fluid dynamics are slowly asymptotically approaching higher exergy efficiencies: the system-immanence tends to its final end. No, what is urgently needed is a system change to chemo-electric or solar-electric novel systems like hydrogen-supplied fuel cells or solar photovoltaics which are not Carnotian heat engines. Elevating source-to-sink exergy efficiencies means exergizing energy.

… is not really anything new: Antoine Lavoisier (1743–1794) and Henry Cavendish (1731–1810) were the first to mention hydrogen in the literature. In 1766 H. Cavendish spoke of ''inflammable air'' and A. Lavoisier named it ''hydrogen'' in 1787. Half a century later, around 1839, two friends, the Welshman William Grove (1811–1896) and the German Christian Friedrich Schönbein (1799–1868), published their findings on hydrogen-supplied fuel cells. That between one and two centuries had to pass before hydrogen energy arrived at the verge of taking its inherent place in the world energy market is not a singular phenomenon. Other novel energies and their converters also needed (and will need) time. What the energy world faces is how to construct a bridge from the well established and economically lucrative *hydrogen economy* which utilizes hydrogen as a commodity to the *hydrogen energy economy* and its utilization of hydrogen as an energy carrier. On that way, nothing of what has been learned over the centuries-long development of the hydrogen economy is lost; more on the energy aspect is to be added prior to full establishment of the hydrogen energy economy. The petroleum and natural gas industries, the auto makers, the technical gases industry, and the energy utilities have begun to commit themselves to hydrogen energy; addressing concerns helps both hydrogen and industry to succeed. Hydrogen energy starts to become a reality!

… is the so far final addition to energy diversity; it tends to close the anthropogenic energy cycle: from the renewable energies of the first solar civilization to coal, to oil and gas and nuclear fission back to renewable energies, now of the second solar civilization, and finally to hydrogen energy's taking care of renewable energies' storage and transport requirements. Along that line the anthropogenic energy cycle needed around two centuries and a half. Never in this relatively short period of time did humans use only one form of energy; never did a novel energy fully replace its predecessors, the ever growing energy demand needed them all. After coal, oil, natural gas, and nuclear fission beginning in the 18th and continuing in the 19th and 20th centuries, in addition to striving for energy and particularly exergy efficiencies as well as the utilization of renewable energies, the 21st century is on the verge of becoming the century of hydrogen energy and its technologies. Hydrogen is the oil and gas of the 20th and the coal of the 19th century. Steadily getting away from oil and natural gas and building up the hydrogen energy economy is the task. We are well on our way, the growing atomic hydrogen/carbon ratio H/C makes it obvious: It tends to a dual triangulation from high carbon to low carbon to no carbon, and, as a consequence, from (almost) no hydrogen to low hydrogen to finally high hydrogen:

Coal: oil: natural gas: hydrogen = <1: 2: 4: ∞

Today, two-thirds of all atoms in fossil fuels burnt are already hydrogen atoms; the trend points to ever higher hydrogen numbers.

… dematerializes the energy system: it is the conversion of energy matter which causes environmental and climatic harm, not the conversion of energy; that is why dematerialization of energy is so important. Since the specific atomic masses of hydrogen and carbon are 1 and 12 [g/mol], respectively, the ongoing process of shifting from the carbon rich/hydrogen poor hydrocarbon energy economy to the future hydrogen rich/carbon poor hydrogen energy economy is accompanied by a continuous dematerialization process. Specifically, energy gets lighter and lighter over time. The »Energy Era-of-Light« may be the appropriate label for the 21st century, because:

- efficiencies make more energy services from less weighty primary energy raw materials; renewable energies have no operational primary energy raw materials per se; and hydrogen is the *lightest* element in the periodic table of elements,
- most renewable energies utilize directly or indirectly the *light* of the sun,
- their and hydrogen's utilization *lightens* the burden on environment and climate, and
- all of the aforementioned shed *light* on what will become the criterion for the 21st century of energy: energy sustainability.

One thing should not be forgotten, though: in some cases the flip side of lightness is bulk!

… helps triggering the next industrial revolution:

- The first industrial revolution was triggered by the steam engine,
- the second industrial revolution by electrification, and
- the third industrial revolution is triggered not by only one single technology but rather a whole range of technologies (see the »Epilog«), such as energy decentralization, decarbonization, hydrogenation, dematerialization, low weight to weightlessness, biotechnology, information and communication technology, micro-miniaturization, nanotechnology, …

… asks for good global energy governance: it seems that 19th and 20th centuries' thinking and acting in terms of primary energy raw materials is still dominating the world energy scene. How many tons of coal, barrels of oil, cubic meters of gas or kilograms of uranium are to be traded, at what cost, and with which relevance for the environment and climate change—these questions still appear in the foreground of argumentations. The 21st century, however, sees more and more heavy energy consuming countries unalterably dependent on fewer and fewer energy suppliers; national energy self-sufficiency is increasingly possible for only a small number of countries. The power of supply oligopolies grows. National energies lose, global energy wins.

In this situation, the countries of the world tend to do two things: they revitalize their energy efficiency technologies in order to slow down the need for (imported) primary energy feedstock; and they tend towards good energy governance for the benefit of both energy rich, though technology poor, and energy poor, but technology rich nations. Efficiency technologies increasingly grow into the role of »national energies«: that is part of 21st century energy thinking and acting.

Benjamin Franklin (1706–1790), foreign secretary of the newly independent New England colonies, stated already three centuries ago, ''We are bad farmers, because we have too much land.'' Paraphrased we get ''We are bad energy engineers, because we have too much energy''—too much cheap energy feedstock, stated more precisely, since cheap energy feedstock is the most elusive enemy of energy security! How prospective Franklin's thinking was!

… adds value to the energy economy: J.A. Schumpeter's (1883–1950) ''Innovations are the driving forces of economic growth'' was valid, is valid, and will be valid when hydrogen energy adds value to the energy economy through:

- undoubted environmental and climate change benefits,
- its avoidance of irreversibilities and, thus, its exergizing ability, providing more technical work from less primary energy,
- slow down of physically unavoidable energy value degradation = entropy increase,
- its activating »national energy« in the form of energy science and engineering skill, thereby enabling nations to compensate for the imponderabilities of foreign energy markets,
- the reduction of import dependency and, thus, the avoidance of the price dictates importing countries are suffering under,
- stimulating hydrogen technology development and export; ''ecological reasoning not only asks for avoidance and renunciation, but also and primarily for unparalleled technology development''!
- helping to decarbonize fossil fuels and, thus, furthering their use until their point of depletion,
- switching from the global fossil fuel trade to a global hydrogen trade by decarbonizing fossil fuels and removing pollutants already on the energy seller's side,
- decentralizing the national energy scheme, thereby activating so far dormant virtual distributed energy potentials downstream where people live,
- making tradable huge so far untapped renewable potentials and thereby utilizing the only closed energy material cycle ''solar and water from the earth's inventory to hydrogen and water, after hydrogen/oxygen recombination returned to that inventory''; all other cycles are materially open cycles,
- not least, professionalization of fallow lying energy potentials at the back end of national conversion chains.

… is not a panacea, but it is considered the still lacking cornerstone of the anthropogenic sustainable energy building. Economics and ecology are the drivers; hydrogen energy is the enabler. Without hydrogen, expecting energy sustainability is irrational. Hydrogen energy technologies are the choice: hydrogen does not take the energy system to heaven, but it saves it from an environmental and climatic disaster.

… a priori helps to further energy awareness:

- With or without hydrogen a switch from fossil energies to renewable energies is due; but with hydrogen huge amounts of renewable sources otherwise lacking storability and transportability can enter the global energy trade,
- with or without hydrogen, reduction of irreversibilities in Carnotian energy conversion is due; but with hydrogen the switch to exergetically efficient combined cycles is facilitated,
- with or without hydrogen decarbonizing fossil fuels is due; but with hydrogen in combined cycles the exergy efficiency rises significantly.
- One item requires hydrogen indispensably: no low-to-medium temperature fuel cells without hydrogen, either pure hydrogen or hydrogen reformate.

… energy in the forthcoming »terrestrial man to the moon« project indicates what we are facing: other than the historical man to the moon project, which was the endeavor of one nation, the project of the 21st century has to become a worldwide endeavor, no nation excluded, either with its hydrogen production experience, or its hydrogen storage, transport and distribution infrastructure, or its engagement in early adoption of hydrogen energy. A few examples: all nations experienced in the space launch business are predestined to take over the market sectors of handling, storing, transporting or combusting large amounts of hydrogen. Nations involved in portable electronics will be (and already are) switching to hydrogen-supplied fuel cells to replace low longevity batteries. Or nations with a long history in coal production now face the challenge of hydrogen-supported decarbonization and carbon capture and storage (CCS) for the benefit of the environment and climate. And finally, those nations in the world blessed with large capacity renewable energy potentials (hydro, wind, solar, ocean, others) will sooner or later face the necessity of adding the storable and transportable chemical energy carrier hydrogen in order to enable their renewable sources to contribute to the global energy trade.

… is the core argument in the Centennial Memorandum of the International Association for Hydrogen Energy (IAHE), submitted to the heads-of-state of the G8 summits of 2007 in Heiligendamm, Germany and 2009 in Italy, and asking them to give hydrogen energy top priority in their national and international considerations. The memorandum reads in part: ''Hydrogen energy: the abundant clean energy for humankind as a means of mitigating anthropogenic climate change, avoiding environmental challenges, and decelerating the world's ongoing oligopolization of conventional energy raw materials is the permanent solution to the upcoming energy and climate change catastrophe.''

*Abbreviations, Acronyms, Glossary*

APU auxiliary power unit
BAU business-as-usual
bbl barrels (of crude oil), 1 barrel = 159 l
Bergius, Friedrich 1884–1949, winner of the 1931 Chemistry Nobel Prize
Bio-natural gas biogas meeting natural gas specifications
BtL biomass-to-liquid
BZ Brennstoff-Zelle, (fuel cell)
C carbon
CCS carbon capture and storage (or carbon capture and sequestration)
$CGH_2$ compressed gaseous hydrogen
$CH_4$ methane
CHP combined heat and power system
$CO_2$ carbon dioxide
$CO_2$(e) carbon dioxide equivalent of non-carbon-dioxide compounds
COE cost of electricity
Dewar vacuum insulated container, after James Dewar, 1842–1923
Diesel fuel after Rudolf Diesel 1858–1913, the inventor of the diesel engine
DMFC direct methanol fuel cell
EIT economies in transition
Elms fire St. Elmo's fire (St. Elmo, also known as Erasmus of Formiae, the patron saint of sailors), electrostatic discharge in an atmospheric electrical field
Entropy energy devaluation, in closed systems ever increasing, never decreasing
EOR enhanced oil recovery
ER equivalence ratio of fuel and oxidizer
FC fuel cell
Fermi Enrico Fermi, 1901–1954, nuclear scientist
G8 the group of eight highly industrialized nations
GDP gross domestic product
$GH_2$ gaseous hydrogen
GHG greenhouse gas
GT gas turbine
GWP global warming potential
$H_2$ hydrogen
$H_2O$ water
HHV higher heating value
HRSG heat recovery steam generator
HT high temperature
HVDC high voltage direct current
IAHE International Association for Hydrogen Energy
ICE internal combustion engine
ICEHEV internal combustion engine hybrid electric vehicle
IGCC integrated gasification coal combustion
IJHE Elsevier's International Journal of Hydrogen Energy
IPCC Intergovernmental Panel on Climate Change
ISAM integrated starter-alternator motor
ISO TC International Organization for Standardization, Technical Committee
It's Hytime it's hydrogen time (http://www.itshytime.de)
KOH potassium hydroxide
kW kilowatt
$LH_2$ liquefied hydrogen
LHV lower heating value
LNG liquefied natural gas
LOX liquefied oxygen
LPG liquefied petroleum gas
MCFC molten carbonate fuel cell
MEA mono ethanol amine
MHR (high temperature) modular helium reactor
mpgge miles per gallon gasoline equivalent
MW megawatt
$N_2$ nitrogen
$N_2O$ nitric oxide

$NaBH_4$ sodium borohydride
Negentropy compensation for entropy increase (e.g., through solar irradiance)
NG natural gas
$NO_x$ nitrogen oxide
O&M operation and maintenance
OEM original equipment manufacturer
Ohmic resistance heating after Georg Simon Ohm, 1789–1854
ORC organic Rankine (steam) cycle, after William J.M. Rankine 1820–1872
Otto engine after its inventor Nikolaus August Otto 1832–1891
Pabst von Ohein Hans Joachim Pabst von Ohein 1911–1998, renowned jet engine engineer
PAFC phosphoric acid fuel cell
PEMFC polymer electrolyte membrane fuel cell: hydrogen purity 99.99% (vol.), »4 × 9«
PHEV plug-in hybrid electrical vehicle
POX partial oxidation of hydrocarbons
ppb parts per billion
ppm parts per million
ppmv parts per million, by volume
PV photovoltaic
Pyrolysis gasification under oxygen exclusion
Retentate non-reacted leftover process flow (e.g., in a NG reformer)
rpm revolutions per minute
S sulfur
S/C steam-to-carbon ratio
Selexol physical solvent (of carbon dioxide)
Slipstream hydrogen inexpensive hydrogen at the filling station from a nearby IGCC plant
SMR steam methane reforming
SOFC solid oxide fuel cell
SOT solar thermal (power plants)
SPE solid polymer electrolyte
SUV sport utility vehicle
Syngas synthetic gas consisting of CO, $H_2$, ($CO_2$)
tkm ton-kilometer
UPS uninterruptible power supply
VES (Verkehrswirtschaftliche Energiestrategie) a transport energy strategy (in German at http://www.bmvbs.de/-,1423.2458/Verkehrswirtschaftliche-Energi.htm)
Wobbe index interchangeability of fuel gases

## 4. Anthropogenic climate change and hydrogen energy

It has only been 20 or 30 years since anthropogenic influence on the atmospheric greenhouse effect irretrievably began governing human thinking and acting. Energy, industry, transportation, agriculture, trade, buildings, and, not at all least, the behavior and attitude of individuals and society and the decisions of policy makers vis-à-vis environment and climate—no area of potential greenhouse interaction is being excluded. From the start of industrialization around 1800 the atmospheric $CO_2$ concentration has grown from 280 to 380 ppmv (2007) (ppm parts per million, v volume). Annually 36 billion tons of emitted $CO_2$ (2007) are anthropogenic, of which 29 billion come from fossil fuel combustion and industrial processes; the remaining 7 billion are the consequence of deforestation and agricultural industries. The major emitters are the industrialized countries, with the USA, China, Russia, Japan, India, and Germany at the top, in that order. A rough estimate says that every additionally emitted anthropogenic 30 billion tons of $CO_2$ raise its atmospheric concentration by c. 2 ppm. To be added are other greenhouse gases such as $CH_4$ and $N_2O$, whose global warming potentials (GWP) are 21 kg $CO_2$e/1 kg $CH_4$ and 310 kg $CO_2$e/1 kg $N_2O$, respectively. Other greenhouse gases (GHGs) are diverse fluorine compounds.

The Intergovernmental Panel on Climate Change (IPCC) stated in its Synthesis Report 2007 that »warming of the climate system is unequivocal«, that »eleven of the last twelve years (1995–2006) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850)« and »rising of the sea level is consistent with warming«, so are decreases in snow and ice cover, an increase in precipitation in certain areas and a decline in others, the growing intensity of tropical cyclones in the North Atlantic, and increasing ocean acidification due to $CO_2$ uptake. Fig. 1 documents an increase from 13.5 to 14.5 °C in global average surface temperature between 1850 and 2000, an increase from −150 to +50 mm in global average sea level between 1870 and 2000, and a decrease from around 37 to 35 million $km^2$ in the Northern Hemisphere snow cover between 1920 and 2000.

The IPCC report further states that ''global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004'' (Fig. 2), and ''global atmospheric concentrations of $CO_2$, methane ($CH_4$) and nitrous oxide ($N_2O$) have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousand years.'' The report concludes that »most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations«. The climate process is highly nonlinear.

Fig. 3 brings best estimates (dots) and likely ranges (bars) of warming assessed for six different scenarios for 2090–2099 relative to 1980–1999. The best estimates indicate temperature rises between 1.8 and 4 °C, with the bars extending over a wide range from around 1 to 6.4 °C. What we learn is that the temperature rise over one century can be dramatic, and that there is still room for reducing the uncertainties of scenarios. Even more dramatic is the message that ''anthropogenic warming and sea level rise continue for centuries due to the time scales associated with climate processes and feedbacks, even if GHG concentrations were to be stabilized.'' What has been concluded time and again is once again confirmed here: Starting immediately with aggressive mitigation is imperative, although it will not be possible to compensate for past errors.

Fig. 4 shows for seven sectors the economic mitigation potentials by 2030 in Gt $CO_2$e/a over three emission trading certificate values, <20, <50 and <100 US$/t $CO_2$e. The evidence? Firstly, the mitigation potentials of buildings are the highest, followed by agriculture, industry, energy supply and the other sectors; secondly, the potentials for non-OECD/EIT

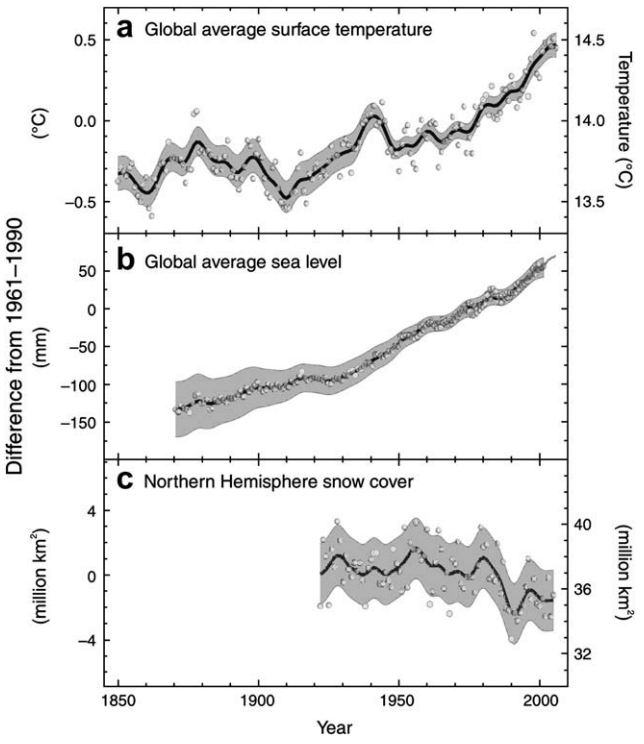



**Fig. 1 – Changes in temperature, sea level and Northern Hemisphere snow cover Source: IPCC.**

countries (EIT economies in transition) are (much) higher than those for OECD countries; and thirdly, it is surprising that the influence of certificate pricing for the sectors transport and waste is almost negligible. If we sum up the <100 US$/tons $CO_2$e potentials of all seven sectors we end up with some 23 Gt/a $CO_2$e, and for <20 US$ we are still at 13–14 billion tons. The IPCC comments that ''modeling studies show that global carbon price increases from 20 US$ to 80 US$/tons $CO_2$e by 2030 are consistent with stabilization at around 550 ppm $CO_2$e by 2100.'' So, the mitigation potential seems real; the time needed, however, is very long. Stabilization cannot be achieved in less than almost one century, and not (only) by deployment of a portfolio of technologies that are either currently available or expected to be commercialized in coming decades. — So far the IPCC synthesis report of 2007. Let us now consider the economic and technology consequences of stabilization in more detail.

Nicholas Stern, former chief economist of the World Bank, published in 2006 his review »The Economics of Climate Change« with these major findings: ''Climate change could have very serious impacts on growth and development''; ''the costs of stabilizing the climate are significant but manageable''; ''delay would be dangerous and much more costly''; ''the benefits of strong and early action far outweigh the economic costs of not acting''. In detail, the review estimates that if we do not act, the costs and risks of climate change will be equivalent to losing at least 5% (and under certain circumstances 20% or more) of global Gross Domestic Product (GDP) each year, now and forever. On the other side, the cost of measures to reduce emissions to avoid the worst impacts can be limited to one fifth of that amount, i.e., to 1% of global GDP each year. Stern claims that the climate change impacts can be substantially reduced, if atmospheric greenhouse gas concentrations can be stabilized between 450 and 550 ppm $CO_2$e compared to today's 430 ppm $CO_2$e with an unaltered yearly rise of 2 ppm (equivalent ''e'' indicates the climate change effect of the non-$CO_2$ emissions $CH_4$, $N_2O$ and fluorine compounds compared to $CO_2$ emissions), of which 380 ppm stem from $CO_2$ as that greenhouse gas with the present comparatively major impact. About 450–550 ppm by 2050, i.e., a yearly addition of 2 ppm, is considered »safe« by the political class, the resulting billions for emission mitigation «allowable». Consequently, stabilization in the range of 450–550 ppm by 2050 requires cutting today's global emissions by at least 25%. That means that the dominant emitters, the industrialized countries, have to reduce their emissions 60–80% by 2050, which is identical with the recommendations delivered already in the early 1990s to the German government and parliament, respectively, by the Enquête Commission of the

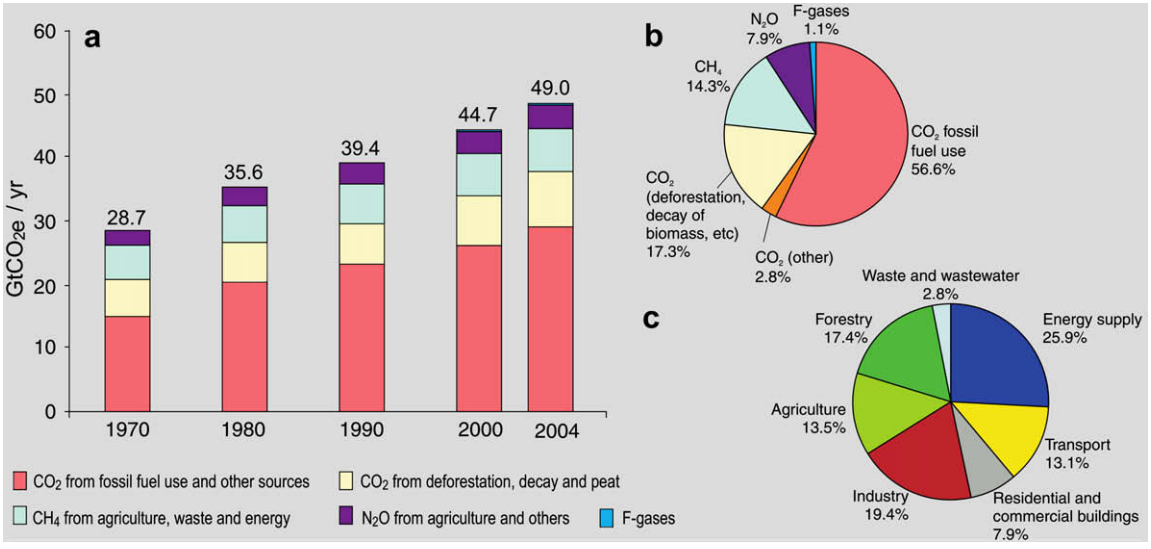



**Fig. 2 – Global anthropogenic GHG emissions Source: IPCC.**

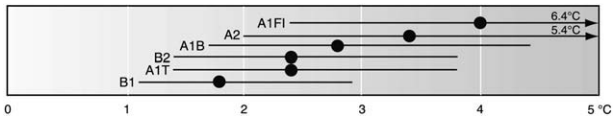



**Fig. 3 – Warming by 2090–2099 relative to 1980–1999 for nonmitigation scenarios Source: IPCC.**

German Bundestag, ''Protection of the Earth's Atmosphere''; the recommendations were unanimously agreed upon by both sides of the aisle.

Bluntly, N. Stern speaks of climate change as ''the greatest market failure the world has ever seen'' interacting with other ''market imperfections''. He compares the failure with the global challenges of the world wars of the 20th century and the world recession of the 1920s and 1930s. To fix these imperfections and safeguard them from market failure requires a whole range of countermeasures. So far, however, very little has been and is being done to reduce emissions, although according to the United Nation's Kyoto Protocol industrialized countries (still excluding top polluters such as the USA and economies in transition like India and China with their rapid industrialization processes and, thus, their rapid approach to the emission levels of industrialized countries) have agreed upon a reduction of their 1990 emissions by 5.2% in the period between 2008 and 2012. On the contrary, on average the world has emitted more greenhouse gases instead of less.

Notwithstanding, let us try to see what reduction possibilities can meet the aforementioned challenges. Seven steps can be envisioned: first, stop deforestation and alter industrial processes in agriculture; second, establish worldwide $CO_2$e emission certificate trading as an economic means of mitigation; third, raise energy efficiencies and in particular exergy efficiencies along all links of energy conversion chains, i.e., reduce the irreversibilities in established Carnotian systems and switch to combined cycles with fewer irreversibilities, such as electricity plus heat, electricity plus hydrogen, electricity plus chemical commodities, all of them of maximum technical work (=exergy) extracted from energy; fourth, generate electricity from nonfossil renewable and nuclear sources; fifth, if generated from fossil sources, decarbonize and thus hydrogenize and dematerialize the conversion processes; sixth, introduce hydrogen technologies into the end use sectors where exergetically miserable on-site boilers in buildings and engines in autos need to be replaced by exergetically efficient hydrogen-fueled fuel cells or hydrogen adapted and exergetically optimized ICEs; seventh, cap other emissions like methane, nitric oxides, and fluorine gases with in part still small but rapidly rising $CO_2$ equivalences: in one word, be or at least become conscious of the counteracting ability of innovative technologies and make policy makers and entrepreneurs aware of the unequivocal: energy policy is technology politics!

We have to consider an extraordinary catalogue of low to zero-carbon technologies which are afoot, or in labs, or under long-term investigation. Afoot are wind converters approaching unit capacities $\leq$10 MW each and in August 2008 a little less than 100 GW worldwide in total; further afoot are photovoltaic generators (PV generators) whose efficiencies are on a steady upward trend and approaching, according to cell type, 12–20%, in concentrating devices even more than 20%; further, concentrating solar thermal power stations with some hundreds of megawatts on line or planned with their appreciable efficiencies which are much higher than those of even the best photovoltaic generators, although they need direct solar light whereas the PV generators work with both direct and distributed light; and, heat-producing, gasifying and liquefying biomass facilities and combined cycles as regular market products in the portfolios of the energy utilities industry.

Technologies in the research and development labs are clean fuel cells of all sorts for simultaneous production of electricity and heat for portable, stationary and mobile applications; hydrogen production from high-temperature nuclear heat; hydrogen production from coal, including capture of $CO_2$ and its secured long-term storage, safely,

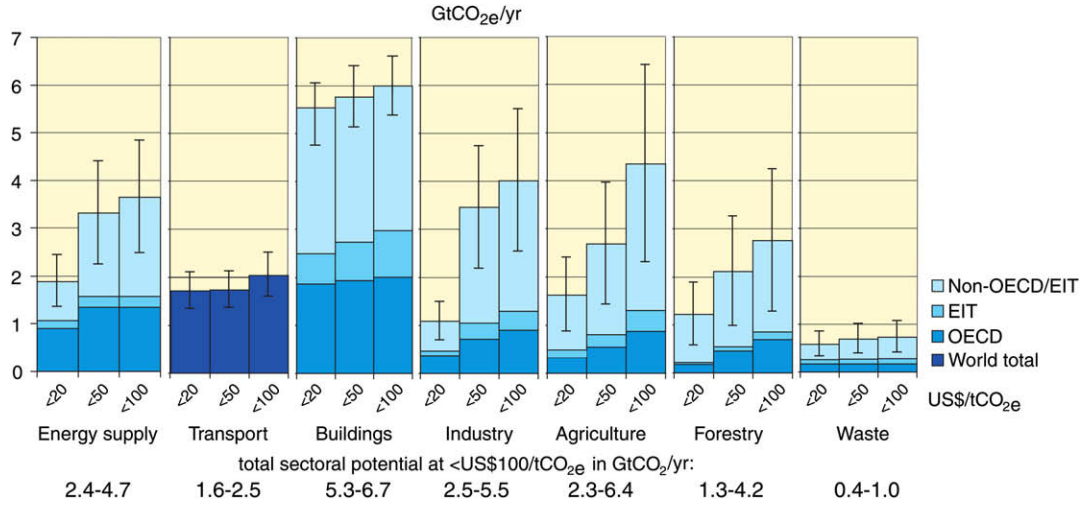



**Fig. 4 – Economic mitigation potentials by sector in 2030 estimated from bottom-up studies Source: IPCC.**

reliably, and durably; investigations of the geophysical, geochemical and geobiological behavior of $CO_2$ underneath the earth's surface or the sea floor.

And finally, long-term investigations deal with metal hydrides of practically applicable energy percentages per weight of some 5–8 wt%; hydrogen in aviation; hydrogen utilization and transport at sea; the combination of liquid hydrogen and HVDC electricity in »supergrids« where hydrogen has two functions, cooling the HVDC line and delivering energy. A thorough collection of hydrogen technologies—today, tomorrow, and later—can be found in »7. Hydrogen Energy Technologies Along the Entire Conversion Chain.«

In a paper by Ref.[58] (see the literature list) the overall technological challenge of decarbonization is described. The authors imagine over the next 50 years a triangle between business-as-usual emissions [billion tons carbon/year] and stabilization of the 2006 emissions (Fig. 5), divided into seven »wedges« (1 wedge is equivalent to 1 billion tons of carbon, 7 wedges correspond with today's approximately 7 billion tons of anthropogenic carbon emitted) which have to be reduced over the next 50 years if emissions are to be stabilized.

Fig. 6 shows 15 wedges (and an open one as an indication of potential future wedges to come) of ways to mitigate emissions, such as efficiency and conservation, power generation, carbon capture and storage, renewable sources, agriculture and forestry. The challenges are almost unimaginable! A few examples only: build 1600 new coal-fired power plants of 1000 MW each; increase 40-fold today's wind power potential; operate the 2 billion autos expected by 2050 at 4 l/100 km; add carbon capture and storage to power plants and generate hydrogen for 1.5 billion cars. Truly, the challenge adopts the character of a marathon, by all means not a sprint! [43,44].

To conclude this chapter: of course, technologies are not the only mitigation means; the behavior of individuals and societies vis-à-vis climate change is also extremely important. Yet, building up the climate consciousness of the public, of industry representatives, and policy makers is a major goal not yet finally achieved by far.

The technologies aim at two targets. (1) They raise the energy efficiencies of the established Carnotian conversion system and switch to higher exergy-efficient combined cycles; they produce more energy services from less primary energy raw material: what is not needed to provide more services does not interfere with the greenhouse! And (2), they replace heat-engine-related Carnotian conversion technologies with their limited further incremental efficiency potential with hydrogen supported combined cycles of inherently higher exergy efficiencies. Maximizing an energy system's exergy means aiming at extracting the maximum of technical work from energy and minimizing the interference with the greenhouse.

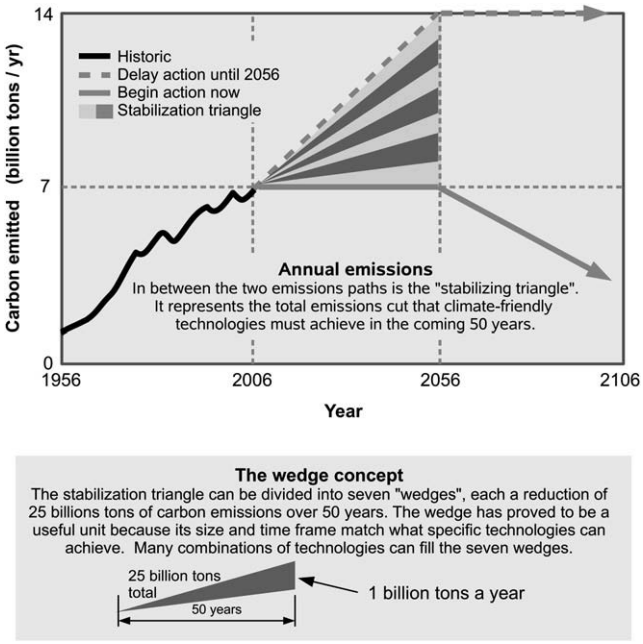


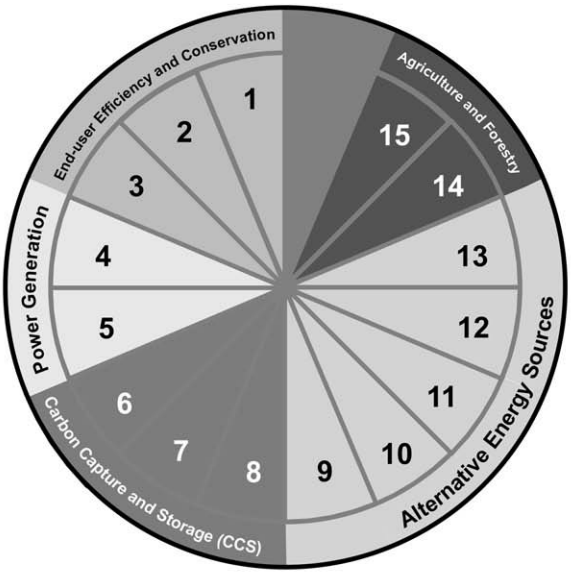

**Fig. 5 – Annual carbon emission, 1956–2006 historic, 2006–2106 prospective Source: [58].**

## 5. Anthropogenic energy history and hydrogen energy

Up until far into the 18th century humans utilized exclusively renewable energies of the first solar civilization. Wind blew into the rotors of windmills or the sails of ocean-going ships; solar irradiance helped field crops to grow, wood and peat warmed homes, running water turned waterwheels. Modern energy history covers a rather short period of time, not much more than 200–250 years. It began with the opening of the first industrial coal mine in England in the second half of the 18th century: the industrialization of the world began.

Fig. 7 shows the energy triangle of the primary energy history of the last almost two centuries. All three types of primary energy (raw materials) or feedstock are depicted as isoshares: on the left side of the triangle coal, on the right the two fluid hydrocarbons oil and gas, and at the bottom the two operationally carbon-free renewable and nuclear energies. The thick dark line is history, it begins outside the right lower corner prior to the turn of the 18th to the 19th century when oil and gas were not yet in use and the renewable energies of the first solar civilization were consecutively replaced by growing amounts of coal. In the later 19th and then in the 20th century oil came into use and helped further replace the renewable energies, and also began to replace coal. A sharp turn from the 19th to the 20th century in the lower left corner marks this point in history. From then onwards through the entire 20th century the operationally zero-carbon energies, consisting of a re-growth in the amount of renewable energies, now of the second solar civilization, and, starting in the middle of the century, the appearance of nuclear fission, remained almost constant at c. 15%. Coal shrank to today's c. 20%, and oil and gas climbed up to 60%: This is the situation humans were in at the turn of the 20th to the 21st century. Now, where to go from there?

One thing seems unavoidable: experts state that the number of people on earth, some 6.7 billion in 2008, is expected to further grow continuously, though perhaps with a slightly smaller gradient over time, to 9 billion or even more




| | | |
|---|---|---|
| 1 | End User Efficiency and Conservation | Increase fuel economy of two billion cars from 30 to 60 mpg |
| 2 | | Drive two billion cars not 10,000 but 5,000 miles a year (at 30 mpg) |
| 3 | | Cut electricity use in homes, offices and stores by 25 percent |
| 4 | Power Generation | Raise efficiency at 1,600 large coal-fired plants from 40 to 60 percent |
| 5 | | Replace 1,400 large coal-fired plants with gas-fired plants |
| 6 | Carbon Capture and Storage (CCS) | Install CCS at 800 large coal-fired power plants |
| 7 | | Install CCS at coal plants that produce ***hydrogen*** for 1.5 billion vehicles |
| 8 | | Install CCS at coal-to-syngas plants |
| 9 | Alternative Energy Sources | Add twice todays' nuclear output to displace coal |
| 10 | | Increase wind power 40-fold to displace coal |
| 11 | | Increase solar power 700-fold to displace coal |
| 12 | | Increase wind power 80-fold to make ***hydrogen*** for cars |
| 13 | | Drive two billion cars on ethanol, using one sixth of world cropland |
| 14 | Agriculture and Forestry | Stop all deforestation |
| 15 | | Expand conservation tillage to 100 percent of cropland |
| 16 | | |

**Notes:**

Wedge 1) Worldfleet: size in 2056 could well be 2 billion cars. Assume they average 10000 miles/a.
Wedge 4) "Large" is 1 GW capacity. Plants run 90% of the time.
Wedge 5) Here and below, assume coal plants run at 90% of the time at 50% efficiency. Present coal power output is equiv. to 800 such plants.
Wedge 6) Assume 90% of $CO_2$ is captured.
Wedge 7) Assume a car [10000 miles/a, 60 miles per gallon equivalent] requires 170 kg of $H_2$ a year.
Wedge 8) Assume 30 million barrels of synfuels a day, about a third of today's total oil production. Assume half of the carbon originally in the coal is captured.
Wedge 10,11) Assume wind and solar produce, on average, 30% of peak power. Thus replace 2100 GW of 90%-time coal power with 2100 GW(peak) wind or solar plus 1400 GW load-following coal power, for net displacement of 700 GW.
Wedge 13) Assume 60-mpg cars. 10,000 miles a year, biomass yield of 15 tons a hectare, and negligible fossil-fuel inputs. World cropland is 1500 million hectares.
Wedge 14) Carbon emissions from deforestation are currently about two billion tons/a. Assume that by 2056 the rate falls by half in the business-as-usual projection and to zero in the flat path.

**Fig. 6 – Carbon emission saving potentials Source: [58].**

in 2050. For the time being, 80 million, approximately the population of Germany, are added year by year. This growth, combined with the increasing demands of newly industrializing countries, asks forever more energy! One response out of a whole collection of possible responses (which are not depicted in Fig. 7) could be what is called ''business-as-usual''

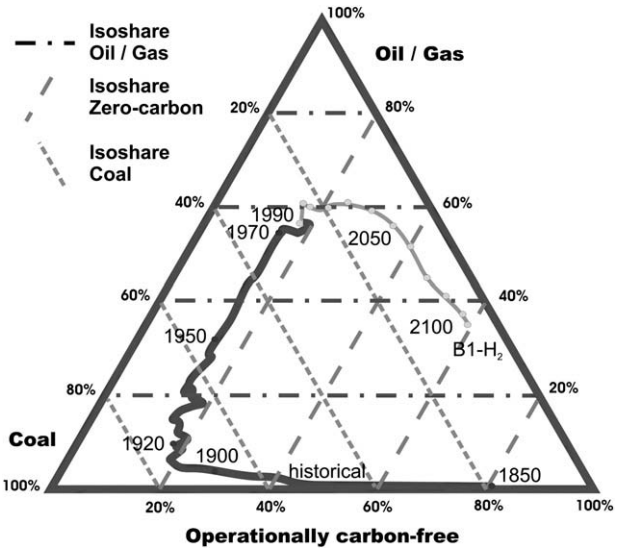



**Fig. 7 – The Energy Triangle Source: [4].**

(BAU), which means more oil and gas, approximately today's contribution of coal, more nuclear and a little more renewable energy. Since there is not too much room left in the upper corner of Fig. 7 for a BAU strategy, it seems that this will be of limited (temporal and quantitative) »success«. In addition, the extended use of ever more oil and gas, into the 60–80% range, will of course result in ever stronger (and politically and diplomatically dangerous) dependencies on supply oligopolies. Further, more nuclear power plants, even of the fourth generation with their expected higher safety regime, would require many countries of the world to abandon their hesitant or even negative attitude towards nuclear energy. And hard coal power plants, even those of the admirable exergy efficiencies of 50% of forthcoming modern designs, result in ever more irresponsible greenhouse gas emissions, if not privileged with carbon dioxide capture and storage (CCS) equipment; similar effects must be expected with more oil and gas.

Harnessing more renewable sources seems to be the solution, now utilizing the technologies of the second solar civilization like modern wind converters, fuel cells, solar photovoltaic generators, solar thermal power plants, electrochromic windows, passive solar buildings. So far, however, because they lack storability and transportability, more or less all renewable energies are utilized only locally, at most regionally; truly large macroeconomic renewable contributions to the world energy trade need the chemical energy carrier hydrogen for storage and transport. One example in

Fig. 7 is the light grey dotted line whose downward gradient could perhaps be steeper, which means less zero-carbon energies over time and more coal, or it could be less steep, requiring more renewables and less coal.

Contributing renewables to the global energy trade is not a question of potential; huge amounts of renewable sources are untapped worldwide. From an energy standpoint, wind in Patagonia blows in vain, solar in Australia waits to be harnessed, river giants in Siberia flow ''uselessly''—to give only these examples—unless their secondary energies heat and electricity are converted to hydrogen which can be transported as pressurized $GH_2$ via continental pipelines or as $LH_2$ aboard cryogenic tanker ships on transoceanic routes to the major energy importing countries of the world. Of course, renewably generated electricity can also be sent via overhead lines or perhaps as high voltage direct current (HVDC) to areas with major electricity users, but for distances of 1000 km or more hydrogen is economically more advantageous, and if at the outlet of the transport system a storable chemical energy carrier is asked for, that is the role for hydrogen, too.

In earlier energy discussions it was heard here and there that the hydrogen energy economy is a question of ''if'' or ''whether'' or ''possibly''. Now, with the knowledge depicted in Fig. 7 it has become a matter of ''how'' or ''when'' or ''which way first''. In current energy thinking hydrogen has become indispensable for two major reasons: the earth's huge renewable sources will be tapped only when hydrogen facilitates their contribution to the world energy trade system, and the other reason, for the decarbonization of fossil fuels, particularly coal, hydrogen is inherent.

At the end of this chapter a look at the end of the 21st century is taken: Fig. 7 depicts human energy history of the last 200 years and tries to perpetuate irreversibly the result into the 21st century. It seems that a triangle-shaped energy cycle is inscribed in Fig. 7, beginning with renewable energies of the first solar civilization in the late 18th and preceding centuries via coal, oil, gas, nuclear fission and electricity, and ending after two to three centuries again at renewable energies, now of the second solar civilization, and their energy carrier hydrogen. The path traveled is from no carbon via low and high carbon back to low and no carbon, and consequently from high amounts of renewables to low amounts of renewables and back to high amounts of renewables, and, not least, from no hydrogen use to low hydrogen use to high hydrogen use. In retrospect, the use of fossil fuels proved to be a short interim (compared to human presence on earth), and nuclear an addendum. In foresight, hydrogen energy will complete the »energies-of-light« scheme (see ''6. Technology Progress and the World Economy''), because carbon with its relative atomic mass of 12 is eliminated, and renewables of no weight and hydrogen with its atomic mass of 1 dominate. The future energy system will become dematerialized and inexhaustible (as long as the sun shines, i.e., for some estimated 4.5 billion years to come).

Fig. 8 tells us that decarbonization and hydrogenation are nothing really new. The shift from coal via oil and gas to operationally non-carbon renewables, nuclear and hydrogen is not a jump function but the final result of a century-long continuous development. In the last 120 years the carbon tonnage per unit of energy [tons C/kilowatt-years] already

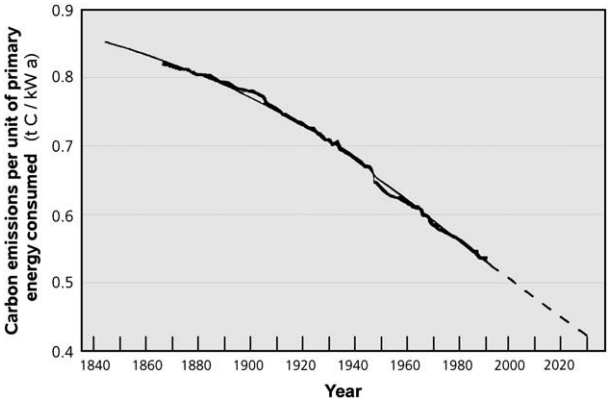



**Fig. 8 – Energy decarbonization Source: [40].**

decreased by c. 35%; the dotted line indicates the switchover to less and less carbon and, since the energy demand grows, more and more hydrogen.

Another insight into the continuous shift from solid via liquid to gaseous energy carriers is provided in Fig. 9. What is seen is the relative percentage of market share over the last century and a half, and a prospective view well into the 21st century. The quantity of solids like wood, hay and coal shrink unremittingly; liquids are about to reach their production maximum after which they will decline, and gases are on a perpetual rise from methane-containing natural gas to prospectively hydrogen. Nothing is said about what the hydrogen is produced from. Of course, in a first phase the production will remain as it has traditionally been, with hydrogen coming from reformed natural gas, from gasification of coal or partial oxidation of heavy crudes, and from electrolysis of water (see ''11. Hydrogen Production''). Stepwise more and more hydrogen will be introduced from $CO_2$-sequestered fossil fuels and from renewable and nuclear electricity, and eventually from high-temperature nuclear heat. And more and more decentralized productions from renewable energies will join the game. Whether centralized or decentralized production will prevail remains to be seen.

Fig. 10 brings the value of hydrogen-containing fuels plotted as a function of the relative atomic hydrogen-to-carbon (H/C) ratio, around 1 for solids, around 2–3 for liquids, and around 3 to infinity for gases. Clearly seen are the areas for solids like coal, for liquids like crude oil, the transportation

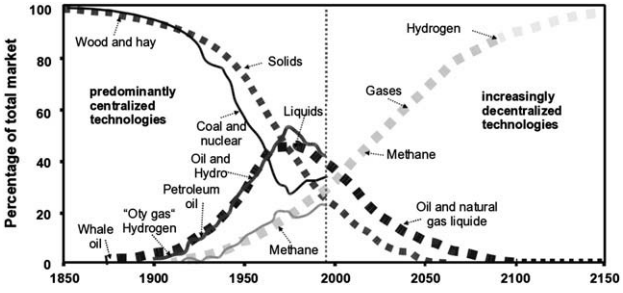



**Fig. 9 – The global energy systems in transition Source: [22].**

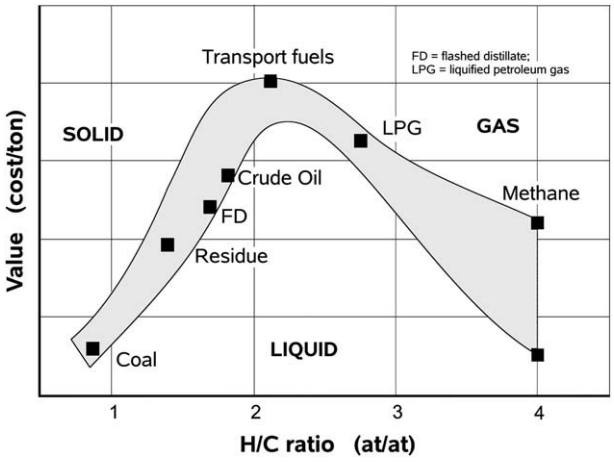



**Fig. 10 – Value of hydrogen fuels Source: [12].**

fuels gasoline and diesel and liquefied petroleum gas (LPG), and finally for gases like natural gas containing methane and, not depicted here, hydrogen. What can be learned?

One can read in the literature that energy hydrogenation adds cost. Yes, but this is not generally true. Not surprisingly, coal's cost is the lowest; the switch to liquids is accompanied by a cost increase since the distillation required for transport fuels is particularly cost intensive, but the cost for gases comes down again. The question is, at which cost level will hydrogen enter the picture? If produced from gasified coal it benefits from coal's relatively low cost; the case is similar if it is reformed from natural gas. Electrolytic hydrogen, however, requires inexpensive electricity which, at least in Europe, is hardly imaginable, unless nuclear electrolytic hydrogen or inexpensive hydrogen from nuclear high-temperature heat becomes available and societally accepted. The additional cost for the liquefaction of hydrogen is only justified by applications which absolutely call for $LH_2$, such as at filling stations and onboard aircraft or spacecraft or ocean-going vessels. The liquefaction energy is around 1 kW h per 3 kW h of hydrogen.

## 6. Technological progress and the world economy

The waves of technological progress and the waves of the world economy are correlated. Novel technologies, inventions and systems optimizations are followed by economic prosperity, or, the other way around, technological decline precipitates economic weakness. In some cases, these waves were given names, such as the steam engine age, the electronic era, the space age. Fig. 11 gives an indication of exemplary waves experienced during the last 250 years: steam engines, coal and iron industries in the 18th century were succeeded by railway technology and cement industries in the early 19th century; the later 19th century was extremely inventive and saw electricity, the automobile with its onboard gasoline or diesel engines; the telephone; plastics, nuclear technologies, aviation and space travel, and electronic technologies were brought to market in the 20th century.

In the late 20th and early 21st centuries something peculiar happened, more or less all novel technologies have something in common: they are of low to no weight! Electronic communication technologies replace weighty letters; miniaturization and micromechanics in electronics dematerialize them; airplanes are produced of low weight carbon fiber plastics instead of weighty metals like aluminum, titanium or steel; high-temperature ceramics replace steel, and in the energy realm technology-driven efficiencies make more energy services available from less heavy weight energy raw materials; solar primary energies have no weight at all, and hydrogen is the smallest element in the periodic table of elements. Truly, dematerialization is under way.

An ''Era-of-Light'' appears to be the appropriate label to characterize the 21st century of energy.

Dematerialization of energy prevails. Renewable energy carriers are of light weight; they lack the first link in their energy conversion chain, they have no weighty operational primary energy raw materials per se; energy efficiency reduces the necessary amount of energy raw materials, it contributes to energy services of light weight; hydrogen has the lowest

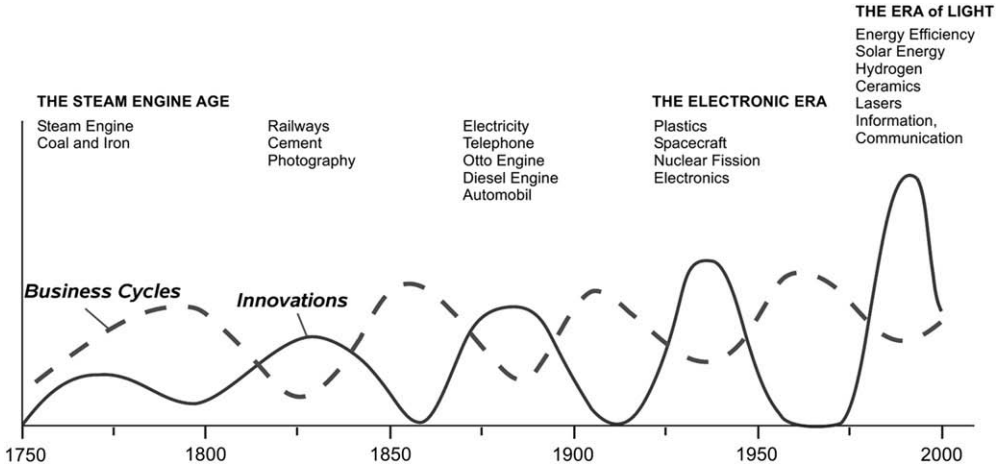



**Fig. 11 – Waves of technological progress and world business cycles Source: VDI-Nachrichten 1998.**

mass of all elements in the universe, renewable hydrogen energy lightens the burden on environment and climate, and, thus, sheds light on the clean and abundant energy scheme of the 21st century. If weighed on the sustainability scale, truly, light weight hydrogen is a heavyweight.

A general observation corresponds with the Era-of-Light: in industrialized nations the percentage of services in their gross national product (GNP) grows relative to that of production; in some countries it has already reached around 80%, with a tendency to increase still further. Services are of much lower weight than industrial products. Lower weight means easier handling, less transport energy, a step towards sustainability.

A word particularly on energy: in general, energy means energy raw materials and conversion technologies. Two trends can be observed, both pointing into the same direction, technology wins, raw material loses: (1) From coal to oil to natural gas and further to electricity and hydrogen, the weight of the primary energy raw material shrinks; for the two secondary energy carriers, electricity and hydrogen, it is or tends towards zero; and (2), the more efficient the conversion technology, the less weighty material is needed to produce more energy services of low to (almost) no weight. Photovoltaic generators and solar collectors on roofs or passive solar heating of buildings take an extreme position, they convert weightless solar irradiance directly into electricity or heat without a detour via weighty coal-, oil-, or gas-supplied steam or gas turbines and electrical generators.

In this context, macroeconomic observations are enlightening. In the early periods of industrialization, nations with indigenous energy raw materials on their own territory were extremely successful, coal and steel were stabile fundaments of their welfare economies. On the other hand, nations without indigenous natural resources did less well, they had to rely on the ingenuity and skill of their scientists, engineers, and craftsmen. Now, the picture has radically changed. Energy raw material poor but technology rich nations have developed into the wealthiest nations of the world (such as Switzerland, Japan, and in Germany the southerly Federal States of Bavaria and Baden-Wuerttemberg), and the others still struggle to rid themselves of what was once considered beneficial natural wealth: rust belts around the world bear witness! The consequence again and again: »Technologies compete, not fuels«! [52]

Accordingly, two recommendations to parliaments and industry, both in Europe, asked for political action: (1) Already in the early 1990s, the German Bundestag's Enquête Commission ''Protection of the Earth's Atmosphere'' decided unanimously on both sides of the aisle to recommend to the Federal Parliament and Government that the country be run at an energy efficiency of 60% instead of today's 34% (2006). The commission was convinced that its recommendation was not a question of technologies—the technologies were there or would be available—but one of economic viability and political will, and time. And (2), a few years later, the Federal Institutes of Technology in Zurich and Lausanne, Switzerland, recommended the development of a 2000 watt society. What does that mean? Nothing less than that 2000 W h per hour and capita [watt-hours/hour·capita = watt/cap], not more, should be the average energy demand of each inhabitant of Switzerland (including trade and industry). Time, industrial preparedness, and political will are the deciding conditions, technology is and will be available. The situation in other countries is more complicated: the individual energy demand spreads from near zero for the poorest developing countries to 11 kW/cap for North America or particularly energy rich countries that supply themselves and the world; the world average is around 2 kW/cap. The incentive for much higher energy efficiencies is the more marked the less indigenous energy the country in question can rely on: efficiency technologies are tantamount to energy, they are ''energy''! The world average of 2 kW/cap should be approximated from both sides: the developing world coming from the bottom upwards, and the industrialized countries from their much higher values downwards. Incidentally, efficiency technologies are environmentally and climatically cleaner than the energy they convert. Increasingly stringent environmental and climate change mitigation obligations will force an approach towards the world energy intensity average!

## 7. Hydrogen energy and time

Novel energy technologies need time, usually much more than impatience is inclined to tolerate. Many decades, in cases up to half centuries or even centuries are the typical time requirements until their irrevocable market presence. Fig. 12 brings two examples, heat engines and lamps, and their historical development. What is seen?

Thomas Savery, Thomas Newcomen and James Watt, all three in Britain, published their steam engine development results in the 18th century. Th. Savery's patent on his engine is even dated 1698; he named it ''The Miner's Friend'' because steam engines in those days were helping to pump unwanted water out of underground coal mines. The early engines had meager efficiencies, no more than a few percent of the coal's energy content were converted to mechanical energy. Today, around three centuries later, modern steam and gas turbine combined cycles asymptotically approach and even surpass 60% electric (=exergetic) efficiency, and the final figure is not yet reached. But let's realize that it took three centuries for this development, evolving via many dissimilar designs for steam engines, steam turbines, and later internal combustion engines and gas turbines—three centuries!

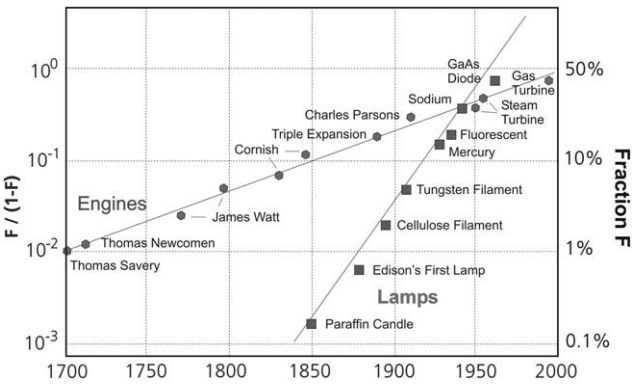



**Fig. 12 – Efficiency improvement of engines and lamps Source: H. Ausubel and C. Marchetti.**

The figure also shows the development of lamps. Over one century and a half ago light came from wax candles with an efficacy of about 0.1%. Edison's first lamp achieved a little less than 1%, and today's gallium-arsenide diodes achieve some 50%. But again, 150 years had to pass!

Could it have been accomplished any quicker? Could the development have been accelerated? Most probably not! Fig. 12 attempts an explanation: for centuries, the development lines for both heat engines and lamps were straight lines in half-logarithmic plotting. It so seems that humans would have had little influence on a potential acceleration. Examples: Otto Hahn split into two the nucleus of the uranium atom in 1938 in Berlin, in the 1940s Enrico Fermi erected the first nuclear reactor underneath the terraces of a stadium in Chicago, and now, 70 years after the first nuclear reaction a system change to hydrogen fueled up-and-coming chemo-electric fuel cell conversion will join the market, a radically different design than what is plotted in Fig. 12. The fuel cell is not a Carnotian heat engine; although it simultaneously provides electricity and heat, it is electrically (=exergetically) more efficient than the Carnotian heat engine-generator combination, and it comes in typically very small-to-small capacities (watts to a few megawatts). Its future development may get a steeper gradient than that of the heat engines, although it has also been known for 170 years already. The aforementioned straight lines for lamps and engines are sigmoidal in character and are thus significant for any other converter under consideration.

Generally, the market approach of a product is regularly depicted by a S-shaped curve. It begins with a slow introduction, turns at a certain point in an ''explosion'' into market dominance, and then fades out in saturation. Between start and end many decades may pass by. — Two practical examples as illustrations: gas turbines and nuclear energy. Gas turbines first: in 1791 a first English patent was granted. Much later, Hans Holzwarth (1877–1953) devoted much of his time to the development of his turbine, with little success. In the 1930/40s Pabst von Ohain's research led to practical gas turbines operated as jet engines aboard the German war planes Heinkel He 178 and Messerschmitt Me 262. And now, around one century and a half after the mentioned English patent, gas turbines on the ground together with steam turbines in combined cycles generate electricity under commercial conditions with convincing electrical efficiencies around 60%. — And now to nuclear: In the 70 years since the first nuclear reaction, 439 reactors were built worldwide with a capacity of some 393 GW; 32 reactors with 28 GW are being constructed or planned (2007), and the end is not yet visible.

A conjecture may help in understanding why novel energy technologies need so much time: Of course, any novel technology has research and development problems in itself: materials and tools are not at hand; algorithms have to be specifically developed; the origin of failures along the development road must be understood before they can be tackled. Failures and negative research results are positive results too, which is regularly misunderstood by individuals outside the research area. Financial setbacks need to be overcome again and again, whenever other items in the research labs are felt to deserve higher priority. Many other parameters have to be accommodated before a research and development result can finally be presented. But, let us make no mistake: in general, up to this point only some 10% of the entire road from initial vision to a stabile market share have been traveled, and it is not realistic to expect much more. What then comes is the market with its own distinct parameters of business activities, marketing, economic viability, micro- and macro-economics, international trade, codes and standards, etc. Consequently, the ''classical'' novel technology process consumes time, much time!

In the meantime, the ''old'' technology isn't sitting there waiting for its death blow! Its development potential is not zero. The technology is well known, its pros and cons have been experienced, in some cases over very long times; availability, cost, safety, and supply security are givens. Generations of engineers have been educated in the old technologies; they are familiar with their advantages, and conscious of their disadvantages. So, why not develop further what is at hand, instead of taking unknown and insecure routes? Regularly, the novel technology forces the old one towards new frontiers! The competition between the two is open (and in cases fascinating!), sometimes the old technology ''wins,'' sometimes the novel one. Again, both need rather long periods of time.

Let us give two examples from the transportation sector: Vehicles need to be adapted to the environmental and climatic challenges, operational pollutants have to be reduced, and greenhouse gas emissions need to be eliminated. What could be more obvious than switching over from the hydrocarbon fuels now in use to environmentally and climatically clean hydrogen fuel and replacing the more than one hundred years old internal combustion engine (ICE) with a modern fuel cell?! But, no surprise, the ICE fiercely resists; it defends its survival by completely meeting the strict environmental regulatory codes EU1 to 5 (EU6 soon) to the point of measurability limit. It became more efficient and, as a consequence, it emits fewer greenhouse gases. The EU's call for an average of 120 g of emitted $CO_2$ per kilometer driven is not out of reach. — Or another example: the modern truck (25 tons) is already achieving 0.8 l/100 tons km and 21 g $CO_2$/tons km. (For comparison, the middle class passenger vehicle with an imposed load of 500 kg is at 17 l/100 tons km and 403 g $CO_2$/100 tons km). And, what is perhaps the most convincing argument: the unit price of the marketed ICE is still only some 10 €/kW. The fuel cell is miles away from that price tag, it is working hard to catch up, but, again, it needs time.

As an example for ''energy needs time'', Fig. 13 gives a convincing picture of the two hundred years long step-by-step development of land transport. It started in the late 18th century when carts, horses and their »fuel« hay or oats, were stepwise replaced by steam, later diesel locomotives and their fuels wood, coal, and later diesel oil. About every 70 years a novel technology entered the transport market. In the late 19th and then in the 20th century individual and mass transport of passengers and goods on land and in the air took over most of the market. Again, ''technologies compete, not fuels''. The arrival of a new transport technology always triggered the market change; the availability of specific fuel followed suit.

In all cases certain expectations were connected with the novel technology: locomotives allowed for higher speeds and

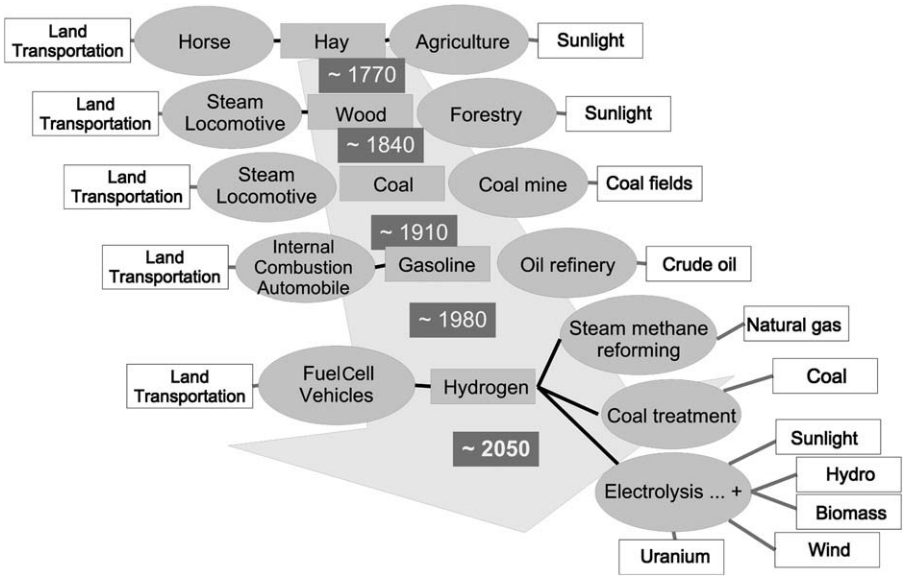



**Fig. 13 – Land transport Source: [52], with additions from [69,70–72,74–79].**

longer distances than horse drawn carts; diesel locomotives were cleaner than coal-fired steam locomotives and offered easier handling of the fuel; air transport made it possible to travel around the globe in reasonable times; and the passenger vehicle stands for individuality. Now, since strict and challenging environmental and climatic cleanliness criteria have to be met, it seems unreasonable to expect the trend to break. Consequently, what follows now? The answer is the fuel cell and a whole range of renewable energy and hydrogen technologies. Supposedly overstated, ''no-energy energy supply'' is the creed (no-energy means principally no operational primary energy raw materials for solar and solar-hydrogen energy technologies). Primary energy raw materials are on the losers' side, and, once again, technologies are on the winners'. Evidently, the beginnings of the up-and-coming technologies were 10–20 years ago, and they will occupy the next 70 years, ''until something better comes along'' (magnetic levitation? evacuated tubes? submersible ocean travel? … and who knows what all else?).

Eventually, innovations are pushed by ''early starters'' (regardless of whether they finally become the market winners or not). Do we see circumstances anywhere benefiting early hydrogen technology starters? Yes, we do: there are countries which, within their traditional industrial development scheme, have accumulated certain preferred hydrogen technology skills, manufacturing capabilities or operation experience. For instance Japan and the USA: they seem to be well prepared to become (and in some fields already are) active in the large and versatile field of hydrogen-supported portable electronics. Or, space faring nations around the world have gathered experience for now more than half a century in reforming, liquefying, storing, transporting, handling and combusting large amounts of hydrogen (and, of course, oxygen), both gaseous and liquefied. And these days, there is no major automobile manufacturer in the world not engaged in the research and development of onboard hydrogen and its utilization in low temperature mobile fuel cells or adapted ICEs. Billions are involved, and the times have long passed when cynics quipped that Big Auto's hydrogen and fuel cell development was being financed out of petty cash.

In addition, heavy industry centers of the coal industry, major oil and gas producers, gas traders, and chemical companies have been well aware of hydrogen and its technologies for a very long time. Traditional hydrogen commodity users are considered well prepared to play a role also in the hydrogen energy economy (for details see Annex 2). As a result, there is no need for hydrogen energy to start from scratch; there are lots of active ''hydrogen islands'': connecting them nationwide is the task! What we face is not too dissimilar from what happened at the turn of the 19th to the 20th century when the electricity market began to evolve. Even after a complete century it has by far not yet reached saturation. On the contrary, for (more than) a century we had one secondary energy carrier—electricity—now we are getting two—electricity and hydrogen.

## 8. Energy efficiency, no: It's exergy efficiency!

The attentive political observer takes note that elevated efficiencies are politically beyond all dispute as measures against anthropogenic climate change. The EU Ministerial Council's formula (2007) reads: ''$4 \times 20$'' or 20% less primary energy, a 20% share of renewable energies, and 20% less greenhouse gas (GHG) emissions, each to be achieved by 2020. The G8 summit in Heiligendamm, Germany (2007), even discussed halving greenhouse gas emissions by 2050 (a decision confirmed by the G8 summit in Hokkaido, Japan, in 2008), i.e., in the extremely short time of only some 40 years from now! And Germany envisaged the ambitious goal (in reach?) of raising its national energy efficiency increase from today's c. 1% or a little more to 3% annually.

Here is not the place to appraise whether these decisions are technologically and economically justified, whether it is reasonable to assume that they can be realized, and, the most important touchstone of all, whether they will be able to sufficiently restrict the anthropogenic greenhouse gas effect in its consequences for humans, their artifacts, fauna and flora (see ''4. Anthropogenic Climate Change and Hydrogen Energy'').

It is trivial to state that kilowatt-hours not required thanks to more effective conservative energy use as well as elevated efficiencies are environmentally and climatically positively relevant, and that operationally carbon-free renewable and nuclear energies do not contribute to the greenhouse gas effect at all.

Not at all trivial, however, is—that is the central point of this paragraph—knowing which efficiency is meant, energy efficiency or exergy efficiency. Exergo-thermodynamics tell us that each energy conversion step along the complete energy conversion chain, link by link from production via storage, transport, dissemination and finally utilization of energy services, splits up energy into exergy and anergy: energy = exergy + anergy. Obtaining more exergy from energy is the real goal of each energy conversion, because more exergy means more available technical work. This is the ultimate energy challenge and it can be compared with J. W. Gibbs' free energy available to do external work (Josiah Willard Gibbs, 1839–1903). Earlier American literature speaks of ''energy availability'' meaning available technical work. Exergy can be converted into every other form of energy, anergy cannot. What practical exergy investigators urgently need is to admit that they cannot »unlearn« (uninvent, uninnovate) and to recall the physics of exergo-thermodynamics which was (again) published in the 1960s (e.g., Figs. 14 and 15) and which, blameworthy as it is, have been almost forgotten in the meantime. Since exergy increments within the established prevalent Carnotian system tend asymptotically towards their final maximum, exergy efficiency engineering is increasingly becoming a matter of system change to combined cycles, from electricity only, or heat only, or chemical product only, to simultaneously produced electricity and heat, or electricity and hydrogen, or electricity and chemical commodity, etc. Farsightedness in thermodynamics, or, more precise, in exergo-thermodynamics is the real goal, not tackling day-to-day efficiency deficits in the applications based on commonly utilized Carnotian energy thermodynamics!

As will be seen in the following paragraphs, hydrogen energy is an irreplaceable mosaic stone in this picture. Hydrogen helps to bring forward energy conversion systems which avoid conversional irreversibilities and, thus, avoid exergy destruction and exergy losses, or unused exergy and the according build-up of huge amounts of anergy of no anthropogenic usage! Hydrogen helps energy-systems-of-change to approach the maximum of available technical work being extracted from energy: this is the superior parameter the layout of each energy installation ought to regard—it ought to, but in too many cases it doesn't, so far.

The situation: after more than 200 years of national energy the energy efficiency of the industrialized country Germany, to take that example, is some 34% (2006), and that of the world

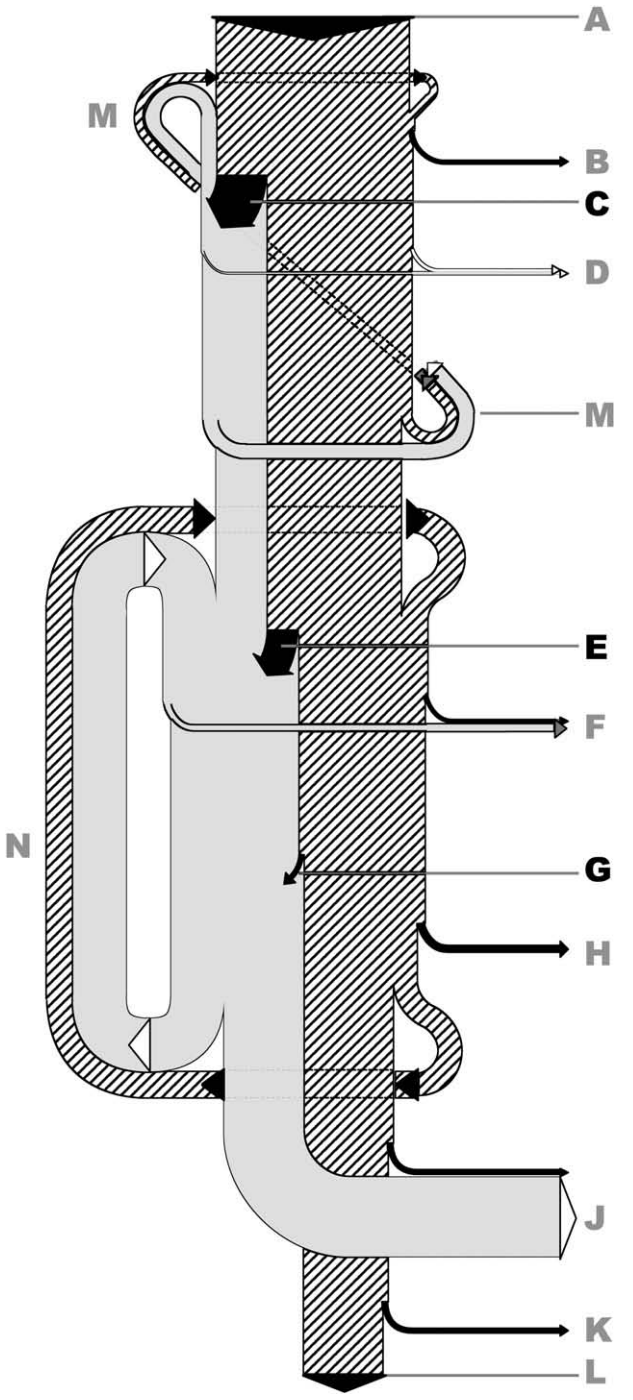



**Fig. 14 – Exergy/anergy for a steam power plant Source: [47] A, Exergy in (100%); B, Unburnt; C Irreversible Combustion; D Radiation; E Irreversible Heat Transfer I; F Stack; G Irreversible Steam Flow; H Mechanical, Electrical, Magnetical Loss; J Condenser; K In-house Use; L Electricity = Exergy out (40%); M Air Preheat; N Water Preheat.**

not much more than 10%. Germany has to introduce 3 kW h of primary energy into the national energy economy in order to provide 1 kW h of energy services after having completed the run through the entire national energy conversion chain, and, bitter to say, for the world the ratio is 10: 1! Truly, the

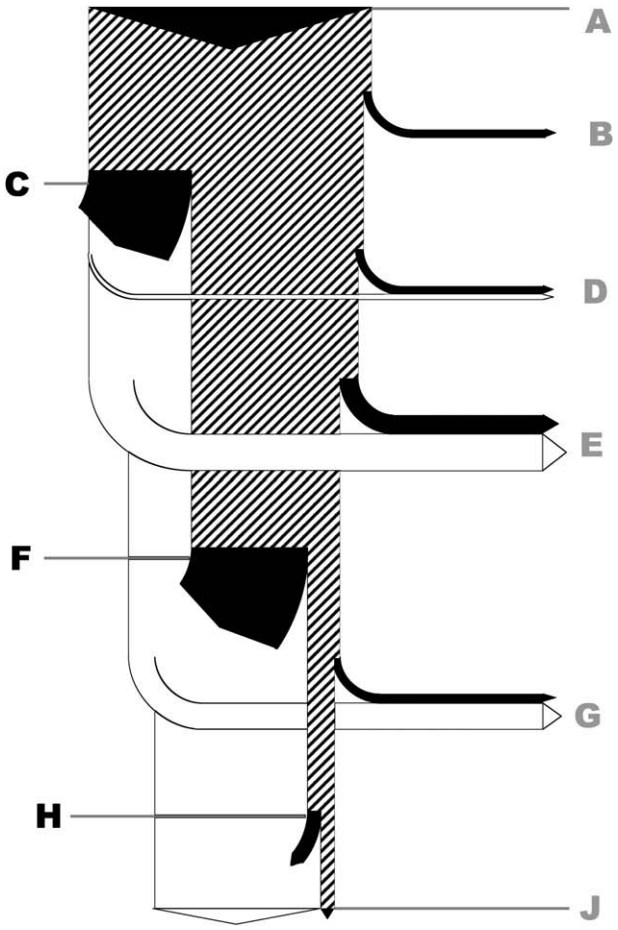



**Fig. 15 – Exergy/anergy for a coal-fired central heating system Source: [47]; A Exergy: in (100%); B Unburnt; C Irreversible Combustion; D Radiation; E Stack; F Irreversible Heat Transfer I; G Distribution; H Irreversible Heat Transfer II; J Heating Energy, Exergy: out (63.9%).**

industrialized country's energy efficiency is really not too impressive at all, but that of the world is devastating, energetically, economically, and ecologically. And this is only one side of the coin. The other side, even more devastating, is that Germany's exergy efficiency is c. 15%, while that of the world amounts to only a few percent.

In reality the world's energy system with its deplorably meager exergy efficiency is an anergy system garnished with a small amount of exergy. The system inherently contains large irreversibilities (indicated in Fig. 14 (C,E,G) and Fig. 15 (C,F,H) by the large black arrows on the left) and thus produces enormous amounts of heat of no worth to users, conveyed to the ambience and radiated into space. Potential users are elsewhere and the temperature of their heat requirement is a different one. The state-of-the-art energy system is not sustainable for many reasons. Here is one relevant to our exergy argumentation: the energy raw materials in use are finite and their consumption lacks negentropy to compensate for the inherent entropy increase. The case is otherwise with a renewable solar energy system, whose entropy rise is immediately compensated by the negentropy flow from the sun (as long as it shines). Solar-hydrogen benefits from these physical facts.

What does all this practically mean? We said that the energy system of the world produces much too much heat of the false temperature at the wrong location (=anergy). However admirable the envisaged electrical efficiencies of modern hard coal stations are, arriving at or even slightly surpassing 50% (=exergy efficiency), thermal power stations still irreversibly provide combustion losses, heat transfer losses, and energy flow losses throughout the system, predominantly because of the installation's exergy destruction (Fig. 14), and this adds up to huge amounts of anergetic heat of inappropriate temperatures at locations where no user buys them. Or another example: the boiler in a central heating system of a residential or commercial building has a similar problem. It generates flame temperatures of up to 1000 °C, although the room radiators require only 60–70 °C. The energetic efficiency of converting the chemical energy of light oil or natural gas fuel into heat is superb, it reaches almost 100%. The exergetic efficiency, however, of heat delivery of the »right« temperature to the room heating radiators is miserable, only a little more than 10% at most, again because of irreversibilities in combustion, in heat transfer to the heat exchanger, and because of the energy throughput through the entire system, (see arrows on the left in Fig. 15). — And there is a similar heat problem in the internal combustion engine of the automobile: only 20% (30% at the utmost) of the energy content of gasoline or diesel goes into traction (=exergy); the much bigger part is discharged into the environment via irreversible heat exchange in the cooler or irreversible tail pipe exhaust (=anergy). — Altogether, the energy system in place is in fact an anergy system which provides, quasi as a by-product, a little exergy, too, it's absolutely sad to have to say that, after two centuries and a half of energy engineering!

Certainly, talk is cheap; it's easy for the reviewer to lament the miserable exergetic condition of energy installations in the world without trying to look for ways out of the dilemma: First of all, it is astounding how little the laws of exergothermodynamics, known since Gibbs, have so far entered legislative thinking. The laws of parliaments and the laws of nature have grown increasingly divergent, and it cannot be expected that the laws of nature will yield [38]. Efficiency increase, i.e., more energy services from less primary energy, remains part of the system. However, it is not recognized that exergy efficiency increases have a huge, though dormant virtual potential which requires a system change to non-heat-engine-related systems! Exergizing the energy system asks for shifting the baseline. ''Virtual'' means that the potentials are real though hidden, and so far untapped. Through exergy thinking and acting they will be tapped.

Let us try to make this clear using the already mentioned three examples (there are many more in all energy sectors: industry, transport, buildings, trade, …). The first example: we spoke about the admirable elevated electrical efficiencies of around 50% of modern coal-fired power stations, verified through asymptotically ever higher temperatures (from a high-temperature materials technology point of view more and more difficult to obtain); these efficiencies remain within the applied system. But with an electrical efficiency of 50% still half of the energy content of the coal is not converted into technical work (=exergy). A system change towards much higher exergy efficiencies, such as the combined production of

hydrogen and electricity via air separation, coal gasification, $CO_2$ and hydrogen separation, and combined cycle power generation, all more or less marketed technologies, is presented in ''11. Hydrogen Production''.

The second example: the already mentioned boiler of the central heating system of a building is energetically excellent, almost 100% of the energy content of natural gas or light oil fuel is converted to heat, although to heat of a temperature for which no user exists. Exergetically, however, the boiler is miserable, because it is exergo-thermodynamically simply absurd to generate flame temperatures of up to 1000 °C with the objective of supplying room radiator temperatures of some 60–70 °C. If a hydrogen-fueled low temperature (<100 °C) or middle temperature (≤200 °C) fuel cell is installed in the boiler's stead, it firstly generates electricity (=pure exergy) from 35 to 40% of the fuel's energy, with the remaining heat still sufficing to warm the building over most of the year. A thought experiment says if the present 15 million boilers in Germany were replaced by fuel cells of, say, 5 kW (electric) each, an IT-controlled virtual »distributed power station« of 75,000 MW would develop. This comes near the present centrally-structured national installations of some 100,000 MW; it approaches an exergetization par excellence of the country's central heating system! (Thought experiments seldom become real, although there is often a certain truth in them. Here, the »truth« says that a distributed competitor of significantly higher exergy efficiencies will have emerged to challenge the central electricity utility system in place: welcome competition which for the time being lies fallow!) All the aforementioned is not inevitable, but it indicates where we ought to be heading for.

The third example deals with the internal combustion engine in autos. Here, it is not denied that there are still exergo-thermodynamic potentials within the conventional system and that they are being stepwise activated by continuous further development. The Otto and Diesel engines, as inventions of the late 19th century both more than one hundred years old, are still not yet fully mature; there is still potential, particularly when the entire auto system is taken into account. However, what is of interest here is the system changes towards exergetization: renewable hydrogen or hydrogen from $CO_2$-sequestered fossil fuels, from nuclear electricity or, better, nuclear high-temperature heat fed into a hydrogen-optimized internal combustion engine (ICE) or a low temperature fuel cell. Both are environmentally clean, and without $CO_2$ emissions along the complete life cycle (well-to-wheel) contributing to the greenhouse effect, they are climatically clean, too. For the engineer the development »race« between the two is highly exciting, and the outcome is not decided yet. To make a long story short, despite all the past development aims for steam engines, Stirlings, flywheels, gas turbines, Wankels and other prime movers aboard automobiles, the fuel cell is the first real alternative in the history of engine technology to truly be taken seriously. Not being a Carnotian heat engine, it is an exergetically highly efficient, clean, quiet, compact and non-vibrating competitor to the ICE. However, the ICE is not sitting there, waiting to be finished off. Although it is more than one hundred years old, it meets the extremely strict legislated codes EU1 to 5 (6) and is thus by definition environmentally clean, and its potential to reduce $CO_2$ emissions is not zero. Perhaps the most convincing argument vis-à-vis the fuel cell is that the ICE is in around one billion copies in stationary and mobile operations, being reproduced in 100 million copies p.a., and marketed for some 10 €/kW! From this figure the fuel cell is still miles away, but it is picking up momentum and trying hard to catch up!

Summing up: higher energy efficiencies within the operational system in place are appreciated. The real break through, however, to economic, environmental and climatic responsibility asks for higher exergy efficiencies and, thus, a system change to combined cycles, which seems expressly suitable for indigenously energy poor, though technology rich industrialized nations. They enjoy an almost inexhaustible and, by the way, renewable »energy« potential in the scientific knowledge of their scientists and the skills of their engineers and craftsmen. Energy technology science and skills are »energy«! Wise energy policy prior to active technology politics provides an entry into the technology-driven hydrogen energy economy and the accordingly necessary system change to the small-to-medium size energy converters fuel cells of capacities of less than watts to a few megawatts at the back end of national conversion chains. The center of gravity within national chains moves towards their back end. The conventional wisdom of national energy policies is to ensure at economically viable cost the delivery of sufficient amounts of primary energy raw material, which is then converted in the national conversion chain with meager exergy efficiencies stepwise into secondary energies, end energies and so forth, finally to energy services. After the system change to exergetically highly efficient combined cycles, secondary energies become more important than primary energies. Thinking and acting in primary energy raw materials was 19th and 20th century; thinking and acting in exergy-efficient energy conversion technologies is 21st century!

An interesting though abstract scheme pointing in the right direction is energy cascading, i.e., utilizing heat or cold in steps from higher to lower or from lowest to higher temperatures, respectively. Cascading of heat or cold helps to maximize exergy and minimize anergy. The present industrial infrastructure, however, is far from consistent cascading, to put it mildly. Barriers are the geographical dislocation of consecutive users, which does not favor neighborhood industrial structures, dissimilar market requirements, and others. The aforementioned switch to combined cycles producing electricity and hydrogen are cascades of practical application (detailed information on cascading is found in ''10. Hydrogen Energy and its Technologies along the Entire Conversion Chain'').

The dispassionate energy economist may now object that such a system change needs decades, if not half centuries to centuries, and trillions worth of investments. Certainly, it is impossible in the twinkling of an eye to systematically convert the energy system in place into something else and pay for it with petty cash. In addition, the longevity of just installed (and still to be installed) investments worth billions (power stations, refineries, pipeline grids, tanker fleets and the like) are also many decades. It is irrational to expect their dismantling prior to the end of their economic life. But, climate change doesn't give way to economic considerations. The expectation of being able to reduce the anthropogenic

greenhouse effect to a tolerable level simply by continuing developing, perhaps at a slightly accelerated pace, today's energy system is deceptive. The 2 °C figure of policy makers as the anthropogenic atmospheric temperature increase considered »allowable« is arbitrary; and even its realization is not at hand. At the latest after future gigantic hurricanes and floods à la ''Katrina'', at the latest after the melting of land-based Greenland and Antarctic ice and the successive rise in ocean level and flooding of the earth's marshlands where one billion people live, at the latest after arable land which used to feed entire populations has turned into dried-out deserts, all this followed by streams of millions of climate refugees washed ashore where the wealthy »highlanders« live, then at the latest will the call for a system change get louder. To answer the call of being exergo-thermodynamically well-equipped, not more, not less, is the objective of this argumentation.

Human imagination is rather finite; its temporal intrusion into the future is only a few years, if that. Regularly, foresightedness is modified by unforeseen surprises, because it is simply an extension of the present. Examples for such surprises are wars, tanker shipwrecks, the intended and fiercely publicly opposed disposal of an oil platform in the North Sea, diplomatically irritating ''playing'' with the throughput throttle of an international natural gas pipeline, nuclear reactor accidents, or simply presidential remarks from a major oil exporting country. The almost immediate consequences are jumps in the price of oil, followed by the other fuels in the global energy trade system, price jumps which hit the nearly unprotected energy buying countries with their extremely high import quota and rather small exergy efficiencies (energy-short Germany's national import quota is 77% (2007), its exergy efficiency a little more than 15 %!).

An effective barrier against such surprises is a system change to an exergy-efficient hydrogen energy supported energy system. One does not have to be a prophet to say that whatever will come, exergy is the insurmountable maximum of technical work which can be made available from energy! Its limit is set by exergo-thermodynamics. So far, no country of the world has ever touched this limit. The goal is within reach, but it's a long way to Tipperary. Anthropogenic climate change calls for taking this way and seeing it through! Hydrogen energy helps; it crosses the border and enables this system change. Hydrogen exergizes!

## 9. Hydrogen, electricity – competitors, partners?

Electricity and hydrogen have in common that they are secondary energies generated from any primary energy (raw material), none excluded, fossil, nuclear, and renewable. Once generated, they are environmentally and climatically clean along the entire length of their respective energy conversion chains. Both electricity and hydrogen are grid delivered (with minor exceptions); they are interchangeable via electrolysis and fuel cell. Both are operational worldwide, although regionally in absolutely dissimilar capacities.

And their peculiarities? Electricity can store and transport information, hydrogen cannot. Hydrogen stores and transports energy; electricity transports energy but does not store it (in large quantities). For long (i.e., intercontinental) transport routes hydrogen has advantages. The electricity sector is part of the established energy economy. Hydrogen, however, follows two pathways: one where it has been in use materially in the hydrogen economy almost since its discovery in the 18th century. To date, it is produced worldwide as a commodity to an amount of some 50 million tons p.a., utilized in methanol or ammonia syntheses, for fat hardening in the food industry, or as a cleansing agent in glass or electronics manufacturing. And, along the other pathway it serves as an energy carrier in the up-and-coming hydrogen energy economy which started with the advent of the space launch business after World War II. Essentially, the hydrogen energy economy deals with the introduction of the—after electricity—now second major secondary energy carrier hydrogen, and its conversion technologies. Hydrogen-fueled fuel cells can replace batteries in portable electronic equipment such as television cameras, laptops, and cellular phones; fuel cells are being installed in distributed stationary electricity and heat supply systems in capacities of kilowatts to megawatts, and they are operated in transport vehicles on earth, at sea, in the air, and in space. It is never a question of the energy carrier alone, hydrogen or hydrogen reformate. On the contrary, environmentally and climatically clean hydrogen energy technologies along all the links of the energy conversion chain are of overarching importance. Of course, technologies are not energies, but they compare well with ''energies''. Efficient energy technologies provide more energy services from less primary energy (raw materials). Efficiency gains are »energies«! Especially for energy poor, but technology rich countries, efficiency gains come close to indigenous energy!

A trend is clearly visible: increasingly, the world is moving from national energies to global energies, and energy technologies serve as their opening valves. $CO_2$ capture, sequestration and storage technologies bring hydrogen producing clean fossil fuels to life, and hydrogen-supported fuel cell technology activates dormant virtual distributed power. Both technologies are key for the hydrogen energy economy which, thus, has the chance of becoming the linchpin of 21st century's world energy.

### 9.1. *Mechanization, electrification, hydrogenation*

The electricity industry began more than 100 years ago with Siemens' electrical generator and Edison's light bulb. Electricity is a success story which, truly, is not yet at its end. In industrialized regions, electricity is almost ubiquitous, fitting in locally and temporally, environmentally and climatically clean, and affordable—more or less.

In the late 18th century James Watt's steam engine initiated the mechanization of industry. A good century later, electrification came into use; it largely replaced mechanization and permeated into almost all energy utilization sectors such as production, households, communication, and railways. Literally and seriously, ''electricity is readily available at the socket'', really never to be worried about! However, there are weaknesses: blackouts are suffered under, seldom, but once in a while, and many a developing nation's electricity

supply with its frequent black outs is as good as almost inexistent. Further, although battery development is in full swing and progress has been achieved, it is still not easy to operate an automobile over long distances with electricity, much less—if ever—an airplane or a spacecraft.

The question is, can hydrogen be of help wherever it has advantages relative to electricity, wherever electricity is useless because it cannot be stored in large amounts, or wherever electricity and hydrogen together can offer solutions which are inexistent for either one alone? Is it true that, after mechanization in the late 18th and then in the 19th century, after electrification in the late 19th and then in the 20th century, we are now at the start of the 21st century on the verge of hydrogenation of the anthropogenic energy system? Answering this question is not too difficult, because we see clear signals: Historically, with the switchover of the anthropogenic energy centuries from high carbon via low carbon to no carbon, i.e., from coal via oil and natural gas to hydrogen, the atomic hydrogen/carbon ratios for coal: oil: natural gas: hydrogen have become $\leq$1: 2: 4: $\infty$. Decarbonization and hydrogenation are continuously increasing, and, since the atomic masses of hydrogen and carbon are 1 and 12, respectively, dematerialization of energy is increasing, too. Already today, two-thirds of the fossil fuel atoms burnt are hydrogen atoms; the trend continues.

What is the status of the hydrogen energy economy? There are still only a few industrial sectors where hydrogen serves energetically; all the other areas use it as a commodity. Energetic use includes the space business, which would even be inexistent without access to the highly energetic recombination of hydrogen and oxygen in the power plants of space launchers; submersibles, where low temperature high efficiency hydrogen/oxygen fuel cells guarantee extended underwater travel and low to zero detectability because the water exhaust is contourless after onboard condensation and possible subsequent utilization as drinking water or for sanitary purposes for the seamen; refineries for the production of reformulated hydrogenized gasoline and desulfurization of diesel; and in cooling systems for large electrical generators.

Fuel cells as replacements for short life batteries in portable electronics such as laptops, camcorders and cellular phones, energized with the help of hydrogen or hydrogen rich methanol cartridges; natural gas or hydrogen-supplied fuel cells in distributed electricity and heat supply or as replacements for boilers in central heating systems in residential homes and office buildings; fuel cells as APUs (auxiliary power units) in vehicles or airplanes; hydrogen and internal combustion engines or fuel cells onboard busses or autos; finally, liquefied cryogenic hydrogen instead of kerosene in aviation, one and all, these areas are still in the phase of research and development, or at most in their demonstration phase. The technologically driven hydrogen energy economy—no doubt—is at its beginning and probably has to face decades yet before mass market readiness.

### 9.2. *Domains, partners, competitors*

Let us now come back to our question posed at the beginning: Electricity, Hydrogen – Competitors, Partners? We distinguish three realms where hydrogen and electricity:

(a) have their respective domains,
(b) are partners,
(c) compete with each other.

To (a) belong aircraft and spacecraft engines; they are/will become undisputedly hydrogen domains, simply because you cannot fly or operate an air- or spacecraft with electricity, the necessary battery sets would be much, much too heavy and bulky (exceptions: thermionic converters or nuclear reactors for deep space missions). Electricity's domain, on the other hand, lies in the communication sector, in providing light, and in all areas of production electricity is indispensable.

Under (b) we find all the chemo-electric energy converters, the electrolyzers and the fuel cells which convert hydrogen efficiently environmentally and climatically clean into heat and electricity in combined heat and power (CHP) applications in industry, in households, and office buildings; here hydrogen and fuel cells are an unbeatable combination!

Finally, under (c) we essentially find mobility tasks which can be performed with either electricity or hydrogen: rail transport in Europe is powered by grid delivered electricity; for continental distances, however, as for instance in Canada or in Russia, it may be questionable whether railway electrification through electrolytic hydrogen-powered fuel cells will not become the economically more viable solution, replacing the traditional overhead electricity contact wire which, for thousands of kilometers, might be the more costly and irksome investment (this idea is D. S. Scott's).

Earlier, the situation in the individual transport realm wasn't as clear as it is today. As long as there was hope to see on the roads efficient, battery supported, low weight marketable electric vehicles in large numbers, it was not too easy for the hydrogen vehicle to make its point. Now, after many decades of development of long-range auto batteries in the drive train with only rather meager success, the route for hydrogen surface transport in busses, in limousines, later in trucks and lorries is wide open[1]. However, the decision is still due as to whether there will be a fuel cell or a hydrogen-adapted internal combustion engine under the hood, because the »novel« fuel cell has not yet won, and the »old« combustion engine still has potential, consequently it is not forced to give up. The »race« between the two is highly exciting for the thermodynamicist and the engineer, but it is not decided yet. The fuel cell needs convincing cost, performance, cleanness, and efficiency advantages in order to compete successfully with the more than one hundred years of solid experience of the reliable reciprocating piston engine. Cost is the harshest criterion.

One particular partnership development of electricity and hydrogen is worth pointing out: the stationary fuel cell in CHP installations or in the central heating systems of buildings is small and compact with capacities of four orders of magnitude from kilowatts to a few megawatts. As a decentralized energy converter it tri-generates locally and simultaneously

[1] The ongoing electrification of individual city transport of some 50 or 60 km range with the help of newly developed lithium-ion batteries is considered not a contradiction. On the contrary, the battery powered vehicle is an electric vehicle and, thus, in a certain aspect a harbinger of the up-and-coming implementation of the long-range electrical vehicle powered by hydrogen.

electricity and heat and/or cold; consequently, the nation's electrical grid losses are nil (they for the time being sum up to c. 4 % in Germany; in other world regions they are sometimes significantly higher!). The distributed fuel cell park with potentially millions of installed fuel cells compares well with a virtual IT-controlled power station whose capacity easily matches the capacity of the central installations (e.g., for Germany c. 100,000 MW). Competition between the traditional national energy conversion chain's front-end electricity generation and novel fuel cell supported back-end generation is foreseen—and welcome. It will be interesting to see which kilowatt-hour of either end of the chain will become the less costly, which the environmentally and climatically cleaner, and which the more reliable!

### 9.3. *Exergetization*

If it comes true that the conversion chain's back end of a national energy system becomes a convincing power generator and, thus, a mighty competitor to the established traditional power plant park at the chain's front end, something thermodynamically very important will have occurred: the fuel cells supplied by hydrogen or hydrogen reformate will have exergized the energy system! Exergizing technology examples were given in »5 Energy Efficiency, No: it's Exergy Efficiency!« and included the replacement of the home heating boiler with a hydrogen-fueled fuel cell, or the changeover from the not too convincing 20 % (at most 30 %) exergy efficiency of current autos to fuel cells or adapted ICEs, both hydrogen fueled and efficient to a non illusory 50 %!

Stationary fuel cells generate exergetically efficiently and simultaneously electricity and heat, and meet with their fuel cell-specific temperature regime between 80 and 900 °C the exact relative temperature demand of households, industry, and vehicles. Let us never forget that ecological reasoning not only asks for waiving claims and avoiding materialism, but also for unparalleled technology development in order to improve the so far rather poor efficiency of anthropogenic energy use, which was bitterly underestimated for centuries. Hydrogen-supported technology is becoming a harbinger of this development!

Traditionally, electricity is produced at the front end of a national energy conversion chain and used at its back end. There may be a thousand kilometers between front and back ends. Now, with millions of envisioned fuel cells' supply at the chain's back end, electricity is also produced there, and that is in the vicinity of the electricity users. This is of cardinal importance, because the back end of a national energy conversion chain governs the overall efficiency of a nation, since each kilowatt-hour of energy services not demanded at the chain's end because of efficiency gains results in 3 kW h of primary energy (raw material) not necessary for the nation's economy to be introduced at the front end (Germany's present national energy efficiency ~34 %!). In the world, the relation is 1: 10 (the present world efficiency ~10 %). That's it what is meant by the sentence ''Hydrogen and fuel cells exergize the energy system!'' They make more electrical and thermal exergy services out of less primary energy. Electricity is pure exergy.

### 9.4. *Hydrogen supply*

Wherever energy is discussed one question is repeatedly asked: where does the hydrogen come from? There are three answers which would be similarly answered for electricity: from fossil fuels, from renewables, or from nuclear fission. (1) from fossil fuels via reformation or partial oxidation or gasification, preferably from natural gas, like today, or from coal, in future with capture and sequestration of co-produced carbon dioxide in order to prevent its release into the atmosphere. (2) from renewable electricity via electrolysis, but not before a number of further decades of development and in competition with the direct use of renewable electricity in the power market; or (3) from nuclear fission, if society accepts it.

### 9.5. *A thought experiment*

Let us end this discussion with a thought experiment: statistically, Germany's more than 40 million road vehicles are operated only 1 h per day; they are parked for 23 h. Let us imagine that they have fuel cells under their hoods with a capacity of, say, 50 kW each and are plugged in when parked in the home garages or on employee parking lots. Consequently, only 5 % of Germany's car fleet operated at standstill would provide some 100,000 MW, which compares well with the capacity of the central stations on-line today. We said it earlier: thought experiments seldom become real, but mostly a certain truth is in them. Here are two truths, the one reads: in the long run, will it really be compatible with the seriously taken energy and transport sustainability so urgently needed to leave useless a whole fleet of ''power stations on wheels'' [32] with a potential capacity 20 times higher than is in traditional use today, with a price tag as low as some 10 €/kW?! (The engineer knows well that a mobile, highly dynamic engine with 10,000 rpm, and a service lifetime of 3000 h is technically and economically absolutely something different from a stationary power station with 3000 rpm and a life of 80,000 h prior to the first full maintenance standstill). And the second truth: Mobile fuel cell vehicles will only be supplied with hydrogen fuel, because any hydrocarbon fuel used instead means the necessity of a hundred-million-fold mobile carbon dioxide collecting devices—a technical and economic impossibility!

### 9.6. *The secondary energy sector ever more important*

To end this chapter: hydrogen and electricity – competitors, partner? None of the aforementioned arguments negates the legitimacy of either electricity or hydrogen; each has its domain; they compete on certain issues, and here and there they are partners. Relative to the primary energy (raw materials) sector, the secondary energy sector grows more and more in importance. It begins to dominate the energy scheme of a nation. It will consist in the future of two secondary energy carriers, electricity and hydrogen, developed in tandem!

We said it, novel energies need time! It seems almost always too late to start creating consciousness and further awareness. People live and work downstream and ask for

reliable, affordable, and clean energy services. Since the hydrogen energy economy moves the center of gravity within the national conversion chain towards its end, exactly where these people live, professionalization of their supply is needed, not unlike professionalization at the chain's front end where we are accustomed to the professional operation of power plants, refineries, coal mines and the like. Delay is the foe of success. Consequently, it's HYtime!

## 10. Hydrogen energy technologies along their entire conversion chain

A comparison of materially open-ended and closed energy systems is provided in Figs. 16 and 17.

The traditional system takes something irrevocable from the earth's crust, converts it mechanically, chemically or nuclearly into something else and gives it back to the geosphere; often global distances separate the two locations. In the nuclear case what remains has long, in some cases very long half-life periods (e.g., plutonium c. 24,000 years) and is radiotoxic and radioactive. In the case of fossil fuels the residuals are unavoidably associated with environmental pollutants and the release of greenhouse gases into the atmosphere. Through numerous open ends the environment and climate are burdened; with the help of additional technologies and systems optimization engineers try to close up these open ends, sometimes with only poor or no success.

The renewable hydrogen energy system is different: All sorts of technologies convert solar irradiance, wind, hydro (or geothermal heat, tidal or ocean energy, others) into both the secondary energies heat and/or electricity, which are then used to split de-mineralized water electrolytically (or thermolytically, or otherwise) into hydrogen and oxygen. The oxygen is released to the atmosphere or utilized chemically; the hydrogen in gaseous or liquefied form delivers the energy for the hydrogen energy economy, as a gas in the heat market, re-electrified through fuel cells or gas turbine/steam turbine combined cycles in the power market, and in all transportation sectors on land, in the air, in space, and at sea. Water is taken from the earth's water inventory; water, after hydrogen usage and recombination with oxygen (from air), is returned to that inventory, physically and chemically unaltered. The locations, though, of water extraction and water return may be global distances apart.

Like any other energy conversion chain, the hydrogen chain consists of five links: production, storage, transport, dissemination, and finally utilization. Primary energy raw materials (feedstock) are converted to primary energy, further to secondary energies, end energies, useful energies, with the conversion ending with desired energy services such as warmed or cooled rooms, energy support in transport and production, illuminated living spaces, city streets or workplaces, and all sorts of communication. The renewable energies lack the first chain link (from primary energy raw material to primary energy), they begin with primary energies like solar irradiance, wind energy, upstream hydropower potential, etc. Providing energy services is the sole motivation for the run through any energy chain, there is no other motivation. The links preceding the energy services have no justification in themselves, they serve to supply services and contribute to meeting the supply conditions in terms of amount and security, cost, safety, environmental and climatic cleanness.

In countries with high energy imports sometimes complaints are heard like, "we are energy undersupplied, we have too little energy!" No, what is really meant is that the amount of energy services for running the country is insufficient, partly because of a lack of primary energy, but mainly because of lamentably small energy and exergy efficiencies. And these are exclusively a matter of technologies.

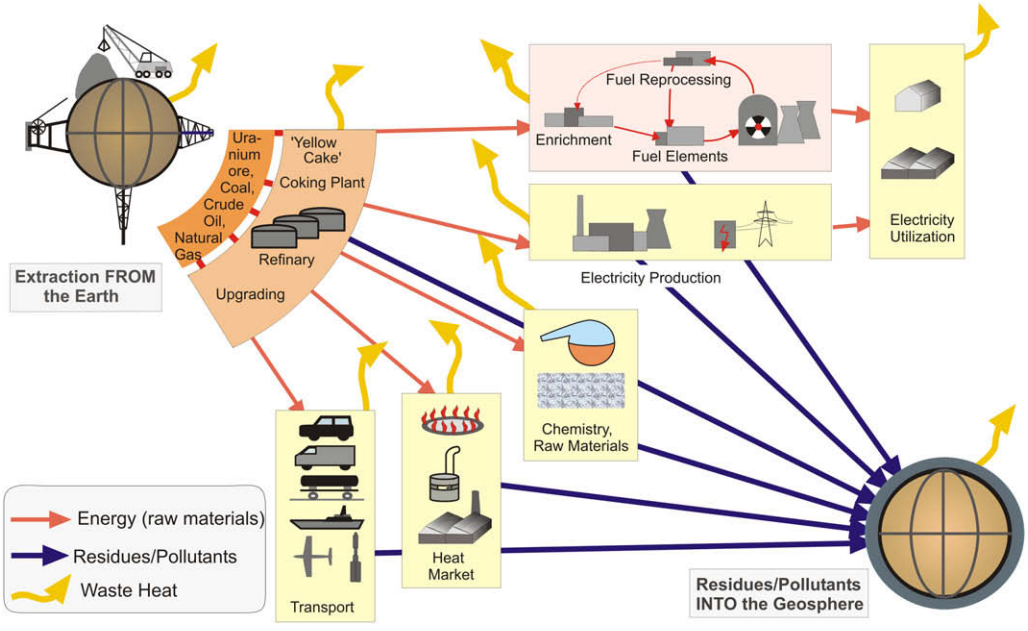



**Fig. 16 – Materially open-ended energy systems.**

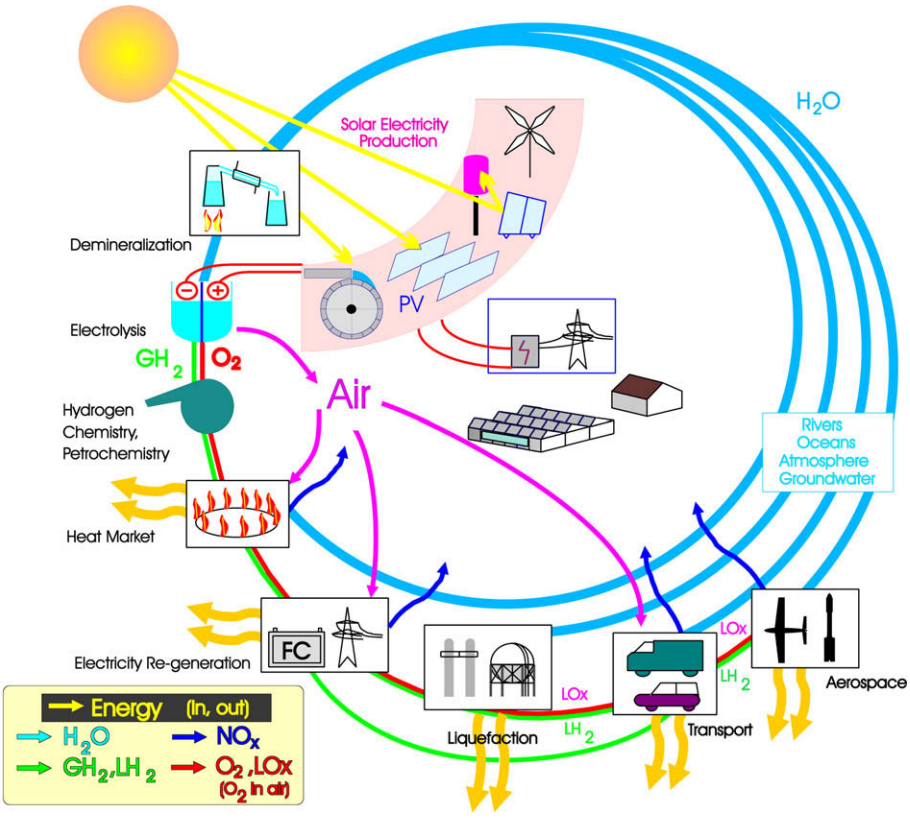



**Fig. 17 – Materially closed hydrogen energy systems.**

In Tables 1–3 three technology categories for the hydrogen chain links are listed—state-of-the-art, midterm, and longer term; let's comment:

At present, hydrogen is produced predominantly by steam reforming of natural gas, labeled steam methane reforming (SMR), through gasification of coal, and, where cheap electricity is available, through electrolysis of water. Nuclear electricity is used where nuclear operations are societally accepted, e.g., in France. With the exception of demonstration projects, in no case where hydrogen is produced from fossil fuels in macroeconomic scales is the co-produced carbon dioxide yet being captured and safely stored away. Renewable hydrogen is nowhere operational in large quantities. A great number of studies and demonstrations are under way, e.g., where photovoltaic generators or solar thermal power plants and electrolyzers work together, or where wind electricity must be transported over long distances to the energy user, e.g., from off-shore wind parks to on-shore users. In all demonstrations it has been seen that the intermittent renewable energy offer and the electrolyzer's dynamic behavior are fairly closely correlated, the electrolyzer responds rapidly to the varying electricity yields from solar and wind converters.

Clearly, from an environment and climate change standpoint, renewable hydrogen is the ultimate choice, sometimes you read the "primary choice". However, still more or less all renewable energy technologies, however admirable their development and market progress over the last years were (and presumably will continue to become), work financially under highly subsidized conditions. Slowly, particularly with galloping oil and gas prices and renewable technologies' further technological development successes, they are approaching market conditions and will get there, realistically, in another few decades to come.

**Table 1 – The Hydrogen Energy Technologies – Production.**

State-of-the-Art (with incremental further development)

- Reformation of natural gas
- Gasification of coal
- Partial oxidation of heavy crude oil
- Electrolytic hydrogen from hydropower
- Hydrogen from nuclear electricity

Midterm (c. 10 years from present)

- Electrolytic renewable hydrogen from wind, PV, solar thermal power, and other renewable sources
- Hydrogen from biomass

Long term (in 20 years or more)

- Hydrogen-supported decarbonzation hydrogen from fossil fuels with carbon capture and storage (CCS)
- Hydrogen from coal with the help of high-temperature nuclear heat
- HT electrolysis
- Radiolysis, thermolysis, photocatalysis of hydrogen

**Table 2 – The Hydrogen Energy Technologies – Storage and Transport.**

State-of-the-Art (with incremental further development)

- Hydrogen liquefaction
- Hydrogen cartridges in portable electronics
- Metal hydride containers
- Embrittlement-proof hydrogen pipelines,
- Continuous or batchwise GH2 or LH2 transport
- Hydrogen in refineries
- Hydrogen in the space business

Midterm (c. 10 years from present)

- Pick-a-back hydrogen in natural gas pipelines: »NaturalHy«
- 700 bar filament-wound mobile hydrogen tanks
- Vacuum insulated liquefied hydrogen ($LH_2$) tanks with low boil-off

Lonterm (in 20 years from present)

- »supergrid« – a $LH_2$ cooled superconducting high capacity cable with simultaneous $LH_2$ transport
- $LH_2$ tankship transport
- $LH_2$ loading and unloading harbor equipment
- Carbon nanostorage

**Table 3 – The Hydrogen Energy Technologies – Dissemination and Utilization.**

State-of-the-Art (with incremental further development)

- Hydrogen in space transportation
- Spaceborne fuel cells
- Fuel cells in submersibles
- Hydrogen-fueled low temperature fuel cells in portable, stationary, and mobile applications
- Hydrogen in ICEs and gas turbines
- Hydrogen-fueled mobile auxiliary power units (APUs)

ICE Internal combustion engine
Midterm (c. 10 years from present)

- Hydrogen/oxygen spinning reserve
- Hydrogen and the high efficiency ICE
- Hydrogen filling stations
- Hydrogen in airborne APUs
- Fuel cells replacing airplane ram air turbines

Geothermal steam temperature rise through mixing with steam from $H_2/O_2$ recombination
Long term (in 20 years or more)

- Hydrogen jet fuel in air transportation
- Hydrogen as the laminarizing agent in aerodynamics
- Hydrogen and the drive train in sea-going vessels
- Hydrogen propulsion in ICE or fuel cell locomotives

Consequently, until full market conditions are achieved for renewable technologies, further development towards marketability of hydrogen on the one side and renewable technologies on the other side should be pursued in parallel on a dual carriageway prior to dovetailing their individual results. No reason is seen not to proceed with hydrogen's addition to the energy mix on the marketplace, although renewable technologies are not yet fully market ready. Renewable hydrogen is the ultimate goal, but it is not the precondition for the entry of hydrogen into the market! In the meantime, lots of so far irregularly utilized or even flared hydrogen capacities facilitate their utilization: Fig. 18 shows for Germany as an example the amounts of hydrogen energetically so far not used, a total of almost 1000 M $m^3$/a, equivalent to the average consumption of some 7850 fuel cell busses. In addition, hydrogen from some ten thousand sewage plants in the country may be utilized as a transport fuel in the interim.

A strong argument in favor of the utilization of hydrogen energy prior to the maturity of renewable technologies is that »clean coal« via air separation, coal gasification, capture of hydrogen and carbon dioxide and finally combined cycle electricity generation is inherently connected to hydrogen. Dual benefit is offered by this exergetically highly efficient process: simultaneously cleaning-up coal and producing hydrogen energy! The process is not new: it was invented by Friedrich Bergius (1884–1949), who in 1931 received the Chemistry Nobel Prize for his work on making gasoline from coal. The process is still in industrial use in South Africa (and perhaps elsewhere).

With respect to storage and transport of hydrogen (Table 2) a whole collection of technologies are worldwide fully operational for gaseous and liquefied hydrogen or metal hydrides; all that has been learned there over the past century is welcome preparation for perpetuation into the forthcoming hydrogen energy economy. A special transport method makes headway and deserves particular attention: transport of hydrogen up to a capacity of 10–15 % pick-a-back in operational natural gas pipeline grids without major technical modifications. An ongoing European project labeled ''NaturalHY'' (http://www.naturalhy.net) studies the various technology and handling consequences like hydrogen embrittlement of materials, hydrogen loading and off-loading techniques, and change in energy throughput of the natural gas/hydrogen combination. With the addition of hydrogen the heating value of the mixture decreases, the Wobbe Index, though, remains nearly the same. All in all, it is expected that hydrogen storage and transport in natural gas pipelines will be a welcome inexpensive means of utilizing approved technology also for a novel energy carrier. At least for a first and limited period of time an additional expensive hydrogen pipeline system investment would not be needed. That applies to centralized hydrogen production or off-ship hydrogen at the front end of the hydrogen conversion chain and to distributed hydrogen utilization at its back end.

Many an argument speaks for centralized vis-à-vis distributed hydrogen production. It is obviously easier to collect and sequester carbon dioxide from a small number of large units than from millions of distributed small ones: here professionals are at work, and the coal, oil, and gas industry and the merchant gas traders well know how to reform natural gas or gasify coal, both in capacities justifying expected low cost. The marine industry and the natural gas traders are well experienced in handling liquefied natural gas (LNG) in tanker ships and harbor equipment, as well as in re-gasifying the cryogenic liquid prior to its introduction into the gas grid.

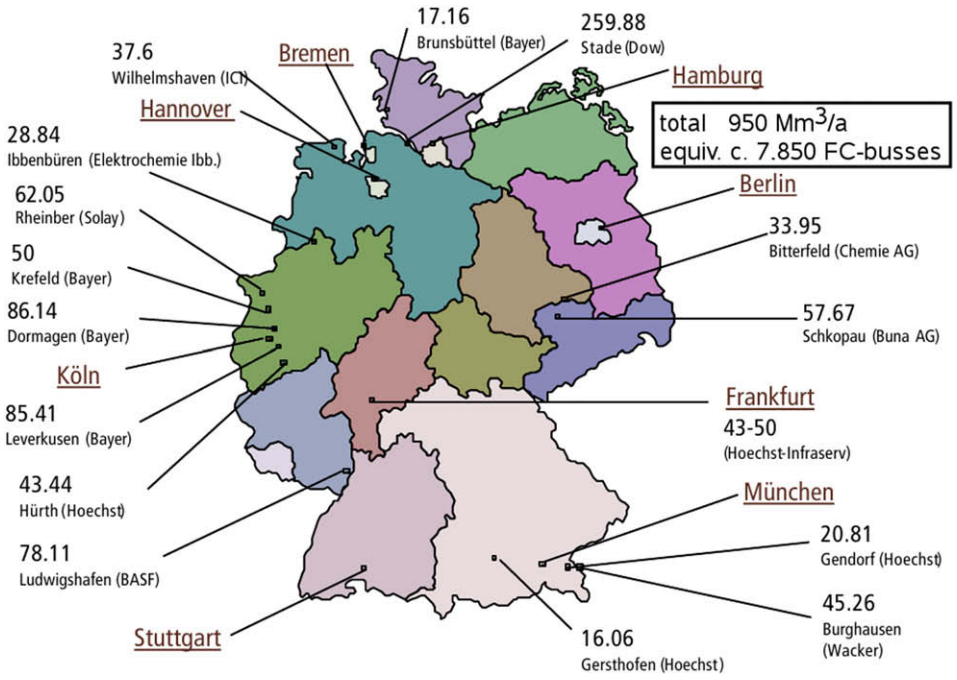



**Fig. 18 – Hydrogen ($Mm^3/a$) as a by-product of German industry Source: [16].**

Whatever pros and cons may have emerged, all experience gained is beneficial for the point in time when global hydrogen trade begins. One disadvantage must be faced, though: so far, in all those cases where fossil fuels are involved almost nowhere is carbon dioxide captured, sequestered and securely stored away commercially in large amounts in underground storage facilities under an impermeable overhead rock cover. In a few demonstration projects, e.g., in the North Sea or in the Gulf of Mexico, practical experience is being gathered.

When renewable hydrogen is generated in distributed installations and utilized on-the-spot in residential energy systems or onboard vehicles, no carbon dioxide is involved, and hydrogen pipeline grid costs are nil. We said it earlier that time is needed to bring these distributed systems to market. Energy handling at the end of any conversion chain by millions of lay persons is not a sustainable option, but so far a professional regime has nowhere been established similar to what is experienced at the front end of the chain. Professionalization of the chain's end energy services is indispensable. But be that as it may, finally market cost will decide on central or distributed hydrogen production, or both.

A few words on storage: stationary hydrogen storage is at hand, both for gaseous and liquid hydrogen in high pressure steel flasks or cryogenic dewars. Large capacity underground storage for gaseous hydrogen in leached salt domes may build on what has been learned from operational underground air or natural gas storage, though special care needs to be taken to prevent leakage of the smallest element of the periodic table of elements: hydrogen! The most challenging venture is the tank onboard motor vehicles. For a usual vehicle range of, say, 500 km the tank for gaseous hydrogen requires an inner pressure of 700 bar, which from a manufacturing and lifelong safety standpoint is not at all trivial to achieve and maintain. The filling station's pressure will then amount to even c. 1000 bar, requiring compressor energy; if gaseous hydrogen at the filling station is provided by re-gasification of $LH_2$, then the amount of pressurization energy necessary is smaller. The mobile tank is made of filament-wound carbon fibers with an inner steel or aluminum layer. Because of low cycle fatigue of the tank structure as a consequence of frequent charging and discharging ("breathing" of the tank structure) tanks have to be replaced after certain periods of time, in contrast to the one and only gasoline or diesel tank on duty over a vehicle's entire lifetime. The liquefied hydrogen ($LH_2$) tanks have a double wall structure with an evacuated ring volume and multiple wrinkled aluminum foils to avoid heat transfer from the outside to the inside. That the liquefier requires about 1 kW h per 3 kW h of $LH_2$ is state-of-the-art. Depending of the tank size, the boil-off -rate of modern tank designs is a few % per day or less. The allowable inner pressure of the tank is a few bars, which avoids venting of boil-offs until the pressure allowance is reached. If, however, boil-off occurs the idea is to avoid venting and rather utilize the boiled-off hydrogen in a fuel cell to provide electricity for recharging batteries.

Table 3: Local hydrogen dissemination in trucks, trailers or rail cars with onboard pressurized gaseous or liquefied hydrogen is day-to-day practice. Of course, $LH_2$ is more expensive than pressurized gaseous hydrogen ($CGH_2$). Eventually, transport and handling, however, of much higher energy density $LH_2$ will offset the higher price. If gaseous hydrogen is transported pick-a-back in natural gas pipelines, hydrogen separation membranes at the exit points need to be in place.

Three application areas for fuel cells are visible: (1) in portable electronics fueled with the help of hydrogen or methanol cartridges, (2) in stationary applications, and (3) in the transportation sector in busses, passenger and light duty vehicles, later in heavy duty trucks, in aviation and at sea. It so seems that

hydrogenized portable electronics will be the first on the market, because they offer a much longer life than the conventional batteries in use, and, an often heard light side note, because buyers don't care about the cost of the energy involved, which sometimes amounts to some €/kW h! Stationary fuel cells for industrial use will follow, and finally mobile fuel cells will be seen onboard busses and passenger vehicles.

The most challenging effort in the utilization field is selecting hydrogen/oxygen recombination technology, be it either adapted conventional technology like ICEs or gas turbines, or be it newly developed fuel cells. Adapted technology has the advantage of familiarity and market success confirmed over many decades, in some cases up to a century; the market price, the behavior under actual long-life conditions and the operation and maintenance (O&M) requirements are well known; in short, economic viability is given. The fuel cell (Fig. 19), on the other hand, is not a Carnotian heat engine, but an exergetically highly efficient chemo-electric converter serving as a prototypical combined cycle in itself, and it is, thus, an example for the aforementioned system change. It generates electricity and heat simultaneously; it promises few irreversibilities (if no reformer is included, the major source of irreversibility), compact design, no moving parts and, thus, no vibrations and low noise. And, depending on the type of fuel cell, it provides the »right« temperature for heat applications in stationary use: $\leq$100 °C for proton exchange membrane (PEM) fuel cells (FCs), around 200 °C for high-temperature PEMs or phosphoric acid FCs (PAFCs), 600–650 °C for molten carbonate FCs (MCFCs), and 700–900 °C for solid oxide fuel cells (SOFCs). Low to high-temperature PEMs are exactly what is needed for homes or buildings or hospitals, depending under which climate and weather conditions they serve; MCFCs fit the exigencies of many small-to-medium size industries, hospitals and large laboratories, and SOFCs are an excellent topping technology for gas turbine/steam turbine combined cycles.

A thorough exergy analysis of a simulated methane fueled internally reforming high-temperature solid oxide fuel cell plus bottoming gas turbine in the 100 kW range and heat recovery steam generation (HRSG) is given by [28]. The maximum total exergetic efficiency is more than 60 %. In case of fuel cells where the reforming temperatures are insufficient for internal reforming require an extra reformer to supply hydrogen reformate from fossil fuels.

An exergy analysis of hydrogen production via steam methane reforming (SMR) is given by [56]. Some 80% of the world's total hydrogen production uses SMR of natural gas. The process consists of the elements natural gas compressor, water pump, reformer, water gas shift reactor, membrane hydrogen separator, air/methane mixer, and a number of heat exchangers; the temperature is 700 °C. Most of the exergy destruction occurs in the reformer due to irreversibilities in the fuel/steam mixer and as usual in heat transfer and combustion. The total exergy efficiency and the thermal energy efficiency are c. 62 and 66%, respectively. Of the 38% lost exergy a good 80% is lost within the system; the rest exits with the exhaust stream. Intelligent heat management, varying the steam-to-carbon-ratio (S/C), and reducing the amount of retentate leaving the membrane separator are means of maximizing the efficiency. A general exergy analysis of energy converters can be found in [5].

The preferred mobile fuel cell is the low temperature PEM. It fits into the ongoing electrification scheme of the automobile by providing highly efficient electricity for the electric motors in the drive train and for auxiliaries. With only water vapor in the exhaust, PEMs make the vehicle environmentally and climatically clean where it is operated, which is of paramount importance, particularly in the polluted centers of agglomerations. Clean means here locally clean, because whether hydrogen-fueled individual transport is generally clean depends on which primary source hydrogen is produced from, renewable or nuclear electricity, or fossil fuels with or

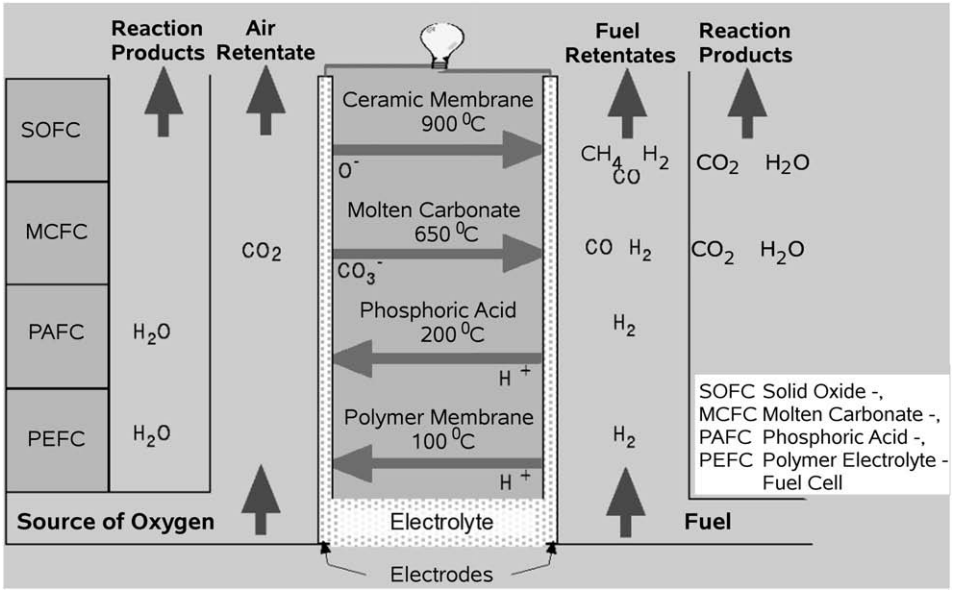



**Fig. 19 – Various fuel cell systems. SOFC Solid Oxide Fuel Cell; MCFC Molten Carbonate Fuel Cell; PAFC Phosphoric Acid Fuel Cell; PEFC Polymer Electrolyte Fuel Cell.**

without capture and storage of co-produced $CO_2$. Replacing the exergetically miserable onboard electric generator with an engine-independent fuel cell may become an interesting first step. Because it is exergetically simply absurd to run a generator of some 5 kW capacity with the help of an engine of, say 100 kW or (sometimes much) more.

Fig. 20 brings an interesting though far away vision of exergetization of industrial schemes: energy cascading. Generally, industrial heat requirements start at temperatures as high as 1700 °C (or higher) for metalworking, and follow a downward cascade through various branches (brickworks, steam power plants, catalytic reactions, heat and cold for buildings, etc.), each with their own specific temperature requirements, finally down to ambient temperature with the remaining heat being radiated into space. Similarly, an upward (negative) temperature cascade is imaginable starting at −155 °C for air separation and stepping down via low temperature metal forming, refrigeration, food storage, finally also to ambient temperature (in the context of this article, of course, the cascade ought to start at the liquefaction temperature of hydrogen at some −253 °C).

The ideal cascade passes heat from one temperature level to the next; exergy destruction is minimized and at ambient temperature the system has optimally extracted exergy from energy! In practice, however, temperature cascading suffers from many barriers, such as geographical user dislocation, dissimilarities of neighboring branches, different market requirements, and many others. Huge amounts of heat are thrown away. So far, exergetically desirable combined systems are in operation only here and there. Combined power and heat cycles in small district heating systems are good examples, and so are inner-company systems especially in the chemical industry.

Now, what does this have to do with hydrogen energy? When hydrogen is produced from coal at the start of its conversion chain (see »11. Hydrogen Production«), hydrogen, electricity and low temperature heat are being produced simultaneously in an exergy-efficient combined cycle. Similar

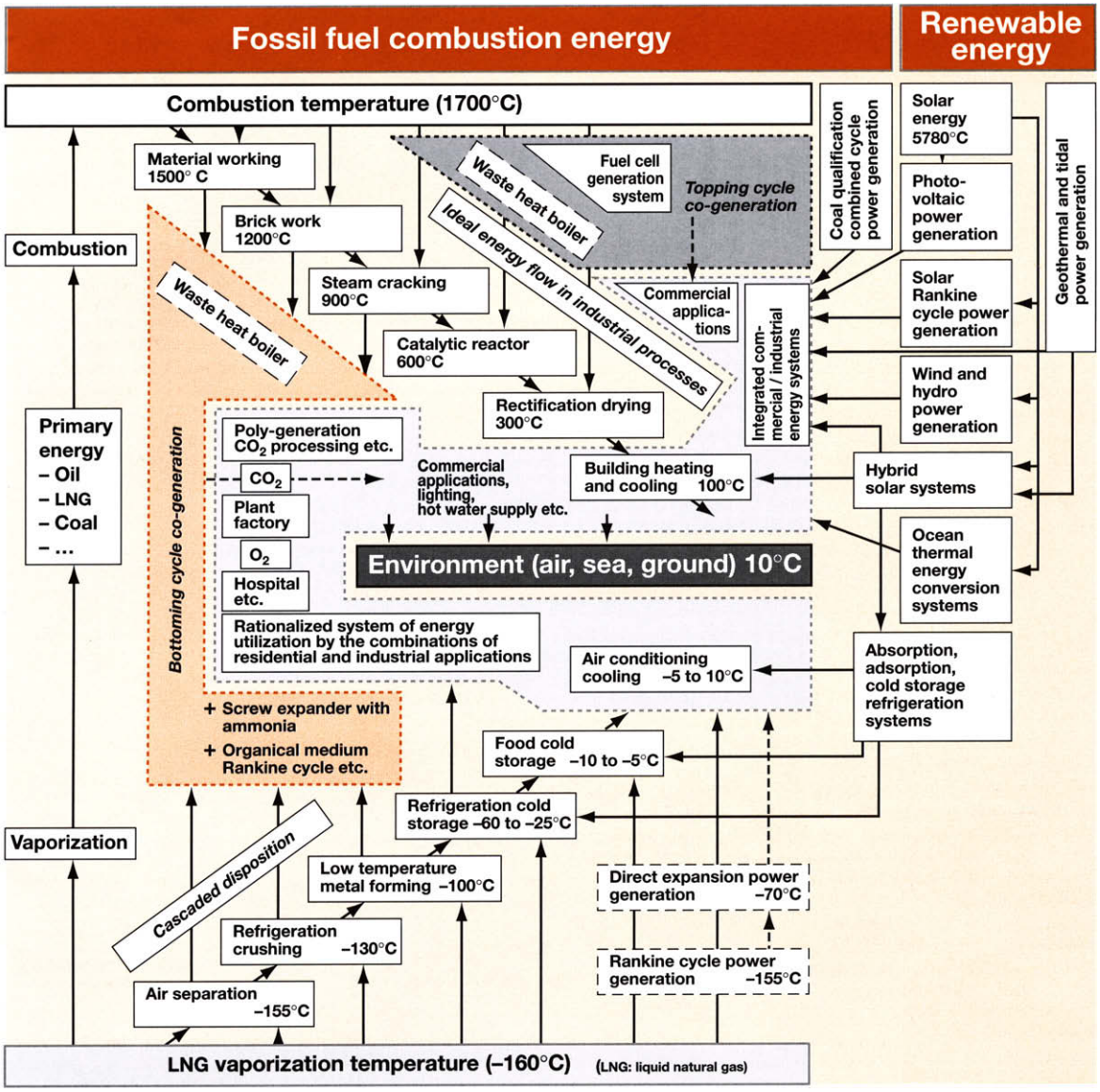



**Fig. 20 – Energy cascading Source: [27].**

things can be observed at the back end of hydrogen's conversion chain: exergy-efficient hydrogen-fueled low temperature fuel cells are in themselves combined cycles simultaneously generating electricity and low temperature heat. Or a last example, liquefied hydrogen onboard an airplane serves of course as the fuel for the jet engines, but it also cools the outer wing and empennage surfaces of the plane and, thus, laminarizes the air flow, thereby retarding the onset of turbulence flow and, thus, reducing the drag. – There are many more examples.

## 11. Hydrogen production

Hydrogen carries secondary energy. Like electricity, the other secondary energy carrier, it is produced from all thinkable primary energies and electrical energy—coal, oil, natural gas, nuclear electricity, nuclear heat, all sorts of renewable energies, and grid electricity. Hydrogen and electricity are interchangeable via electrolyzer and fuel cell; the one makes hydrogen from electricity, the other electricity from hydrogen. Hydrogen from fossil fuels or biomass is a task for chemical process engineers. Typical process technologies are coal gasification, natural gas reforming, or partial oxidation of heavy oil fractions; the required heat is introduced autothermally or allothermally. Obtaining hydrogen from renewable energies is a task for electrochemists. Inexpensive electrolytic hydrogen depends on inexpensive electricity. In order not to weaken hydrogen's inherent character of being environmentally and climatically clean over the entire length of its conversion chain, the chain's first link, the production step from primary energy raw material to primary energy, needs to be clean, too. On principle, that is the case for renewable energies and, consequently, also for renewable hydrogen, since they are free of operational primary energy raw materials per se, and it will become the case when hydrogen production from fossil fuels is environmentally nonpolluting, and co-produced $CO_2$ is sequestered and securely stored away without harming the climate; carbon capture and storage (CCS) is inevitable!

The major hydrogen production technologies are those producing hydrogen from fossil fuels, from biomass, or from water:

- from fossil fuels by steam reforming of natural gas (SMR), thermal cracking of natural gas, partial oxidation of heavy fractions (POX), or coal gasification,
- from biomass by burning, fermenting, pyrolysis, gasification and follow-on liquefaction, or biological production,
- from water by electrolysis, photolysis, thermochemical processes, thermolysis, and
- combinations of biological, thermal and electrolytic processes.

Prior to the production of electrolytic hydrogen two key questions must be answered: (1) why hydrogen, when electricity would do? and (2) which option: central hydrogen production and dissemination by grid or non-grid transport, or distributed production with low or even zero transport expenses?

To number (1): Is the production of electrolytic hydrogen really necessary, or can the envisaged task be performed, perhaps even better, by electricity itself? The reason for this question is obvious: hydrogen production adds an additional link to the energy conversion chain, and additions add losses and cost and sometimes ecological sequels. Areas where hydrogen is unavoidable are air and space transportation, and surface transportation over up to global distances on land and sea. Possibly, short distance surface transport or transport on long-distance rail will be electric (see "9. Hydrogen, Electricity – Competitors, Partners?"). In industry, information and communication and all sorts of service businesses as well as mechanical production are the domain of electricity. Hydrogen energy, on the other hand, is key in refineries, in ammonia and methanol syntheses, and for all sorts of hydrogen treatment in industrial chemistry; hydrogen is needed for biomass liquefaction. In buildings, light and electric or electronic appliances are the domain of electricity. Because of its miserable efficiency, Ohmic resistance heating is fading out of use; higher efficiency compressor heat pumps, however, are booming, and low temperature fuel cell central heating systems depend on hydrogen as the fuel, be it pure hydrogen or reformat.

Now to question number (2), central or distributed hydrogen production? The present energy supply system is clearly centralized: electricity or natural gas or light oil are centrally produces in power stations, gas fields or oil refineries, and the secondary energy carriers electricity, gas and other energy products are then "diluted" via overhead transmission lines, gas grids or oil pipelines, or transported on rivers, via road or rail. At the very end of the chain, filling stations supply road vehicles; the local retailer brings fuel oil for buildings' central heating systems or gas for cooking and heating. Now, the supposedly easiest way would perhaps be to mimic the present system when changing over to hydrogen energy: it is well understood, there is a wealth of experience to tap, and those acting are familiar with the technologies. We said it earlier that hydrogen could well be transported pick-a-back in the operational natural gas grid, avoiding an extra hydrogen transport system. Further, decarbonizing is much easier when hydrogen from fossil fuels is generated in large systems rather than in distributed installations of much smaller capacities: collecting greenhouse gases from millions of distributed emitters is technically and commercially impossible. On the other hand, indications can no longer be ignored that more and more clean distributed installations such as photovoltaics, wind and biomass are harnessing local potentials which were previously lying fallow. It might not be illusive to expect that, at least as an addendum to the central system, solar or wind or biomass hydrogen will be produced on the spot of utilization, thus avoiding long and expensive and inefficient transport lines. Time will tell whether vehicles will be filled up with electrolytic or reformed hydrogen produced in the forecourt of the filling station, whether the family car is refilled with electrolytic hydrogen produced with the help of electricity from the roof of their house, or whether district electricity, heat and hydrogen supply systems will evolve.

Electrolytic production of hydrogen goes back to William Nicholson who in 1800 reported on the electrolysis of water. Principally three process versions of electrolytic dissociation of water have been or are being developed:

- conventional water electrolysis utilizing an alkaline aqueous electrolyte (30 wt.% KOH) with a separation membrane avoiding the remixing of split-up hydrogen and oxygen,
- Solid Polymer Electrolyte (SPE) water electrolysis utilizing a proton exchange membrane; the technology shows similarities with the PEMFC,
- high-temperature steam electrolysis at 700–1000 °C.

The first two technologies are commercially marketed; the third, mainly because of high-temperature material problems, is still far from realization. Fig. 21 shows for all three the cell voltage over the current density.

For conventional and SPE electrolysis the respective cell voltages considerably exceed the theoretical decomposition voltage of water electrolysis of 1.23 volt at 25 °C and 1 bar, which corresponds for the best electrolyzers to an efficiency of 80–85%. For steam electrolysis the cell voltage drops significantly. The best present electrolyzers need between 4.3 and 4.9 kW h/$Nm^3$ $H_2$.

The future of electrolytic hydrogen depends clearly on the price of electricity. So far, major installations with capacities of some 10,000 $Nm^3$ $H_2$/h have only been erected where inexpensive electricity is available, e.g., near big hydroelectric dams such as in Aswan, Egypt, or in locations in Norway or Canada, where major amounts of hydrogen are utilized in fertilizer industries.

Since most probably the future average electricity price will increase rather than decrease (at least in industrialized countries), electrolytic hydrogen may get its market only where the electricity demand is temporarily low, e.g., at night, or where base load (nuclear) power station load control ought to be avoided. Another future area where electrolyzers may find their niche is smoothing out the time-dependent solar or wind electricity yield, or in cases where transporting renewable electricity to distant consumers is more expensive than transporting hydrogen. Demonstration units such as the German–Saudi »HYsolar« installation have shown that the electrolyzer is flexible enough to respond to the fluctuating renewable energy yield with respect to both time and capacity (http://www.hysolar.com). There is hope that solar electricity will soon achieve grid parity with conventional electricity,

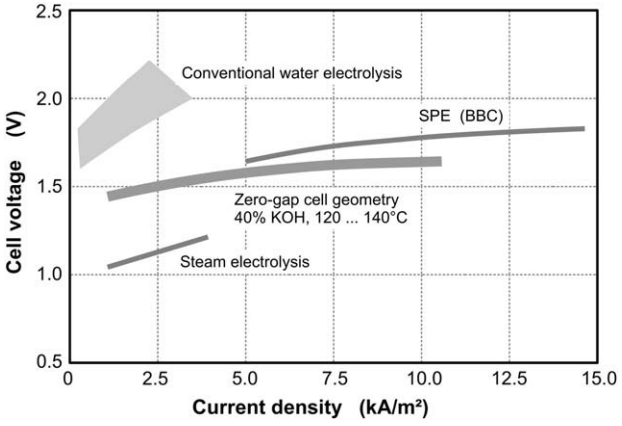



**Fig. 21 – Electrolysis systems Source: [67]. SPE Solid Polymer Electrolyte; KOH Potassium Hydroxide.**

partly because of technology developments, partly because of rising costs for conventional electricity.

A most important item related to the production of hydrogen in general is its exergizing influence on the cleaning-up processes of fossil fuels [39]. Three modern coal plant designs with CCS are under consideration or have begun their demonstration phase. Three typical separations of components from mixtures are key:

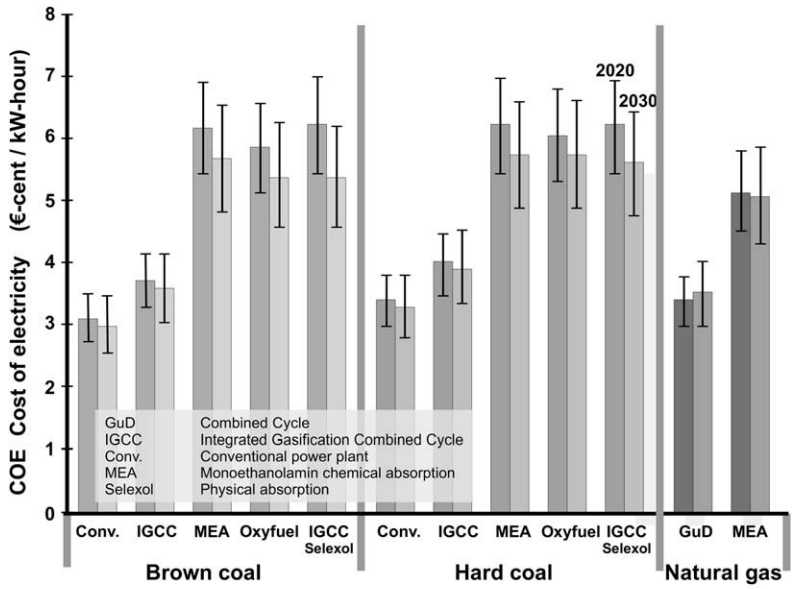
- separation of $CO_2$ from $N_2$ in flue gas decarbonization,
- separation of $CO_2$ from $H_2$ in fuel decarbonization, and
- separation of $O_2$ from $N_2$ in air separation.

Systems under consideration or in demonstration or even in routine industrial practice are:

(1) Integrated Gasification Combined Cycle (IGCC) plants with air separation (in order to get rid of the $N_2$ ballast and avoid $NO_x$ production), coal gasification, CO shift, desulfurization, $CO_2$ capture prior to combustion (pre-combustion capture), and utilization of the final syngas $CO + H_2$ in liquefying Fischer–Tropsch synthesis and methanol production, or utilizing the hydrogen for power production in a combined cycle, or for ammonia syntheses, or as feedstock for the hydrogen infrastructure,
(2) the above plant with air separation and integrated $CO_2$ capture prior to combustion (labeled ''Oxyfuel''), and
(3) a coal plant with $CO_2$ capture after combustion (post-combustion capture) through amine absorption and thermal steam recovery.

All these designs have advantages and disadvantages; the final »winner« has not yet emerged. IGCC is in operation in a few demonstration plants around the world. Post-combustion has one clear plus, since it seems to be easy to add decarbonization technologies to an existing operable plant, something which is not feasible for the two other designs which have to be built from scratch. All three CCS designs are costly and decrease the overall efficiency of the plant; cost estimates vary between 30 and 50 €/ton $CO_2$ removed, with the major cost item being the in-plant membrane $CO_2$ capture, rather than its subsequent liquefaction, transport and final storage. The plant efficiency decreases by 8–12%. Eventually, the cost is hoped to be compensated by reduced $CO_2$ certificate obligations; even welcome »negative« costs are not illusive when, for enhanced secondary oil or coal-bed methane recovery, $CO_2$ is injected under pressure into the oil well or the coal bed.

Fig. 22 brings estimated electricity costs [€-¢/kW h] for dissimilar methods of $CO_2$ capture in brown coal, hard coal, and natural gas plants for 2020 and 2030, compared to conventional plants without capture; the vertical bars indicate estimation uncertainties. What do we see? Relative to the conventional plant, of course, modern technologies and in particular $CO_2$ capture raise costs: natural gas combined cycle plants are expected to have the smallest increase, followed by brown coal and hard coal IGCC, in that order. Then comes the MEA options, again with the smallest increase expected for the natural gas plant. The Oxifuel and Selexol options show not too big cost differences. But all together, the cost rise up to




| Storage Option | Global | | Germany | |
|---|---|---|---|---|
| | Capacity Gt $CO_2$ | Static Range years | Capacity Gt $CO_2$ | Static Range years |
| Depleted gasfields | 690 | 73 | 3 | 8 |
| Depleted oilfields, EOR | 120 | 13 | 0.1 | < 1 |
| Deep saline aquifers | 400 – 10 000 | 43 – 1 062 | 12 – 28 | 34 – 78 |
| Non-minable coal seams, ECBM | 40 | 4 | 0.4 – 1.7 | < 2 |
| *EOR enhanced oil recovery via $CO_2$ injection* | | *ECBM enhanced coal bed methane* | | |

**Fig. 22 – Cost of electricity for CCS in hard coal, brown coal, and natural gas plants Source: [30].**

some 5–6 €-¢/kW h is painful. The appraisal: natural gas is ahead of the others. The question remains, whether or not the ongoing concentration of natural gas oligopolies will give rise to unacceptable price rises or supply shortages, or both, at least in the long run. In both the other cases IGCC is leading, followed by not too dissimilar results for MEA, Oxifuel and Selexol.

In the table of Fig. 22 potential $CO_2$ sinks, both global and for Germany, are given: depleted oil or gas fields, un-minable coal seams, and saline deep aquifers. Disappointing are the rather limited static ranges of depleted oil and gas fields and coal seams. It appears that the only real long-term potential is offered by deep saline aquifers where salty water absorbs carbon oxide. The large variations in capacity and range, though, point to uncertainties; clarification will only come with practical experience.

$CO_2$ storage demonstration test sites are in operation in Australia, Europe, Japan, and the USA. In all four places, $CO_2$ is stored in deep saline aquifers. In non-power-industry plant operations the technologies are mature and operational in large scales; emerging technologies promising less cost and higher storage security are under development. The cost is dominated by the specific $CO_2$ separation technologies (membranes, amines, other), not by $CO_2$ compression, liquefaction and transport. Pipelines or $CO_2$ vessels similar to those in use for shipping LNG or LPG are day-to-day practice. The distances between major $CO_2$ producers and potential storage basins around the world are not too large. Nowhere, however, is it known for sure what the biological, chemical, hydraulic or geological consequences will be over the long term (hundreds of years). It is much too easy to compare $CO_2$ storage with the millions of years of natural gas, coal or oil underground storage and expect no cons; time will tell. Other storage possibilities may be un-minable coal seams, depleted natural gas or oil reservoirs, or deep sea ''lakes'', all of which have their peculiarities. So far too little is known about accompanying degradation of groundwater quality, or about potential damage to hydrocarbons or minerals in sedimentary rock, or the acidification influence on deep sea water or subsoil fauna and flora. Carbonization of minerals, on the other hand, is a welcome consequence, as has been accomplished by nature over millions of years providing stabile and the least mobile carbonates. $CO_2$ storages will not be absolutely free of leakage; an amount of less than 1 % over 100 years is considered ''safe.''

Figs. 23 and 24 give the interesting example of exergy-efficient combined production of hydrogen, electricity and carbon dioxide. What is seen? The conversion of coal into hydrogen occurs in five more or less marketed technology steps (»islands«): the first step is air separation, the second oxygen-supported coal gasification, the third and forth hydrogen and $CO_2$ separation, and the fifth and final step adds combined cycle electricity generation. The results are seen in Fig. 24: with carbon removal of 90%, ready for compression,

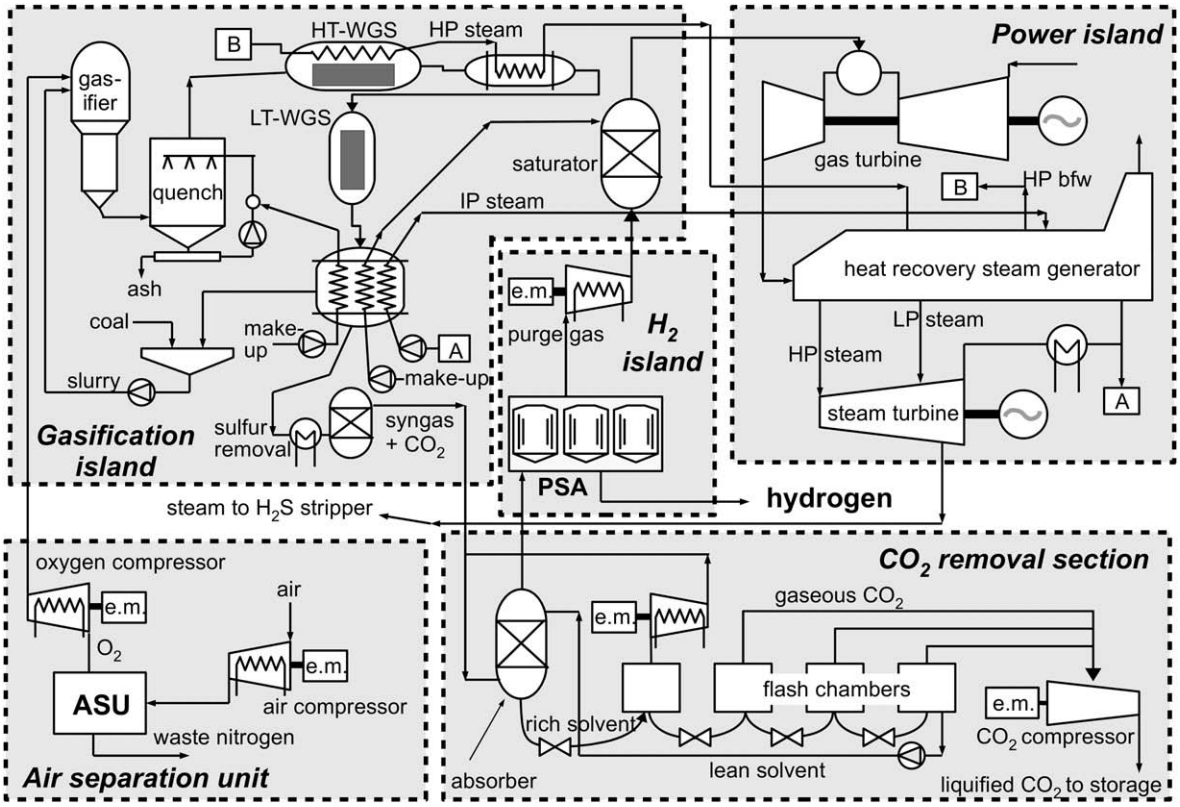



**Fig. 23 – Combined cycle production of hydrogen, carbon dioxide, electricity, and heat from coal Source: [10].**

liquefaction and transport to the storage site, 58% of the coal's energy content is converted to hydrogen and 4% to electricity, together 62%. If an estimated 10% is reserved for $CO_2$ capture, transport and storage, the resulting exergy efficiency is 52%!

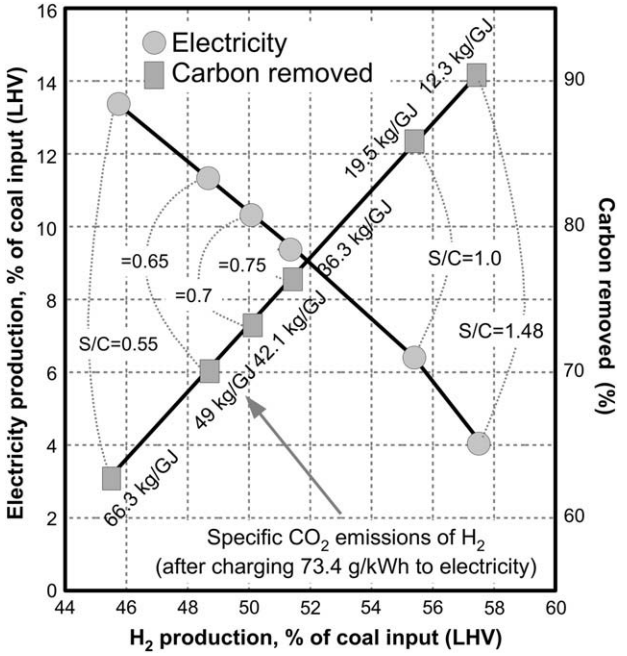



**Fig. 24 – Exergy-efficient combined hydrogen, electricity, carbon dioxide, and heat production from coal Source: [10].**

(for comparison: modern coal-fired power plants are 46% exergy efficient, minus 10% for CCS makes 36%).

## 12. Hydrogen handling, storage, transport and dissemination

Here, thorough practical experience has been accumulated over almost two centuries, starting after the first hydrogen papers of Cavendish and Lavoisier in the late 18th century when the balloons were filled with light hydrogen gas. Today, the technical gases industry, hydrogen chemistry, the space launch business and refineries are among those most familiar with hydrogen, which they handle as a commodity or an energy carrier in their day-to-day practice. All that has been learned there can be considered good preparations for the up-and-coming hydrogen energy economy.

We distinguish traded hydrogen and captive hydrogen, with the latter being produced and used in-house in chemical industries or refineries without being traded. Traded hydrogen is mostly in the hands of merchant gas traders who provide hydrogen to glass and electronics manufacturers, to food industries, to electric utilities for cooling big electrical generators, and, not least, to space businesses for onboard fuel cell supply and, in much larger quantities, as the fuel for the $LH_2$/LOX launcher engines.

Hydrogen is shipped in gaseous or liquefied form using many different means of transportation. Quite a number of

CGH pipeline grids are in operation all over the industrialized world. For example, in Germany a pipeline of 210 km length and c. 30 bar inner pressure has been (and still is) in operation since the 1930s; it serves 18 industrial sites. Higher pressure gas comes in steel flasks (200 bar) on road or rail tube trailers, seldom in pressurized pipelines (40 bar) of industrial grids. Liquid hydrogen is transported on the road in lightly pressurized double-walled cryogenic tanks (dewars) at minus 253 °C, even when the customers' demand is not $LH_2$ but $GH_2$. The much higher hydrogen transport density of $LH_2$ justifies liquefaction prior to transport and, consequently, re-gasification after delivery acceptance. Because of the required high purity in the semiconductor business, hydrogen is delivered as $LH_2$. Economically, one $LH_2$ tanker truck delivers approximately the same amount of hydrogen as 20 pressurized $GH_2$ trailers, not only a convincing example of economic viability but also welcome emission abatement of diesel truck engine exhausts! An unusual means of transport could have been seen in the early days of the Kennedy Space Center when $LH_2$ was delivered in vacuum insulated steel containers on barges from the production sites at the Gulf of Mexico to Cape Canaveral, Florida using the inner coastal waterways.

Sea-going $LH_2$ supply from far away places will become necessary when wellhead decarbonization of fossil fuels already at the seller's site is taken seriously, or when sites of immense renewable potential begin contributing to the world's energy trade. Historically, environmentally and climatically cleaning-up fossil fuels was (and still is) the obligation of energy buyers. For the time being the sellers are well off, they simply ship the »dirty« energy carrier. $LH_2$ tanker transport over ocean distances will be the solution whenever pipeline supply is not feasible. Potential examples are hydrogen from decarbonized coal, say, from Australia or South Africa, or solar hydrogen from Australia or wind derived hydrogen from Patagonia to Europe, Japan, or North America. All that had been learned from ongoing LNG tanker transport at sea and its cryogenic loading and unloading harbor equipment is welcome experience for the start of global hydrogen trade.

$GH_2$ density at ambient temperature and $LH_2$ density at −253 °C are 0.09 and 70.9 kg/m$^3$, respectively. The volume-related energy density of hydrogen relative to gasoline is approximately 0.3: 1, and the weight-related density 3: 1. In many plants around the industrialized world, liquefaction of hydrogen is more or less routine practice, in plants of very small capacities up to very big amounts of some 10 tons $LH_2$ per day. Liquefaction is energy intensive: in the classical Claude process around 1 kW h of electricity is needed to liquefy some 3 kW h of hydrogen. Potentially more efficient liquefiers using magneto-caloric magnetization/de-magnetization of rare earth compounds are still deep in their early laboratory phase. Small onboard re-liquefaction installations for boil-offs are (and will be) installed on sea-going LNG tankers (today) and $LH_2$ tankers (tomorrow); the re-liquefaction temperatures are −163 °C and −253 °C, respectively. Another possibility to avoid boil-off losses is storing the boil-off in metal hydrides underneath the $LH_2$ spherical balls at the bottom of the ship's hull where the additional weight of the hydride installation simultaneously serves as ballast instead of dead weight water tanks (which, by the way, also transport sometimes very disruptive flora and fauna from the water habitats of one ocean area to those of another).

Hydrogen at ambient temperature consists of 25% ortho- and 75% para-hydrogen, spinning in the same or opposite direction as the nucleus of the hydrogen molecule, respectively. Since at very low temperatures ortho-hydrogen is converted to para-hydrogen accompanied by very high boil-off losses, catalytic conversion of ortho- into para-hydrogen already during the liquefaction process is mandatory.

In practice, stationary storage is realized in on-ground high pressure containers for $GH_2$ as well as in vacuum insulated cryogenic cylinders and balls for $LH_2$. The ball with the highest $LH_2$ content so far is located at NASA's Kennedy Space Center at Cape Canaveral, Florida, USA; it serves to fuel the center tank of the space shuttle and contains some 2000 m$^3$ of $LH_2$. In the future $GH_2$ may well be stored in underground leached salt domes. Practical experience with low to high pressure underground air or NG storage has yielded many lessons learned which may be of help for future underground hydrogen storage. One problem here is how to manage the environmentally critical huge amounts of brine during leaching of the dome. For long-distance air, space and sea transport only liquefied hydrogen meets the requirements.

Near- to long-distance surface transport asks for mobile storage of a different design. Onboard road vehicle storage may well handle hydrogen in all three aggregates, high pressure gaseous or liquefied hydrogen or metal hydrides. High pressure gaseous hydrogen tanks at 700 bar are filament-wound tanks of cylindrical shape with an inner metal liner; they have a restricted lifetime because of low cycle fatigue damage due to pressure variations when filling and emptying the tank; the tank »breathes«. Still, lifetime allowances for the tank are much shorter than the vehicle's life, so more than one tank per vehicle life is needed. Because of their weight and the complicated heat management required when filling or emptying the storage tank, it seems that onboard metal hydride storage has lost the business. The low weight-related energy content of the storage of a few percent, however, is the real reason. Low pressure and medium temperature metal hydride storage of some 5–8 wt.% $H_2$ and, thus, an acceptable vehicle range between two fillings would be reasonable. So far, practical laboratory work has not yet succeeded in reaching that goal. Vacuum insulated double-walled $LH_2$ containers with inner temperatures of minus 253 °C at a moderate pressure of maximally 3–4 bar, boil-off rates of less than 1% per day, and a content of 7–10 kg $LH_2$ allowing for a range of 200–300 km is well developed technology; the technology has been under practical test in some hundreds of demonstration vehicles, so far. A leakage-free $LH_2$ filling receptacle valve is in practical use. One critical point is that the cylindrical $LH_2$ container on top of the vehicle's rear axle is bulky, additional length has to be added to the vehicle body; perhaps a longer shaped cylindrical tank within the cardan shaft tunnel will be the final solution. Of course, because of minimum boil-off losses, the outer container shape should be as near as possible to the ball shape of minimum specific surface! In an interim phase as long as not too many $LH_2$ filling stations are in place, the bi-fuel gasoline/hydrogen internal combustion engine makes it possible to bridge the gap: whenever a hydrogen-powered vehicle runs out of fuel without a hydrogen station around, one simply switches to gasoline; temporarily, that is a big advantage of the ICE over the hydrogen-fueled fuel cell car!

To sum up, a wealth of hydrogen storage, transport and dissemination technology is operational and well understood; safety conditions are known and experienced; markets are established. Various well documented stationary storage systems are presented by Ref. [8] (Fig. 25), and mobile storage criteria—present and expected—are documented by Ref. [35] using U.S. Department of Energy (DOE) and U.S. Department of Defense (DOD) storage goals; here specific energy densities by volume and weight are presented for conventional gaseous, liquid, and metal hydride storage systems, but also for future lithium or sodium borates storage media. The respective gravimetric and volumetric data of the latter may increase by a factor of 2–3.

Those technologies of the hydrogen energy economy still not yet marketed at large scales are:

- revitalization of hydrogen production from coal including $CO_2$ sequestration and storage,
- large scale electrolysis of high-temperature water vapor,
- solar and wind electrolysis of water developed in tandem with the respective hydrogen technologies,
- simultaneous transport of hydrogen gas in natural gas pipeline grids including feed-in and phase-out technologies,
- $LH_2$ ocean transport including cryogenic harbor equipment,
- $GH_2/LH_2$ filling stations for mobile users; $LH_2/GH_2$ dispensers for stationary users,
- mining of abiogenic hydrogen rich methane in crystalline gas hydrates from deep sea floors (''Clarathene'').

## 13. Hydrogen utilization technologies

Energy utilization is the final link at the back end of any energy conversion chain where end energy is converted to useful energy and finally to energy utilization services whose efficiencies are decisive for the overall quality of the entire chain. Because each kilowatt-hour of energy services not asked for on the market because of higher efficiencies avoids introducing $x$ ($x > 1$) kilowatt-hours of primary energy raw materials into the national energy economy at the chain's front end. Since the world's energy efficiency is c. 10% and that of an industrialized country like Germany not much more than 30%, $x$ is 10 for the world and around 3 for industrialized countries.

Usually, four national energy demand areas are distinguished: (1) industry, including energy utilities, (2) transportation, (3) buildings, and (4) small enterprises, trade, and military. A rough estimate for industrialized nations shows that areas (1) through (3) are roughly equal in size, and (4) is small. In Germany, the two areas (2) transportation and (3) buildings sum up to two-thirds of the end energy demand of the nation! Both are located at the end of the nation's energy chain where utilization technologies and their efficiencies are key.

Both buildings and transportation demand two forms of energy: one called investive energy for the construction of hardware, its lifelong repair, and dismantling and recycling it at the end of its service life; and the other one called operational energy for the operation and maintenance (O&M) of buildings and transportation vehicles and their infrastructure. The operational energies of buildings, including air conditioning, are provided by various means, such as passive solar, active solar via thermal collectors or photovoltaic generators, ambient energy using heat pumps, natural gas or light heating oil for heat supply during wintertime, and hydrogen-supported heat/power blocks for simultaneously supplying heat and electricity. Of course, insulation of the building's envelopes (walls, roof, windows, cellar ceiling) is of cardinal importance: the better the insulation, the less heat flows from the inside to the outside in winter periods, and from the outside to the inside in summer periods (here, one has to be careful not to interfere with heat gains through passive solar technologies!). ''No-energy'' energy supplied buildings (''no'' = no commercial energy purchased from the market!), even ''neg-energy'' buildings that harness more solar energy than is needed to meet their own demand, are not an illusion. Even under the not too favorable weather and climate

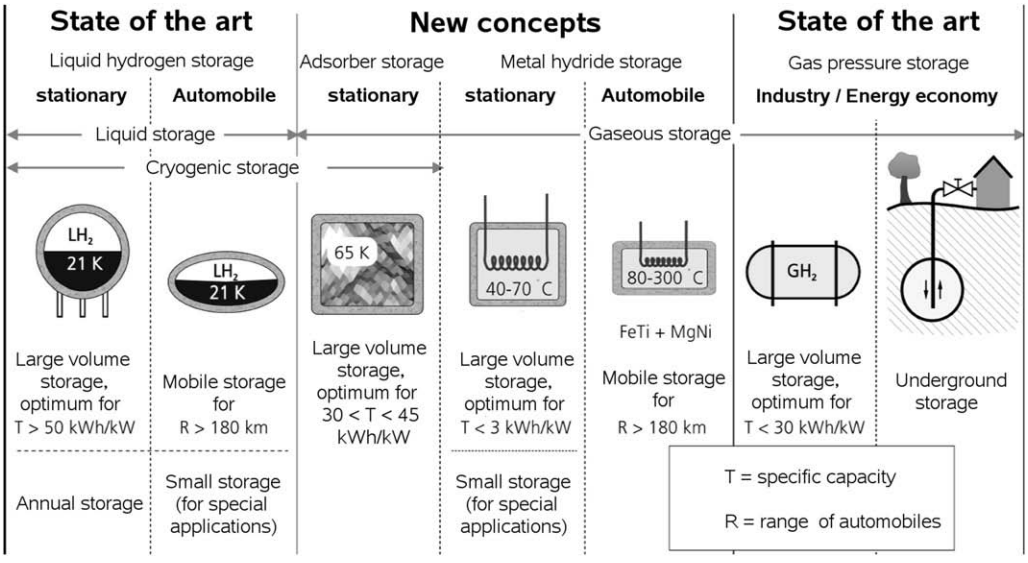



**Fig. 25 – Hydrogen storage concepts Source: [8].**

conditions of central Europe, residential homes with very little (if not zero) market energy needs have been built and operated over a number of years. The task is not a technological one, it is a question of economic viability! For the time being, no-energy homes are still more expensive than conventional homes or, in other words, the oil or gas price is still too low; but that's a matter of time.

Transportation comprises infrastructure, vehicles on land, airplanes in the air and vessels at sea. Land-based infrastructure is provided for: (1) individual transport on urban and rural streets, roads, and highways, and (2) mass transport of passengers and goods on rails. Historically, the continental railway infrastructures of the 19th century have hardly been further developed, except in Europe and Japan. Here, urbanization and settlement density favor rail systems. New technologies were and are being put on line, making possible high speed transport at responsible safety levels. Rail electrification via overhead lines is standard. On the basis of the present power mix, no other transport system is environmentally cleaner and emits less greenhouse gas per passenger and kilometer traveled.

Inter-infrastructure logistics road/rail/sea and road/rail/air or road/rail/waterways are effective and time saving. Globalization asks for harbor and airport effectiveness because some 90 % of global transport of goods sail on ocean vessels, and more and more air freight crosses the skies. On the other side is the system in North America where individual road transport and mass passenger air transport dominate; only bulk cargo is transported on slow rails. Steam locomotives were largely replaced by diesel locomotives, rail electrification is seldom. No other transport system has worse climate consequences than that of North America.

The worldwide system in place depends almost entirely on fossil fuels, or, being more precise, on crude-oil-derived gasoline and diesel; natural gas as fuel or electricity have occupied a small percentage only (a thorough piece on hydrogen and electricity, its parallels, interactions, and convergence is given by Ref. [82,83].

In the majority of countries most of the fuel is imported; heavy users of transport fuel like the USA have in the meantime reached an import quota of more than 50%. The oligopolization of suppliers increases, the number of suppliers shrinks as oil and gas fields are progressively emptied; more of the world's remaining oil and gas resources are in fewer and fewer hands. A geographic ''strategic ellipse'' has evolved of dominating crude oil and natural gas suppliers to the world where the bulk of resources is located, spreading from the Persian Gulf via Iran, Iraq, and central Asian states to as far as Siberia—a not too comfortable situation for heavily crude importing countries! To give an example, Germany has to import 77% (2007) of its energy demand, namely 100% of uranium, 60% of hard coal, 84% of natural gas, and almost 100% of oil. Only uncompetitive hard coal, brown coal, very little hydro and, depending on climate, geography and topology, renewable energies are available indigenously. Vis-à-vis price dictates the country is almost unprotected. Only one ''energy'' is securely in its hands, the energy technology knowledge of its scientists and the skill of its engineers and craftsmen. Their task: to harvest more energy services from less (imported) primary energies—the nation's credo: ''Technologies compete, not fuels!'' (D.S. Scott).

Let us now come to the role of hydrogen energy in buildings and transportation. Today, most of the buildings in the Northern Hemisphere are warmed with the help of natural gas or light oil fueled boilers; they have to provide 60 or 70 °C of room radiator heat. The boiler, particularly a boiler which additionally uses the heat in its condensable exhaust gases, is energetically superb: almost 100% of the fuel's energy content is converted to heat with a flame temperature of around 1000 °C. This, however, is exergetically absurd (see ''8. Energy Efficiency, No: It's Exergy Efficiency!''), because the irreversibilities in combustion, in heat transfer, the heat exchanger and the energy flow through the entire system are tremendous and, consequently, the exergy efficiency is very low: exergo-thermodynamically the large temperature difference between flame and radiator temperature is unjustifiable. Instead, let us imagine that the boiler system is replaced by a low-to-medium temperature fuel cell which at first is fueled by hydrogen reformate from natural gas, later by pure hydrogen when the hydrogen supply system is operable. The fuel cell follows a combined cycle: firsthand it generates electricity (=pure exergy) with an electrical efficiency of 35–40%, and the remaining heat has a temperature which compares nicely with the radiator temperature requirement, so it still suffices to warm the house over most of the year; in extreme winter evenings a small relief boiler is in stand-by mode in order to bridge gaps. The result: the hydrogen/fuel cell system exergizes the energy supply of buildings!

So far the pros, where are the cons? Fuel cells of that kind are still in their development phase; so far, only around a thousand demonstration units have been constructed and operated. And the fuel cell stack's lifetime is insufficient; it is miles away from the experienced 10–15 years lifetime of conventional boilers. Stack degradation makes its replacement necessary after some thousand hours of operation. Not surprising is that so far the fuel cell's price does not meet market conditions; market related mass production has not begun yet.

Another situation is seen in industrial fuel cells with their individual unit capacities of some hundreds up to 1000 kW and temperatures around 600 °C (MCFC) and 700–900 °C (SOFC). They are being industrially produced in first lots, although still in small numbers. They serve as tri-generation combined cycles supplying electricity, heat and cold in hospitals, small-to-medium enterprises, and large building complexes, and, a fine speciality, as uninterruptible power suppliers (UPS) in airports, hospitals, telecommunication control and computer centers. The German natural gas industry and major electric utility companies have committed to combine their knowledge of fuel cells of any kind and generate specific operational criteria for their day-to-day business; for details see http://www.ibz-info.de.

Now to transportation: At sea the first hydrogen/fuel cell demonstration vessels are being studied and demonstrated, and in aviation studies are under way on fuel cells replacing today's onboard auxiliary power units (APUs). Also, studies are pursued on electrification of locomotives using fuel cells fueled by electrolytic hydrogen; investment costs are expected to be lower than those related to electric overhead lines, particularly for very long distances.

In 2008 some 700–800 million passenger vehicles, trucks and busses are operated worldwide in surface transport on

streets, roads and highways, with a reproduction rate of 100 million per year. Gasoline and diesel are the almost exclusively used fuels. The reciprocating piston internal combustion engine is the standard prime mover. The onboard electric power system serves auxiliaries which steadily increase in number and capacity. The present 5 kW for passenger vehicles and 10 kW for trucks and busses do not seem to be the final end of development: vehicle electrification increases. Conventional electrical generators connected to the main engine are an exergetically miserable solution, particularly at vehicle standstill, e.g., at a red traffic light when, say, a hundred kilowatt vehicle engine is being run for the benefit of an electrical generator of only 5–10 kW. The same thing happens on an overnight parking lot in hot climates when the air conditioning system of a truck needs power from the main engine with some hundreds of nameplate kilowatts.

The vehicle's electrification upward trend gets support from higher capacity/lower weight nickel metal hydride and lithium-ion battery development with specific energies per volume and weight, respectively, of 180 W h/l and 80 W h/kg (nickel metal hydride), and 300 Wh/l and 120–150 Wh/kg (lithium ion), further from plug-in or engine supported hybrids with ICEs and electric motors working in parallel or in series. The motivation is better fuel economy under certain driving conditions (inner city with frequent stop-and-go) and cleaner operations. Plug-in hybrids, however, need electricity from the public grid whose capacity must allow for this additional mandate and whose greenhouse gas emissions must be taken into consideration, especially when the bulk of electricity is generated in fossil fueled power stations—unless affordable renewable electricity is available; the future will tell.

Now to onboard hydrogen energy: We distinguish several discussion lines: (1) Gaseous or liquefied hydrogen? An attempt to answer this question is found in ''9. Hydrogen Handling, Storage, Transport and Dissemination''. (2) Hydrogen internal combustion engine or fuel cell as the prime mover? A thorough comparison will be found in ''11. Hydrogen Energy in Transportation''. (3) Hydrogen-fueled polymer electrolyte membrane fuel cell (PEMFC) or direct methanol fuel cell (DMFC); and finally, (4) which vehicle type first, passenger vehicles, busses, trucks?

To question (3) about which type of fuel cell will be the final solution: we said earlier that it will be technically (not to speak of economically) impossible to collect and remove $CO_2$ from hundreds of millions of vehicles disseminated across the world. Consequently, if anthropogenic climate change is truly taken seriously, carbon should not be onboard the vehicle, however meager the carbon concentration of the fuel may be—whether natural gas, methanol, or something else (exception: renewable carbon in biofuels). Further, for low temperature fuel cells hydrogen is the fuel of choice; consequently, carbon containing fuels need reformation to hydrogen. Reformers under the hood bring along additional weight and volume, and, depending on the type of reformed fuel, temperatures of some 700–900 °C for natural gas or 300 °C for methanol. Further, depending on the dynamics of the fuel cell's hydrogen demand, the reformer has to be consecutively accelerated, decelerated, accelerated …, again and again, which is not at all inherently time appropriate for reformer chemistry. Since statistically the fuel cell vehicle is operated only one hour a day (the average for all vehicles of whichever provenance), the annual asset utilization of the reformer hardly reaches more than 1% per year—an absolutely non-convincing economic solution!

Many a design, experimental or manufacturing task was (and still is) pursued in auto industry shops and research labs in order to tackle the aforementioned obstacles, because hydrocarbon fuels onboard fuel cell vehicles have one convincing advantage: their stationary infrastructures are in operation! Putting all pros and cons together, the final result is clear: the low temperature fuel cell will be fueled by hydrogen from large scale central production and/or reformation units outside the vehicle, such as in the forecourts of filling stations; it will not be fueled by onboard reformed hydrogen!

To question (4) about which vehicle type comes first: obviously, in auto industry labs the highest amount of research and development money flows into hydrogen passenger vehicles, either fuel cell or ICE vehicles, busses follow, trucks are on the waiting list. Hundreds of small-to-medium size passenger demonstration vehicles are on the road; quite a number of busses have been and still are part of the routine services of city transport authorities. CUTE – Clean Urban Transport in Europe, a project of the European Union, (http://www.global-hydrogen-bus-platform.com, http://www.H2moves.eu) stands for some 30 hydrogen-fueled fuel cell busses operated routinely in European capitals (a few also during the 2008 Olympics in Beijing, China, and in Australia) with the objective to gather technological, economic and passenger experience. For more details see »14. Hydrogen Energy in Transportation«.

The question remains, how will hydrogen be delivered to the filling station and at what cost? Today, gasoline and diesel and natural gas are transported to the station via tanker trucks or gas flasks on trailers, seldom via pipelines. A dispenser takes the fuel from the underground storage, a lay person operates the fuel receptacle valve, dispensing time is a few minutes. This is the procedure which future hydrogen filling stations will have to match.

In Fig. 26 cost [US$/kg] at a U.S. station is depicted for gaseous and liquefied hydrogen against the size of the station [kg $H_2$/day] (for comparison:1 kg of hydrogen compares energetically with c. 1 gallon of gasoline = 3.785 l). Three methods of delivery are shown: gaseous hydrogen in steel flasks or via pipeline service, and liquefied hydrogen in cryogenic tanker trucks. What is seen? Not surprising, smaller stations have the higher cost, because their turnover is limited. But surprisingly, liquefied hydrogen costs less than gaseous hydrogen. Obviously, the higher energy density of $LH_2$ trucking more than compensates for the liquefaction cost; re-gasification at the station provides gaseous hydrogen, too. Of the different cost influences land cost is the highest (which for countries other than the USA might be different). The cost does not include taxes which, of course, differ from country to country. Also excluded is climate change cost, which depends on the fossil or nonfossil primary energies the hydrogen and the necessary electricity are made from, and the diesel fuel the transport trucks are fueled with.

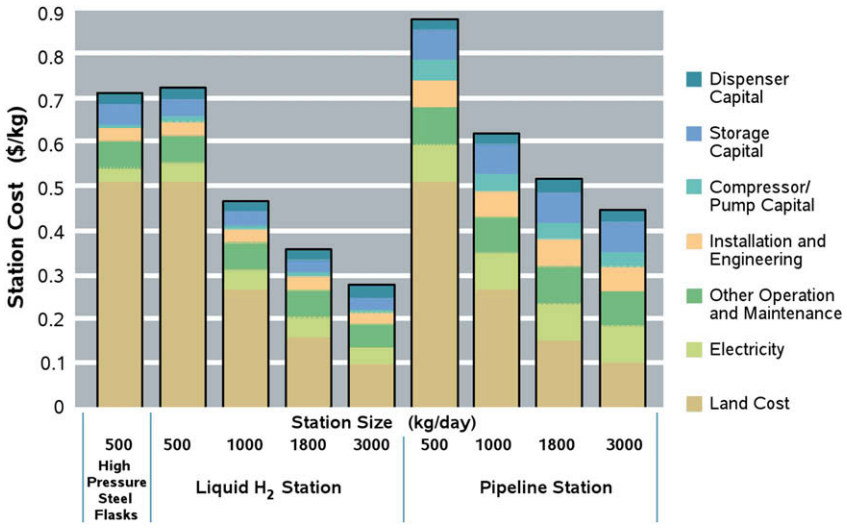



**Fig. 26 – Hydrogen cost at the filling station Source: [82].**

## 14. Hydrogen energy in transportation

Historically, transportation on land, in the air, or at sea was (and still is) almost entirely dependent on fossil fuels; only mass railway transport in a few areas of the world (e.g., in Europe or Japan) uses electricity from overhead lines. However, electrification of transportation in general is increasing. For better navigation, more efficient fuel use, and increasing electrical onboard services, sea-going vessels use turbine-generator sets. Aircraft electricity needs have also continuously increased: fly-by-wire, computerized piloting, and general electrical onboard services need ever more electricity which is supplied on the ground by the electrical grid or generated onboard by gas turbine supported auxiliary power units (APUs); when airborne, electricity is provided by jet engine mounted generators. The electrical system on trucks and busses has increased to voltages up to 42 volts; because of ever more onboard users like air conditioning and operational auxiliaries, capacity increases to more and more kilowatts. The first hybrid cars joined the market a few years ago, with the ability to operate the car in three modes, solely battery supplied, or with electricity from an engine-operated generator, or in a combustion engine mode. The motivation for hybrids is better efficiencies under certain (inner city) driving conditions and improved environmental and climatic cleanness. Canadian and Danish engineers studied electrification of long-haul and commuter service train locomotives not depending on overhead electricity lines [21]. Their studies compared $H_2$-ICEs and $H_2$-PEM fuel cell power trains with conventional diesel engines or coal- or NG-based electric overhead line propulsion. The results are not surprising: $CO_2$ emissions [kg $CO_2$/vehicle·km] for conventional propulsion are the highest, those of $H_2$-PEM fuel cells are the lowest, with those of $H_2$-ICEs in between.

Certainly, the electrification trend goes on, also in passenger cars where more and more auxiliaries such as fans and water or fuel pumps are being decoupled from the vehicle's engine and operated electrically at higher efficiencies. Consequently, electricity requirements increase with respect to voltage and capacity. The question, however, is whether future battery development will not only fulfill the above mentioned requirements, but also those related to the potentially full-electric car! The usual gasoline or diesel fueled auto range of some 500 km per tank-filling has by far not yet been reached by the battery supported electric car. What is still needed is onboard electricity generation parallel to battery supply through engine generation, or through hydrogen-fueled fuel cells: That is the point!

An exergetically efficient first step is to replace the miserably inefficient engine-operated electrical generator by an engine-independent fuel cell. As long as hydrogen is not taken onboard, it may also make sense to install a high-temperature fuel cell and run it on hydrogen reformate from gasoline or diesel. Before the second step is taken, namely the replacement of the internal combustion engine by a low temperature fuel cell and electric drive motors, the decision is due whether the fuel cell is to be fueled with pure hydrogen or with gasoline or diesel reformate. The latter requires a medium to high-temperature reformer which is bulky and brings additional weight onboard; it has, however, the advantage that the stationary fuel supply system remains unchanged. With respect to climate change the situation is clear: only hydrogen brings climate change neutrality to transportation, since it will become technologically and economically impossible to collect greenhouse gases from several hundred million (one billion soon) autos worldwide, with a reproduction rate of around one hundred-million copies per year. Onboard hydrogen is the choice; there will not be interfuel competition!

A follow-on question arises: How is hydrogen stored onboard? Two possibilities have been investigated and developed: high pressure gaseous hydrogen ($CGH_2$) tanks and liquefied hydrogen ($LH_2$) containers. (Before metal hydrides of sufficient energy content by weight and volume are market ready, more, perhaps much more time will be needed.) For today's usual vehicle range of 500 km the tank's hydrogen

pressure in the gaseous case has to be 700 bar, which requires a filling station pressure of around 1000 bar. For the engineer both numbers are absolutely not trivial (and think of future billions of lay persons who are to handle equipment of such pressures at the stations)! The liquefied hydrogen container of modern design and production standard contains some 7–10 kgs of $LH_2$ at an inner pressure of 3–4 bar and a temperature of −253 °C; its boil-off rate tends to less than 1% per day. For safety reasons, both gaseous and liquefied hydrogen filling hoses and fueling receptacle valves at the filling station have to be 100% leakage tight. To date, 56 hydrogen filling stations are operable in Europe, 26 of them in Germany (for comparison: here some 15,000 gasoline/diesel/NG stations are in place).

All this said, still the question is not yet answered whether the ICE or the fuel cell, both hydrogen supplied, will be the technologically, economically and ecologically more advantageous prime mover solution. Let's look at the arguments:

- Although the fuel cell is the much older technology (first publication in 1839), its market presence is still almost nil; until now, it is present in some thousand portable, stationary and mobile demonstration units worldwide, as well as in space probes and in German submersibles. The case is different for the ICE, which came to market in the late 19th century and in the meantime occupies almost the entire mobile and stationary markets; here it is operated in around 1 billion copies with a reproduction rate of c. 10% p.a.
- Consequently, the cost of the ICE is well known; it is marketed for a few 10 €/kW, worldwide competition is harsh. Engineers and craftsmen in OEM industries and repair shops are technologically well trained; their thinking and acting in favor of the ICE is the consequence of more than one hundred years of acquaintance. It is otherwise with the fuel cell: it is at the beginning of its learning curve; historical areas where lessons have been learned are not numerous and limited to certain fields, e.g., the space business, electrochemistry, and lately the research and development shops of automobile, electronics and stationary fuel cell manufacturers. Fuel cell market costs are still literally unknown, since so far nowhere have production lots of a size coming near the potential requirements of stationary and mobile markets been practically experienced. And the lifelong operation costs have only been deduced from demonstration units which are rather small in number and only exist in certain application fields.
- Both hydrogen-fueled mobile technologies, the fuel cell and the ICE, are operationally environmentally clean; there is no major difference in their operational behavior vis-à-vis the environment. Both benefit from better vehicle aerodynamics, lower weight construction materials with higher strength and stiffness, and less friction in gears and wheels. The ICE, meeting the European EU5 pollution regulation codes, is literally pollution-free down to the measurability limit, and so is the low temperature fuel cell (jokers sometimes quip that the gas leaving an ICE exhaust pipe is cleaner than the outside air in certain highly polluted inner city areas of the world, which is, truly, not too far from reality).
- Climatically, however, the picture is not too clear. On principle, greenhouse gas emissions occur during the production process of an energy converter (investive emissions), or they are of operational origin (operational emissions). Both energy converters, the ICE and the fuel cell, may have comparable investive emissions. With respect to the operational emissions, the ICE, because of its lower efficiency, demands more hydrogen fuel per kilometer than the fuel cell, hydrogen fuel which, if produced from fossil fuels emitting non-sequestered $CO_2$, is more $CO_2$ intensive than is the smaller amount the fuel cell demands. If produced from renewable energies, the ICE's additional increment of hydrogen fuel demand is irrelevant since the renewable sources hydrogen is produced from are climatically clean. The fuel cell, on the other hand, is not blessed with a stack life as long as the ICE's life, i.e., some 3000–4000 h of operation, which is the operational life of the vehicle. Two or three stacks need to be consecutively installed to be commensurate with the life of an ICE. More stacks per lifetime again bring more investive emissions (not considering cost!). All in all, taking the entire conversion chain into consideration, it is not yet too clear which installation, the hydrogen-fueled ICE or the fuel cell, will be the one which emits less $CO_2$ lifelong. Further development of both technologies is needed before the matter becomes clear.
- Historically, a great many dissimilar auto engines have been under investigation with the intention to perhaps replace the ICE: the steam engine, the flywheel, the Stirling engine, the Wankel engine, the gas turbine, none has really succeeded, perhaps with the exception of the Wankel engine which is marketed in small lots in Japan. Now comes the fuel cell, and it seems that for the first time in the history of onboard prime movers it has a real chance to successfully compete with the ICE. Certain fuel cell parameters are encouraging: the fuel cell fits excellently into the ongoing electrification trend; it serves as battery recharging device and as electrical generator in the main drive train; it is clean, efficient, compact, not heavier than the ICE, and fits into a conventional engine compartment without major modifications; it is without moving parts and, thus, vibration-free and noiseless, more or less. The electric motors enjoy the welcome typical characteristics of low price when mass produced, excellent efficiency, acceptable weight and volume, and convincing acceleration; motor/generators bring onboard the ability to recuperate brake power. Eventually, the electric motors will be placed in the four wheels of the vehicle (which implies a change in wheel dynamics, though!). The automobile fuel cell industry (Daimler) claims these days that their 68 kW fuel cell idles within 1 s at 90% capacity, that its hydrogen-to-electric efficiency is 52% (at peak power, the efficiency at usual driving conditions even may reach 58–59%), and that both its weight and volume are 220 kg or liters, respectively. — All in all, the highly exciting ''race'' between the hydrogen ICE and the fuel cell is not decided yet. Both technologies still have potential for further development; both strive to increase their exergy efficiencies: the ICE by reducing its inherent irreversibilities through utilizing the huge amounts of waste heat in the cooling system and the exhaust, e.g., with the help of the Seebeck effect where a voltage is generated when two different materials are hermetically brazed together with heat on one side and cold on the other, or by incorporating

an ORC cycle in the high-temperature exhaust stream; and the fuel cell, when using pure hydrogen, by eliminating the reformer with its inherently irreversible (exergy destructing) energy transfer, and by reducing stack degradation in order to stay the entire vehicle lifetime from cradle to grave with one stack—hopefully. »Getting millions of (hydrogen fueled) fuel cells on the road … will require policy that is as smart as the technology itself« [80].

- Now let us in a thought experiment imagine a future period of time when the majority of vehicles are run by fuel cells. What does that mean for the industry structure? Today, the automobile engine is in the hands of the mechanical engineer. Casings are foundry products; crankshafts, camshafts, piston rods come from the forging industry; aluminum pistons are manufactured in foundries; the mechanical work is accomplished in the auto industry's shops. All this, more or less, will be subject to change. Fuel cells have no need for crankshafts or engine casings. Fuel cells will be in the hands of chemical process engineers and electrical engineers. The engine shops of the past will have to close down, while shops for membrane and stack production, for heat exchangers, hydrogen tanks and systems, electrical and electronic equipment will open. An almost complete industrial structure change is foreseen. Of course, this will not be a matter of short notice, a transition phase of many years, presumably decades, is anticipated. Visions seldom become real, but in most cases they indicate the root of the matter. Here an indication is given of a complete revolution of the auto industry's manufacturing infrastructure if the fuel cell is to replace the ICE. Early decisions are due to avoid ruining complete industries: »rust belts« around the world tell an eloquent tale. The tipping point is really two points: each new technology era needs sound technology and market experts; it is up to the latter to investigate in due time the various consequences of introducing the new technology and to act accordingly. It sometimes appears as if exactly here are to be found the reasons for many a failure of past innovations.

In North America, Japan and Europe demonstration fleets of hydrogen-fueled fuel cell or ICE busses have been (and still are) on the road operated by municipal transport professionals; they run under conventional conditions with passenger loads and maintain the usual time schedules. One and all, the experiences are positive; no hazard was reported, no major repairs were necessary. The average lay passenger did not even realize that he or she was traveling in a hydrogen-fueled bus, and when informed of the fact, he or she argued in favor of its cleanness and lauded its noiseless operation. – And the cons? No surprise, both the cost of the bus and the fuel are high: the one will come down to the levels customary for conventional bus production lots of some hundred thousand copies per year for each brand, and the other must patiently wait for ongoing skyrocketing crude oil prices. In the meantime, gathering demonstration experience continues.

Climate change debates boil hot for the time being, also in Europe and also relating the transportation sector. The EU plans to regulate $CO_2$e allowables in passenger vehicle transportation to 120 g $CO_2$e/km, a limit which will hardly be met by high capacity limousines and SUVs. Significantly, the auto industry's voluntary self-commitment to reduce automobile emissions to an average of 140 g/km was clearly missed.

Remedies are offered by a change of fuels to biogenic fuels and hydrogen; in Fig. 27 automotive well-to-wheel $CO_2$e emissions [g/kW h] are compared with fuel cost [€/vehicle·km] for a number of biofuels and for gaseous and liquefied hydrogen, compared to conventional hydrocarbon fuels gasoline and diesel at various crude oil costs per barrel, with or without (German) tax; reference vehicle is a non-hybridized VW Golf. – What is seen?

The $CO_2$e emissions for biofuels, depending on the biomass material they are made from, go down to between 30 to 130 g/kW h, and the emissions for hydrogen even to almost zero, both under tax-free conditions at costs that compare rather well with the tax-free costs of gasoline and diesel (especially under exploding barrel prices for crude oil which, as of June 2008, had temporarily reached the historic peak of 139 US$/bbl). Only $LH_2$ produced with electrical energy from solar thermal (SOT) power plants is an outlier; its installed capacity of a few 100 MW worldwide might not yet be significant enough to make a reasonable contribution to the huge world automobile fuel market.

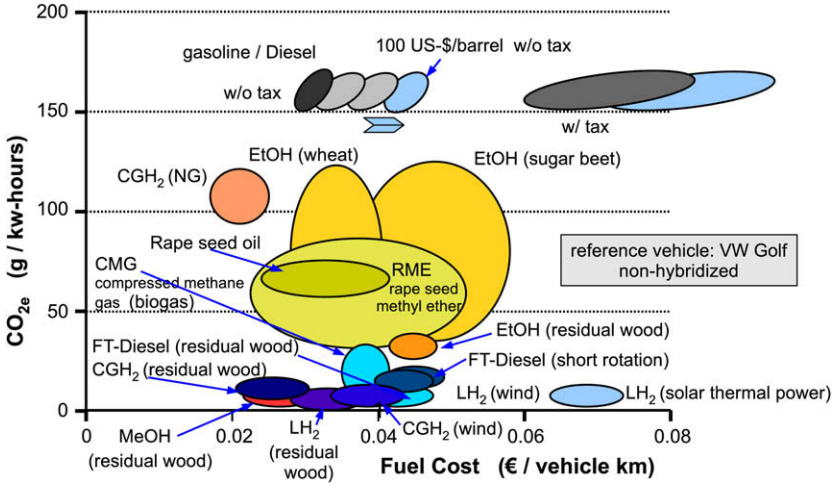



**Fig. 27 – $CO_2$(e) Emissions of transportation fuels related to fuel cost Source: [51].**

All said and considered we conclude that, with the help of biofuels and hydrogen, the greenhouse gas emissions of the transportation sector can be reduced to climate change stabilization levels, at costs which do not jeopardize the market. Two remaining questions are: Will the amounts of biomass from which the biofuels are made suffice for at least a good share of the automobile fuel market, without ignoring the life sustaining priorities of human food and animal feed supply? (see argumentation in ''15. Hydrogen and Biomass''). And the second question: In those cases where hydrogen is made from wind, solar (or other electricity generating renewable sources), is it justified to make hydrogen from electricity when electricity itself is asked for on the market? Or in other words, who is going to win the competition between electricity itself and hydrogen made of electricity, if the potential gross electricity market size is finite? This question has not yet been satisfactorily answered, nowhere in the world.

C. E. (Sandy) Thomas [61] presented at the USA's National Hydrogen Association's annual meeting in 2008 a remarkable paper comparing hydrogen, plug-in-hybrid, and biofuel vehicles; his findings read:

- Hydrogen-powered fuel cell vehicles achieve GHG reductions below 1990 levels by 80% or more, hydrogen ICEHEVs by 60%, and cellulosic (second generation biomass in European terms) PHEVs 25% at best,
- urban air pollution would nearly be eliminated with fuel cell vehicles,
- hydrogen infrastructure cost is not a major issue, and
- hydrogen fuel cell vehicles provide greater cost savings to society than does any other alternative.

It is worthwhile weighing these findings against the aforementioned arguments.

One thing is not questionable: The switch from hydrocarbon fuels to biofuels or hydrogen will not follow a jump function, but rather a continuous process. In an interim period both types of fuels will share market segments, the novel fuels in slowly increasing, the others in decreasing amounts. At the start, hydrogen will not be produced entirely from renewable sources but from the traditional hydrocarbons with the share of renewables growing in parallel (for details see http://www.GermanHy.de). An example is given in Fig. 28, which summarizes the result of a joint (German) project of government, industry and academia, named ''Transport energy strategy (VES)''. What do we see?

Depicted are $CO_2$ emissions in [g/kW h] compared with cost [€-¢/kW h] for an $LH_2$ automobile, the fuel is natural gas and various renewable sources in a share of 50% each; for comparison the data for gasoline without and with (German) tax are added. As expected, the mix offers a significant reduction in emissions, but also a painful cost increase: Gasoline without tax is approximately 60% cheaper than the mix (also without tax). That is the cost of greenhouse gas mitigation through introduction of renewable sources into automobile fuel! Comforting at best is the reflection that today's gasoline price corresponds with a snapshot of the world crude oil scenario; it seems to be unrealistic to expect that the oil price will ever go sustainably down again: no, rising oil prices benefit renewable hydrogen! (for details see ''13. Hydrogen Utilization Technologies'' and Annex 1 ''The German Hydrogen-Autobahn Ring – A Nationwide Project'').

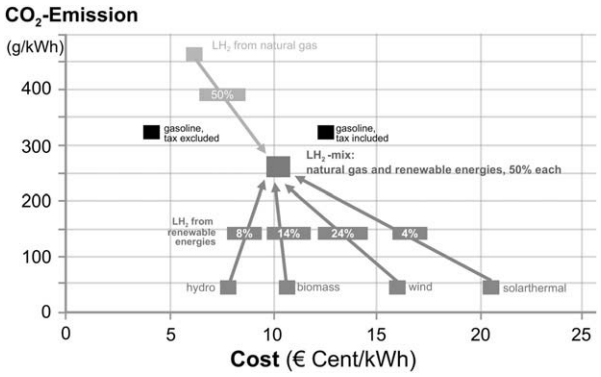



**Fig. 28 – Costs and $CO_2$ emissions of LH2 transportation fuel from natural gas and renewable sources Source: The German Transport Energy Strategy (VES).**

## 15. Hydrogen and biomass

Biomass is renewable secondary energy. Renewable, because when decaying the carbon it releases to the atmosphere in the form of carbon dioxide is taken from the atmosphere during the plants' growth. When energetically used, biomass is biologically or thermochemically treated; it can be burnt to provide heat; it can be gasified or pyrolyzed, fermented, metabolized, or an-aerobically digested to low caloric gas which as »bio-natural gas« can be fed into the natural gas grid or combusted in an internal combustion engine or fuel cell to deliver electricity and heat in a district heating and electricity supply grid. It can be liquefied, the liquid being added to conventional gasoline or diesel or eventually replacing them. Biomass carries carbon and hydrogen (among other things) and needs additional hydrogen (from wherever) when liquefied. Living biomass has a very low solar-to-biomass efficiency of less than one to a few percent; consequently, biomass needs extraordinarily large surface land areas for the production of a given amount of energy, much larger areas than required by other renewable energy technologies like photovoltaic, solar thermal, or wind energy conversion.

There are many competitive applications for biomass such as food production, pharmaceutical and chemical feedstock or construction material, supply of energy, habitat for a great number of flora and fauna species, fixation of carbon dioxide, storage of water, supply of oxygen, forest recreation areas for humans. Utilization of biomass depends on a great number of parameters, such as land area, quality of soil, natural or irrigative water supply, insolation, wind for insemination, availability of workforce, energy (e.g., diesel oil for agricultural machinery and transport vehicles, natural gas and electricity for agro-industries), fertilization, pest control, farming skill, and industries producing marketable products. The energy introduced into the different links of the biomass conversion chain prior to its utilization influences the energy-pay-back

time, telling us how much operational time is needed in order to regain the amount of energy introduced into the whole procedure; often the pay-back time is so long that it barely justifies the biomass energy harvest. If biomass residues or commercially useless biomass like switchgrass or agricultural and industrial wastes or cellulosic municipal solid or fluid wastes are not converted, but rather ''artificial'' biomass from short rotation plantations, then the consequences are destruction and often devastation of biotopes which are thousands of years old. Diversity fades away through introduction of monocultures and soil degradation. Eventually, soils are washed away through wind or floods. Noncommercial wood gathering is today's dominating energy supply method in many of the poorest developing countries. It destroys vast land areas around human habitats, and consequently, longer and longer journeys have to be taken to collect it.

Let us take a closer look at gaseous or liquid products made from biomass. We distinguish first and second generations of biomass; let's begin with the first:

- Biogas, after chemical treatment, moisture removal and pressurization, compares well with natural gas (labeled »bio-natural gas«); the easiest way is feeding it into the existing natural gas grid or, where a grid does not exist, burning it in an internal combustion engine or fuel cell to generate electricity, using the heat in an extra district heating system. Biogas has a density of some 80 kg/m$^3$ and a lower heating value of 48 MJ/kg. With 180 GJ/hectare the yield is reasonable.
- Biodiesel (Fatty Acid Methyl Ester, FAME) comes from rapeseed or soy oil; its lower heating value is 37 MJ/kg, its density 0.88 kg/l.
- Bioethanol from sugarcane (Brazil), corn kernels (USA), or grain ears and sugar beets (Europe) has a density of 0.79 kg/l and a lower heating value of 27 MJ/kg; bioethanol labeled E85 (85 % bioethanol in gasoline) is a common motor fuel in Brazil, the USA, Sweden and elsewhere; in Germany according to federal law 5 % is being added to conventional fuel. A very serious consequence of utilizing bioethanol from corn kernels or grain ears as motor fuel has already been demonstrated in North America and Europe as well as in developing countries where food prices increased significantly after farmers discovered that their income from growing fuel crops was higher than from growing food for humans and fodder for animals. Ethanol from food raw products is not a sustainable solution. Often enough in history when bread prices were raised social uprisings were not far! Bioethanol from cornstalks, straw, wood chips or wastes and residues may turn out to be sustainable, if treated reasonably; this is addressed in the next paragraph which deals with the second generation of biomass. Here, however, productive and long-life enzymes are still not yet available in industrial scales.
- Another critical point is energy-pay-back. Under the Brazilian conditions (weather, climate, soil, labor) the entire sugarcane stalk is processed for glucose and ethanol extraction, and the remaining lignin is converted into process heat in steam plants; the energetic result has a high degree of sustainability (if no extra land had to be provided through deforestation!). The situation is different in the USA and Europe (Fig. 29) where corn kernels are processed. Here the energy needed for the entire process, mostly natural gas, comes from the market, with the consequence that the energy-pay-back is extremely meager. Cynics speak—not too far from reality—of natural gas plants with a small addition of bioethanol!

Now to the second generation of biomass:

- Biomass-to-Liquid (BtL) fuels come from wood chips, bark, straw, stems, stalks, and agricultural, residential or industrial residues; their energy yield is acceptable; the density is 0.80 kg/l, the lower heating value c. 44 MJ/kg. What is still a matter of intensive research and development are the enzymes necessary for breaking up the fibrous material into glucose for further fermentation; a worldwide search for appropriate enzymes is ongoing. If successful, a big leap into the right (sustainable) direction will have been made, because the conflict with food production for humans can be avoided. Simultaneous food and fuel production is the solution when corn kernels and stalks, or grain ears and straw, etc. are harvested and further processed individually.
- Another promising BtL process is flash pyrolysis under oxygen exclusion at a temperature of around 475 °C. The product has a lower heating value (LHV), half that of light heating oil.

In Fig. 30 the exergetic efficiency of hydrogen production from biomass is depicted over the biomass' moisture content. From vegetable oil with no moisture via straw, wood, sludge to finally manure the moisture content increases to 45% and the efficiency shrinks accordingly from 80% to less than 40%; moisture removal is exergy consuming! The largest exergy losses, again because of irreversibilities, occur in the gasifier, followed by losses due to water removal and synthesis gas (»syngas«) compression.

To close this chapter: major biomass capacities and heavy energy users are often spatially dislocated, biomass grows here, and the heavy energy users are there; therefore, diesel oil consuming transportation over sometimes extended distances is mandatory. Two types of biomass are

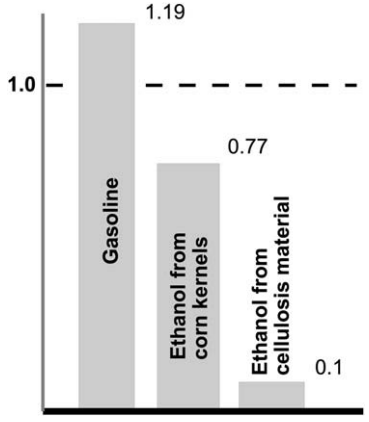



**Fig. 29 – Amount of fossil energy [MJ] for 1 MJ of fuel Source: [66].**

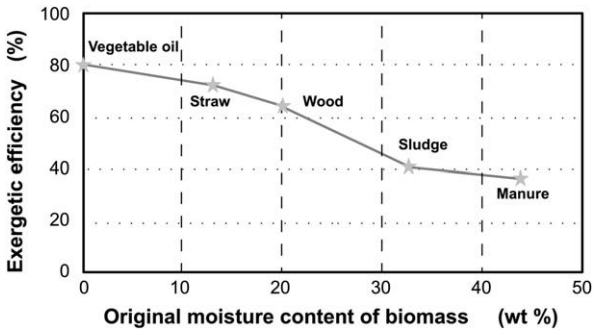



**Fig. 30 – Hydrogen from biomass Source: [46].**

distinguished, on the one side naturally and agriculturally grown biomass, and on the other side wastes, residues or noncommercial biomass. Land for agricultural or forestry biomass has a great many competing utilizations of which food production is the most important. Energy production from residual or waste biomass and from industrial and residential refuse can fulfill two tasks: being environmentally and climatically responsible, and delivering heat, electricity or chemical and pharmaceutical commodities. Utilization of biomass leftovers and industrial/residential wastes is not being questioned. It appears, however, that energy utilization of virginally raised biomass is overestimated and may end up in an illusion. In particular, competition between food production and energy usage needs to be avoided, this competition will never be won by energy! Biomass of the first generation is at an impasse. Once again, thinking ahead, trying to anticipate snares prior to taking action is the mandate: energy policies prior to energy politics! Let's avoid barking up the wrong tree, or, even more precise, any tree at all!

*(In summer 2008, the Commission of the European Union tended to question its earlier regulation of blending gasoline with 10% (first generation) bioethanol by 2020, crediting the use of electric or hydrogen vehicles instead — another step in the right direction of hydrogen in transport!).*

## 16. Hydrogen safety

No technology is absolutely safe! What is lightly heard here and there, ''this or that is absolutely safe,'' cannot, on principle, be justified from an engineering standpoint. Each technology is relatively safe, it has its specific safety standard which, of course, applies also to energy technologies and systems; hydrogen energy is not different. In any case, safety is a consequence of the specific science and engineering attributes of the technology in question, and, thus, its risks under operating conditions.

In Fig. 31 selected safety related data for hydrogen and methane in comparison to gasoline are depicted. Some of the data are not too dissimilar for all three items; others, however, differ significantly. Four categories are particularly interesting for the assessment of hydrogen safety: (1) the diffusivity of hydrogen in air is very high, (2) the ignition energy of an ignitable hydrogen/oxygen mixture is very low, (3) the ignition range is wide, and (4) carbon compounds in hydrogen as well as radioactivity and radiotoxicities are inexistent. Let's discuss:

Like many non-hydrogen gas technologies, hydrogen installations need to be tight in order to prevent leaks or at least keep them as small as ever possible. Since hydrogen is the smallest element in the periodic table of elements and its affinity to oxygen is high, leak tightness is of utmost importance. If, however, leakage occurs or in an accident hydrogen is released to the outside, there is a good chance that no ignitable hydrogen/oxygen mixture is built, or that an ignitable mixture lacks a near-by ignition source, because hydrogen quickly disperses vertically upwards into the airy environment; its diffusivity in air is a powerful acceleration source and, thus, a (sort of) safety element. That is the case when hydrogen is handled in open spaces. In closed rooms precautions need to be taken to avoid hindering the hydrogen from flowing to the outside, such as assuring open outlets in the upper sections of walls, removing barriers of any kind, installing flow accelerators like non-electrically propelled ventilators, and diluting air streams, among other options.

If all precautions against the build-up of an ignitable hydrogen/oxygen mixture have failed, it should be realized that the ignition range for a hydrogen/oxygen compound in comparison to methane or gasoline is much wider, and the ignition energy required for a potential reaction is very small. The frictional electric potential on human skin or a micro-arc from an electric switch may suffice to ignite the mixture. Consequently, in rooms where hydrogen is handled, particular care needs to be taken to avoid even the smallest ignition sources.

Volumes of safety codes and standards have been put together parallel to the decades- or even century-long experience in hydrogen chemistry, in refineries, in the technical gases industry, and in the numerous hydrogen branches where hydrogen is utilized as a commodity. So far, the latest area where safety precautions had to be taken, particularly with respect to liquefied hydrogen, is the space flight business where very large amounts of $LH_2$ (and LOX) are in use as propellants for the jet engines of space launchers. The International Organization for Standardization (ISO) in its Technical Committee ISO TC 197 is establishing the internationally accepted codes and standards for all aspects of the up-and-coming hydrogen energy economy; it is a never ending effort. A productive source of ongoing European hydrogen safety considerations, theoretical and experimental, is http://www.Hysafe.org.

Honestly, all that achieved and despite all lessons learned from past safety events—positive and negative—most probably future accidents will occur. One thing, however, gives confidence: none of the accidents in the aerospace business where hydrogen was involved was causally initiated by dysfunctions of the hydrogen system! Two examples: Addison Bain, in his active time head of the hydrogen regime at NASA's Kennedy Space Center at Cape Canaveral, Florida, USA, thoroughly investigated the 1937 Hindenburg zeppelin crash in Lakehurst, New Jersey. The airship was about to land in a thunderstorm atmosphere with high levels of static electrical potential around. Elms fire was observed around the aluminum window frames of the cockpit. At first, it was not the hydrogen inside the ship which caught fire, but rather the zeppelin's hull, which consisted of a weatherized cotton

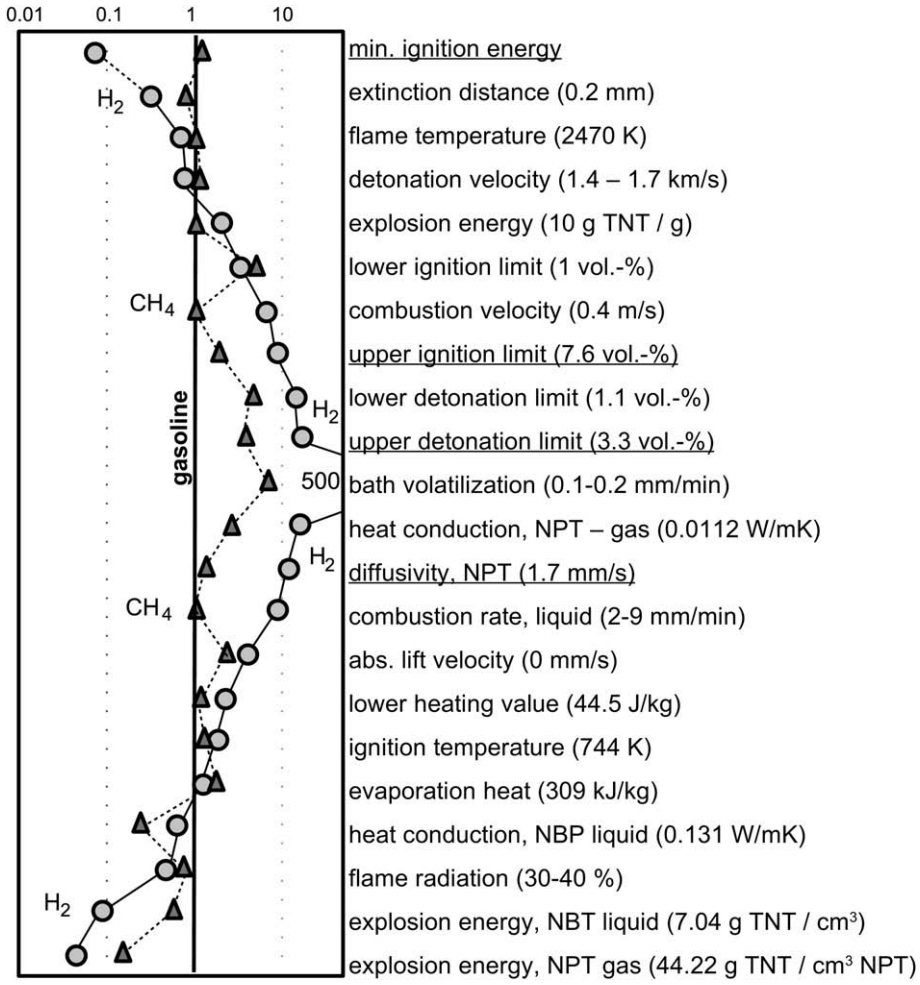



**Fig. 31 – Safety data of hydrogen and methane compared to gasoline Data in brackets for gasoline; TNT: Tri-Nitro-Toluene; NPT: normal pressure and temperature (gas); NBT: normal boiling temperature (liquid) Source: Walter Peschka.**

substrate with an aluminized cellulose acetate butyrate dopant—"a cousin to rocket fuel" (Bain). As a consequence, the hydrogen inside was ignited and the airship crashed. — And the other example: minutes after lift-off in 1986, the U.S. space shuttle Challenger burnt and burst apart. Again, it was not the hydrogen-filled central tank of the shuttle which caused the accident, but one of the solid fuel boosters mounted aside the hydrogen tank which, because of a leaking sealing ring, led a hot gas stream onto the insulation material of the hydrogen tank.

Further, there are two positive safety points: since carbon is not involved in the hydrogen fuel onboard space or future land based or airborne vehicles or vessels at sea, people aboard the vehicles in a potential accident cannot be intoxicated or suffocated. And, since in a future hydrogen energy system radioactivity and radiotoxicities are inexistent, unforeseen long time (unknown) consequences of potential accidents are impossible.

An example: In 1977 two passenger planes bumped into each other while rolling on the airstrip of the island of Tenerife, Spain; kerosene spills caught fire and burned for some 20 min; fumes, smoke and toxicants evolved; passengers died from intoxication or suffocation. Could there have been a similar incident with hydrogen fuel? There are significant differences: In hydrogen planes the liquefied hydrogen fuel is compactly stored in double-walled tanks installed above the passenger compartment and surrounded by the plane's fuselage structure; because of limited space availability no fuel is stored within the wings. If, notwithstanding, $LH_2$ spills occur, the diffusivity of re-gasified hydrogen in air tends to accelerate the flow rapidly vertically upwards. It is not too easy to ignite a $LH_2$ spillage prior to its gasification. The combustion product is water vapor. Toxicants or suffocating combustion products can only stem from the plane's construction material. As the combustion temperature of the hydrogen/air compound is high, particularly radiated heat injuries can occur, in the worst cases fatal ones. As a consequence of hydrogen's diffusivity the combustion time is short.

All in all, when fairly, responsibly, and honestly judged, hydrogen incidents cannot be excluded, but due to the specific attributes of hydrogen their consequences promise fewer fatalities or less severe injuries and material damage. Hydrogen has its specific risks, but its attributes help to alleviate the follow-on effects. No risk can be treated lightly, but engineers who have been working with safety equipment for both hydrocarbons and hydrogen tell us that hydrogen

systems, if the safety rules and regulations are strictly adhered to, are safer than the hydrocarbon systems. In the space launching business, the oxidizing agent is liquefied oxygen LOX which has its own specific safety risks, too. Here particularly fat compounds on equipment surfaces need to be removed in order to avoid self-ignition.

At the end of this section, a few general thoughts: the energy systems we are accustomed to are in the hands of professionals and lay persons. The former run coal mines, oil and gas fields, power stations, refineries, pipelines and electricity grids, liquefaction plants, and tanker ships, and they operate busses, trucks, locomotives, airplanes, and spacecraft. In the hands of lay people are residential energy systems, autos, and electrical and electronic equipment. As an inherent consequence of hydrogen energy, in particular renewable hydrogen energy and its technologies, decentralization of energy increases, such as solar photovoltaic generators and thermal collectors on roofs, hydrogen-fueled fuel cells in the cellars of buildings, and hydrogen from the dispenser at the filling stations, and this equipment ought not remain in the hands of lay persons. Not only safety considerations but also effective and efficient energy utilization ask for indispensable professionalization also at the back end of the energy conversion chain where energy decentralization will be taking place. As a convincing example just one professionalized technology is mentioned, robotized fueling of hydrogen vehicles: The (lay) driver, entering the station, stops at a red light, remains seated in his car and identifies himself and the type of his vehicle by inserting his plastic card. A robot opens the tank lid, inserts the fuel receptacle valve, confirms absolute leak tightness, fills the tank, and finally closes the lid again. The light switches to green. Not even one hydrogen drop was lost. Filling time is similar to what we are accustomed to today, a few minutes. After a while the driver will be notified that the amount of his purchase has been deducted from his account.

A final thought indirectly related to safety aspects: we already mentioned that an increase in efficiency is urgent so that less primary energy produces more energy services. Less primary energy corresponds to fewer safety risks; what is not utilized is of no safety relevance. Finally, since decarbonization replaces more and more carbon with hydrogen, carbon related risks tend to vanish.

## 17. Hydrogen energy: costs and $CO_2$ emissions

Like any other energy, hydrogen energy has to meet a range of criteria before successfully entering the market. The two major, perhaps dominating criteria are costs and $CO_2$ emissions. Of course, costs are key for the entry of any energy into a competitive large scale market, and hydrogen energy is not different. Carbon dioxide is the predominant greenhouse gas with the maximum influence on anthropogenic climate change, followed by methane $CH_4$, nitrous oxide $N_2O$ and fluorine gases. Correctly, all emissions have to be taken into account along the complete energy conversion chain from the very beginning of primary energy conversion to finally energy services utilization.

In Fig. 32 costs [€-¢/kW h $H_2$] and $CO_2$ emissions [g/kW h $H_2$] of gaseous and liquefied hydrogen energy production are shown. Three primary energies have been taken into account: natural gas in the upper part of the figure, coal in the middle, and renewable and nuclear energies at the bottom. No link of the energy conversion chain was forgotten, from production

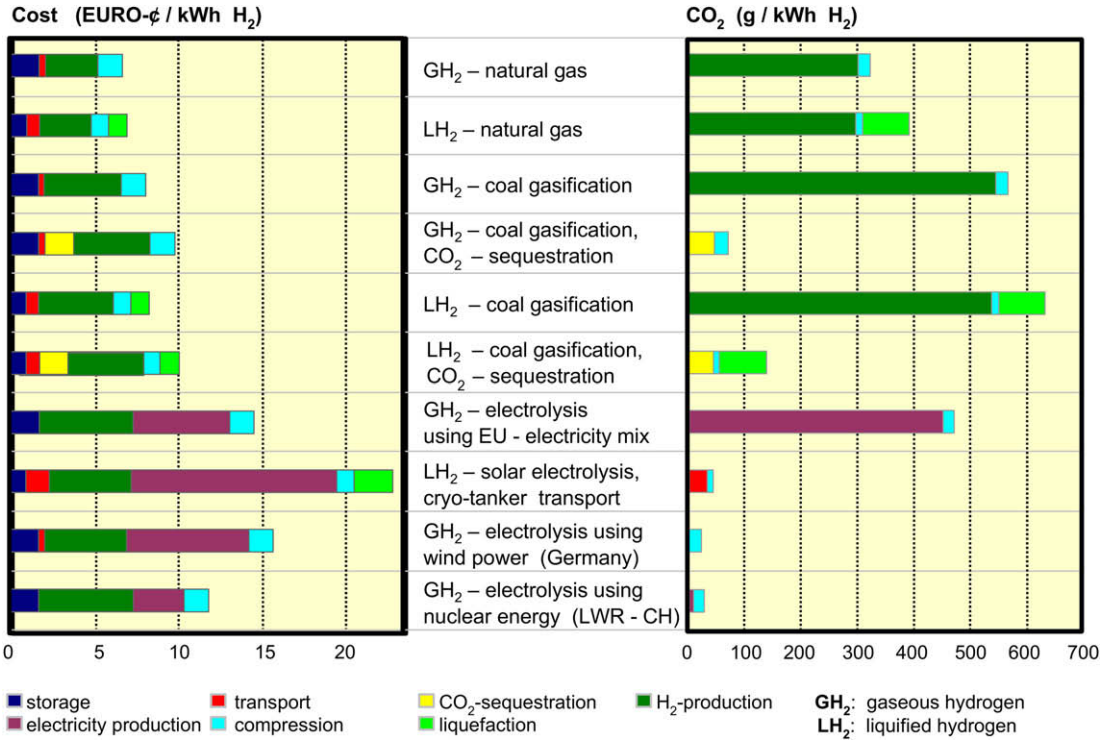



**Fig. 32 – Costs and $CO_2$ emissions of hydrogen production Source: [68].**

via storage, transport, and electricity generation in the case of electrolysis. What is seen?

Hydrogen production from natural gas shows, no surprise, the lowest cost, although moderate amounts of $CO_2$ emissions, if not captured and sequestered. Hydrogen from coal has moderately higher costs, but its emissions without sequester are prohibitively high; $CO_2$ capture and sequester bring them down to acceptable levels. For hydrogen from renewable or nuclear energies the picture changes: now, because renewable energies are not yet fully developed to unsubsidized market levels, costs are prohibitive, and emissions tend to zero. Clearly seen are the cost dominance of electricity production with renewable technologies and the unacceptable $CO_2$ emissions of fossil fuels without capture, sequester and final storage; in both cases further technology development is imperative.

A comparison of sequestered emissions in the coal-hydrogen cases with those of renewable hydrogen gives a clear indication of the importance of capture and sequester. Environmentally and climatically no big difference is seen between hydrogen from sequestered fossil fuels and hydrogen from renewable sources; costs, however, differ significantly. The cardinal question remains: if coal-hydrogen including carbon capture, sequester and storage (CCS) is the climatically clean solution, at least in the interim until unsubsidized renewable hydrogen is market ready, will then the whole $CO_2$ complex of capture, liquefaction, dehydration, transport, storage, and deposition be economically viable and geoscientifically responsible long term?

Clearly, the retrofitted plant share of an operational power plant, a nuclear station and a modern, highly efficient fossil plant deliver the lowest mitigation costs. There are a number of carbon capture and storage methods which, so far, have not yet revealed a priority technology, which is the reason for the wide cost range for $CO_2$-free (better $CO_2$-restricted) fossil plants of 30–50 €/tons $CO_2$. Renewable plants are still far from unsubsidized market conditions, further development which lowers their cost is urgent. Hydrogen production within a cap and trade price bandwidth of 5–30 €/tons $CO_2$ seems marketable; of course, use of nuclear plants requires societal acceptance.

## 18. Energy 2050 at a glance, concluding remarks

This manuscript was written around the turn of 2008/2009; it was written particularly as an accompanying framework text of the forthcoming 18th World Hydrogen Energy Conference which will be held 16–21 May 2010 in Essen, Germany.

Until the mid-21st century we have before us some 40 years, a very short time in energy economic and technology categories. For illustration, let us recall that the first nuclear reaction was experienced by Otto Hahn in Berlin in 1938; now, after 70 years, nuclear power stands for (only) some 7–8% of primary energy equivalent worldwide, and a reactor's operational life is 40–60 years. Coal mines need 20–30 years before the first loaded tipper truck arrives at the mine mouth, and their life may exceed 100 years. Electric utility plants (nuclear or fossil) are seldom decommissioned prior to occasional technology repowering, their total lifetime approaches 50 or more years; hydropower plants are even operated for around 100 years. In the energy utilization realm, buildings are hardly replaced by new constructions only because of a potential improvement of their energy situation. European cities statistically replace their buildings not earlier than after some 70 years, or after much longer time periods, if at all, of artifacts of cultural heritage such as cathedrals, cloisters or castles. Individual mass road transport and commercial aviation massively started only after World War II; in the meantime they have been around for 60–70 years. And finally, novel energy utilization technologies regularly needed also long development time periods: a first gas turbine was patented 200 years ago, but began its triumphal utility not earlier than a few decades ago; the fuel cell was mentioned in literature for the first time already in 1839, but still has not yet achieved irrefutable mass market success, and so on, and so forth: energy, energy technologies need time, many decades up to half to full centuries are typical!

What applies to energy technologies is even more applicable to primary energy feedstock or primary energies. The first solar civilization began with humans' advent on earth and is now reduced to merely noncommercial irksome wood or dung collecting in the world's poorest developing countries. Coal's world success started with the opening of the first commercial coal mine in England in the second half of the 18th century and is today with some 20% of the world's supply still in full swing. Oil and gas, although explored already in the second half of the 19th century, really began their worldwide mass market success not much earlier than after World War II and stand now for some 60% of the world's total energy demand. — It appears that the next two additions to the mix will be energy and exergy efficiency gains, and renewable energies, these now of the second solar civilization. What is clearly seen is the continuous shrinking of national energies and the rise of the now prevailing international energy trade system; only a few nations in the world are 100% energy self-sufficient, though remaining dependent on energy technologies from other countries. What is further seen is that energy is nothing static; ongoing development to energy heterogeneity is the rule. Altogether, energy is associated with very long lead times, energy is a matter of centuries: up until deep into the 18th century exclusively renewable energies of the first solar civilization were utilized, wood, running water, wind; the 19th was the century of coal, in the 20th century supplemented by oil, natural gas and fissionable uranium; now on the brink of a new century there are three more additions: energy and exergy efficiency gains, renewable energies of the second solar civilization, and the secondary energy carrier hydrogen, before towards the end of the 21st century nuclear fusion will have arrived—perhaps.

In Fig. 33 energy and the well being of people on earth are correlated. Some 80 million more humans live on earth each year (approximately the population of Germany). Expected are some 9 billion by 2050. More people means more energy. Industrialization of those regions where more people live means even more energy. The world's average demand is 2 kW h/cap h = 2 kW/cap. The majority of people live below that average; some even have no access to commercial energy at all. All in all, it seems not too farfetched to suppose that the world's energy demand will rise further, only mitigated by

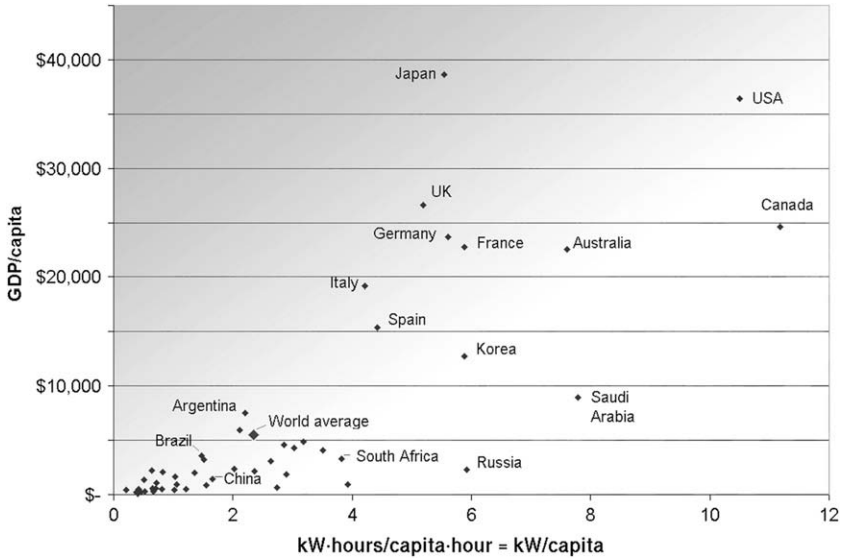



**Fig. 33 – Energy demand vs. the GDP of nations (2005) Source: IEA – Key World Energy Statistics 2006.**

rising efficiencies and, thus, relatively shrinking primary energy demand in the industrialized world.

There is also a close correlation between climate change and energy: energy, its production, handling and utilization has the major influence on climate change (for details see ''4. Anthropogenic Climate Change and Hydrogen Energy''). Three energies whose applications do not emit any of the greenhouse gases influencing the earth's climate may cut the Gordian knot of mitigation: energy and exergy efficiency gains, nuclear fission, and all sorts of renewable energies. The potentials of all three are immense: regularly, modern industrialized nations reduce their annual energy demand by around 1%, Germany even plans aiming at 3% (achievable?), which is not a matter of available technologies, but of economic viability and political will! The forthcoming switch to exergy-efficient combined cycles adds another incentive to demand reduction. By 2050 nuclear fission will still not suffer under uranium supply shortages, although fast breeder reactors may not be operational by then. Both nuclear fission and renewable energies need hydrogen, the one in high-temperature reactors predominately as exergy-efficient high-temperature heat source for allothermal hydrogen-supported coal decarbonization, the other in order to facilitate their contribution to the world energy trade, since so far all utilization of nonstorable renewables is restricted to local, at most regional applications. For a period of up to a half or full century nuclear fusion will most probably still remain a scientific and engineering research and development venture, an absolutely fascinating and challenging one, though.

The three climate neutral energies mentioned relate dissimilarly to energy price levels. Aggressive striving for increased energy and exergy efficiencies is a direct consequence of the exploding price jumps of conventional energies. Cheap energy is the most elusive enemy of energy security, and as well of higher efficiency novel energy technologies. At this stage, freeing renewable energies from their remarkably high subsidies will, besides further technological development, be achieved by elevating energy price levels, the matter will quasi resolve itself. And the third climate neutral energy, nuclear fission, plays a price-smoothing role, since its overall cost calculation is predominantly technology dependent, only a small cost share stems from the fuel, and in addition, its contribution to climate change is nil.

What does all that mean for our glance at 2050? Let us try to avoid the mistake often made when looking into the future, namely simply extrapolating the present situation. First of all, humans are not too well prepared for what the energy world will encounter down the road. Environmentally and climatically clean energy by 2050 is still far from certain. What ought to be in operation 40 years from now must already be in the pipeline today, or it will not be! What will not be in commercial operation at all is easy to see: nuclear fusion. Coal and nuclear fission will continue to provide energy to the world, not only until 2050 but also well beyond that date, coal perhaps in slowly shrinking relative amounts, fission with smaller growth rates, new coal undisputedly with carbon capture and storage (CCS), and nuclear with fourth generation reactors and their expected higher safety regimes or, even more farsighted, with high-temperature reactors run exergetically efficient in combined cycle mode, serving not only the electricity, but also the high-temperature heat market. Oil may retain its supply contribution or it will go down, here two tendencies work in opposite directions: on one side the galloping price trend builds up market barriers which favor competing energy alternatives such as the global hydrogen trade, and on the other side so far economically nonviable and extremely climatically harmful »crudes« like tar sands or oil shales or untouched sources on or below deep sea floors or under ice cover approach commercial viability. Natural gas is the present champion, and it appears that it will remain so at least in our 40 year forecast, which for nations heavily dependent on gas imports will not be too comfortable diplomatically and commercially, to put it mildly. Diversification of

suppliers and supplying modes including $LH_2$ tanker transport is mandatory!

What truly will be novel in the energy arena are the three newcomers: (1) energy and exergy efficiency gains, (2) renewable energies of the second solar civilization, and (3) hydrogen energy. All three are characterized exclusively by technological knowledge and engineering skill, not by the operational feedstock. Renewable energies lack operational energy feedstock on principle, and for energy and exergy efficiency gains technologies are the key to providing more services from less primary energy raw materials. The energy market dominance switches from today's energy raw material providers to those knowledgeable about energy technology science and engineering. Energy technologies become more important than energy raw materials. The center of gravity within the world's energy conversion chain moves towards the chain's back end: environmentally and climatically clean, efficient secondary energies, end energies, useful energies, and finally energy services will characterize human energy supply systems by 2050. Energy raw materials were 19th and 20th centuries, exergetically efficient conversion technologies of low irreversibilities and, thus, low exergy destruction are 21st century!

Hydrogen not only adds to electricity another environmentally and climatically clean secondary energy carrier, it is also indispensable for combined cycle coal utilization; it is essential for tapping exergy-efficient distributed stationary fuel cell power and heat at the back end of national energy conversion chains, and finally, it makes transportation related climate change neutral.

''Who looks ahead, is the master of the day.'' Energy is not a matter of tackling day-to-day inconveniencies, energy is foresight, is thinking and acting in long waves, not in jump functions; energy is nothing for the impatient, a decade is nothing for energy! Winning the energy future is so much harder and much more time (and money) consuming than winning its present; for the time being, energy lives on borrowed time. For visionaries it might be disappointing not to see more of the novel additions to the mix in 40 years' time, and for climatologists the energy approach to climatic cleanness might be unsatisfactorily slow. Three potential influences are—almost—outside the powers of public intervention: oil price jumps as a consequence of the growing oligopolization of suppliers, climate catastrophes, and, perhaps the most serious influence, lacking awareness of the clear indications of forthcoming developments: »We thirst for knowledge, but we are drowning in a sea of information« (N. Postman).

If the next 40 years are truly taken seriously, humans must accept that energy development is nothing completed in a jiffy but something requiring positiveness, patience, pertinacity and resilience. Humans must be fully aware of exergo-thermodynamics, aggressively promote renewable energies, and add the so far last lacking leg of the energy triangle, comprised of: (1) hydrogen-supported cleaned-up fossil fuels, (2) operationally carbon-free renewable energies and responsible nuclear fission, and (3) the two secondary energy carriers electricity and hydrogen.

What hydrogen energy needs is vigor, not fickleness; major capital, not small change; continuity, not ups and downs; and, the most important, conviction, not ambivalence! What we face is nothing less than an energy-system-change, comparable to the step into the electricity age which started more than a century ago and has by no means yet come to an end, or to the step into modern transportation, also 100 years old, although billions of people still have never sat in an automobile or booked a flight ticket. Hydrogen energy offers an innovation push; hydrogen energy is a powerful major job engine.

''Visions are more important than knowledge, since knowledge is finite'' (Albert Einstein), and Ernst Bloch adds, ''Visions need timetables.'' Here, a timetable has been drafted consisting of up-and-coming novel energy technologies in the energy-system-change ahead, and their respective time frames.

We close this concluding remarks with a retrospection on findings already published in the early 1990s: ''Assuming that by the middle of the next century [*note: the 21st century*] it will be necessary to reduce $CO_2$ emissions more than 60%, the development of a hydrogen [*energy*] economy is not only consistent with the call for an energy supply which is as economical as possible. Such $CO_2$ reduction goals even mandate the utilization of these technologies.'' (Fraunhofer ISI – Institut für Systemtechnik und Innovationsforschung and PROGNOS).

### 18.1. *Epilog*

> ''The energy system compares nicely with a bike, if not pushed forward, it tumbles!''

Niles Eldredge and the late Harvard palaeontologist Stephen Jay Gould presented at the Annual Meeting of the Geological Society of America in 1971 a landmark paper introducing into the evolution theory the term »punctuated equilibrium,« meaning that in an extremely limited short period of time species rapidly grow into a higher state of their intellectual being, or novel species enter the scene. After the end of that time period the evolution falls back into its usual almost glacially slow Darwinian pace, until the next punctuated equilibrium comes along.

Quite similar things happen to technologies here and then. Take the short period of a few decades around the turn of the 19th and 20th century: Almost all of a sudden the automobile arrived on the road with its propelling reciprocating piston engine aboard; the electrical generator provided electricity for the manufacturing industry and city street lighting; the telephone made communication easy, from the 1920s onwards even with the help of long-distance cables across the Atlantic; and oil and gas fueled the booming industrialization of Europe and the New World.

But after that rather short period of time, »nothing more« happened. Of course, the auto was further developed, its speed increased, fuel consumption went down, the two-seater developed into a four-, even multi-seater, reliability was improved and safety requirements were met; but, on principal, the original configuration only changed minimally: the vehicle still has four wheels, an Otto or Diesel engine still powers it, the vehicle is still made of steel, mineral oil derivatives still serve as the fuel. Only recently (compared to the more than hundred years of automobile history) have gradual changes turned into principal changes: for the first time in the automobile's history, hydrogen and the fuel cell (''the power station on wheels'') as

well as the vehicle's electronification (''the computer on wheels'') offer the chance of a next punctuated equilibrium.

The good old »steam telephone« arrived at its life's end: It was replaced by wireless mobile telecommunication via satellites; automatic information exchange between personal computers took over; television is available and provides information 24 h a day; the World Wide Web delivers any information any time at any place, and drastic cost reductions up to 99% make communication and information a mass availability phenomenon: the semiconductor and the transistor were—and still are—the key technologies!

Sadly, firms in established industries usually innovate hesitantly, and mostly only in response to new technologies coming over the horizon that threaten their survival. Correspondingly, Max Planck observed» The usual way a new scientific truth becomes generally accepted is not that its opponents are persuaded and stand corrected but that its opponents gradually die out and the next generation grows up with that truth from the start« – a bitter recognition? A realistic one!

Now, when will the next energy punctuated equilibrium occur? We don't really know. But what we already know are the names of what will become part of it. They read: decarbonization of fossil fuels via CCS and, thus, their hydrogenation and dematerialization; read: storage and transport of large scale renewable energies via the chemical energy carrier hydrogen which enables them to take part in the global energy trade system; and read: exergetization of the energy system and, thus, making use of the maximum extractable technical work from energy. In short, an energy-system-of-change is due with combined cycles and energy converters with low irreversibilities and, thus, minimum exergy destruction and exergy losses! Further names for the next energy punctuated equilibria are decentralization of energy and professionalization of the back end of national energy conversion chains, which at this stage is in the hands of the lay population; energy is much too precious to leave it there!

Literally, more or less all expected energy punctuations have to do with hydrogen energy, all together they are epitomized in the up-and-coming hydrogen energy economy: it's HYtime!

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Tax money for R&D in almost all fields of hydrogen energy and its technologies still plays an indispensable role. The funds allocated in industrialized countries around the world have appreciably increased in the recent past. But what is even more important is the identification of those who dedicate the money to the different R&D fields.

Here, the State Government of North Rhine-Westphalia, Germany and especially its administration for Economic Affairs and Energy deserves tribute and recognition: Germany's energy state in an early period of time recognized that the 200 years of the Ruhr area of indigenous coal tend to an end and are to cross the roads from electricity and steel which kept coal alive to electricity, hydrogen energy and stainless steel which will be keeping clean coal alive! It is considered only consequent that the State Government appreciably supports the operations of the 18th World Hydrogen Energy Conference 2010 in Essen, Germany—in Essen, the capital of the historic Ruhr area which was awarded The European Capital of Culture for 2010: Hydrogen energy and its technologies are part of that culture; they are clean, abundant, efficient, and accompanied by an energy-system-change to non-heat-engine related-conversions. The vigor of hydrogen energy avoids the ''rust belts'' under which so many areas of the world suffer.

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## Annex 1

### *The German hydrogen-autobahn ring — A nationwide project*

Time has come to identify the industrialized world with a novel addition to the energy mix and its technologies and, thus, demonstrate hydrogen's maturity and economic viability to the public, to industry and trade, and not least to administrators and politicians.

With a peak price of US$ 4/gallon[2] of gasoline at the U.S. filling station in June 2008, energetically equivalent to US$ 4/kg of hydrogen, the commercial viability of hydrogen energy is near, if not already achieved; even more so when at the same time € 1.5/l of gasoline at the dispenser in Germany is taken into account, energetically equivalent to a fantastic (for U.S. citizens, even for Europeans), though real in day-to-day practice, US$ 8.52/kg of hydrogen!

The hydrogen-autobahn ring from Berlin via Hanover, Düsseldorf, Stuttgart and Munich back to Berlin consists of

[2] In the meantime the fuel prices went significantly down again; this, however, doesn't really change the message: increasing supply shortages and growing suppliers' oligopolization tend to enforce a mainstream upward general price trend! Statistically, the average gasoline price at the dispenser in Germany grew from 1950 to 2008 by c. 2 €-¢ per annum.

some 10–15 hydrogen filling stations (one every 200 to 300 km) designed and constructed by the technical gases industry. The stations are supplied with liquefied hydrogen from the two national liquefaction plants located in Ingolstadt and Leuna right alongside the ring, or with gaseous hydrogen from all places where today hydrogen is being flared, or from the national hydrogen pipeline running pretty much parallel to the ring from the Ruhr area to Cologne over some 250 km.

The first vehicles to be fueled with hydrogen are city busses, light duty vans of small-to-medium size industries or trade companies, and numerous short- to long-range passenger vehicles provided by auto makers in Munich, Ingolstadt, Stuttgart, Rüsselsheim, Cologne and Wolfsburg, all of these locations touched by the envisaged ring. Besides these OEM industries, various hydrogen industries are invited to offer their products to this first of its kind central European hydrogen showcase, thus alerting other markets to join.

## Annex 2

### *A Hydrogen energy tycoon?*

Do we see any Friedrich Krupps, Henry Fords, Werner von Siemens', Cornelius Vanderbilts, Bill Gates' of hydrogen and hydrogen technologies? Do we already see entrepreneurial matadors somewhere in the world who are devoting their thinking and acting, their skills, their financial capital, and their organizational talent to evolving hydrogen markets? To clean hydrogen production, to its different types of storage, to hydrogen transport and trade, to hydrogen utilization technologies? Are we expecting well-known companies to start or be on the verge of starting to become matadors in hydrogen energy businesses?

Yes we do, and no we don't (yet), both answers are true. — Of, course, there are the space rockets launching companies which wouldn't even exist without hydrogen, in this case liquefied, stored, transported and combusted hydrogen; and there are the industrial chemistry companies utilizing hydrogen as a commodity, and, of course, there are the Seven Sisters running their refineries, and there are the methanol or ammonia manufacturers producing their needed hydrogen captively. Chapters "11. Hydrogen Production," "12. Hydrogen Handling, Storage, Transport, and Dissemination," and "13. Hydrogen Utilization Technologies" covered all that.

All aforementioned hydrogen businesses have something in common: they belong to "old" well established markets: hydrogen as space launching propellant began more than half a century ago, and hydrogen chemistry and trade in technical gases are much older still. No, what is meant with our question about the hydrogen matadors refers to those who take care of the novel markets-to-come of the forthcoming hydrogen energy economy: and here the answer is rather modest!

The chapter "10. Hydrogen Technologies along their entire Conversion Chain" brought in three tables summaries of hydrogen energy technologies already marketed in small quantities, or in a waiting position, or still in R&D labs and development shops. But is there a matador visible? One whose key technology is the basis for the up-and-coming economically viable hydrogen energy market? One like Henry Ford, who started the mass production of reasonably priced autos (the legendary "Tin-Lizzy") and gained a world industrial empire; as did Werner von Siemens, whose electrical generator provided the core solution of generating power at one place and using it somewhere else, the still valid solution of geographically disconnected energy production and utilization.

In our times we had Geoffrey Ballard who, with a number of colleagues, founded Ballard Power Systems in Burnaby, British Columbia, Canada; and we have almost all big world auto makers who are developing fuel cell vehicles—a little hesitantly, though, since they are in parallel developing other electric vehicles that get their electricity not onboard but from outside, like the plug-ins, the hybrids, the pure electric battery vehicles, and combinations. For the industry's policy makers' market developments are still not too clearly foreseeable; perhaps here we get a feeling of the frequent change of fuel cell vehicle market entrance dates which automobile companies used to announce.

For stationary or portable fuel cells a wealth of small to very small companies have developed worldwide that are still in their research, development and demonstration phases delivering small lots of products to a limited number of clients. Normally these companies' financial situation is modest, to say the least, if not risky, since they live off risk capital with interest rates of 30% or even higher. Similar things are true for mobile storage developers. An exception to this general observation are perhaps the big players in electronic devices, who have clearly devoted themselves to portable micro-to-mini fuel cells for all sorts of portables like cellular phones, camcorders, television cameras and the like.

How about the major electricity utilities and the coal industry and their inclination to build efficient combined cycle power plants delivering simultaneously both electricity and hydrogen? No, they are still on their usual pathway constructing exergetically excellently efficient coal-fired electricity plants with nearly 50 % efficiency or even a little higher. The engineer and the energy economist admire that, no doubt, but let's be realistic, the remaining 50 % of the coal's energy content is still being converted to high-temperature exhaust heat with no industrial user around; only in the very rare situations when, say, a cement factory or a steel mill is located in the vicinity does the high-temperature exhaust heat perhaps find a market.

Electrolytic wind-hydrogen or solar-hydrogen is even farther away from the market. Still, wind energy converters and solar generators "only" deliver electricity, and when, say, an off-shore wind park needs efficient and reliable electricity transport in order to be connected to its far away on-shore users, high voltage direct current (HVDC) solutions enjoy priority (if the distance and nasty sea floor conditions allow for). — The situation changes when very large amounts of wind or solar electricity are planned to contribute to the world energy scene, e.g., wind from Patagonia in the far away South of Argentina, or solar from Australia, both commissioned to supply Europe or Japan or the USA. In such cases hydrogen as the transportation means is unavoidable. But, far and wide, no major energy company in the world is following that idea yet, not to speak of a matador.

The technical gases industry is well prepared to play an important role in the hydrogen energy field. The major

companies—Linde, Air Products, Air Liquide, Praxair and perhaps a few others—are experts in electrolyzers, steam methane reformers, liquefiers, hydrogen dispensers and filling stations. None of them, however, has developed into a champion's role, leaving all the others behind, so far.

Similarly, ''Big Oil'' is absolutely knowledgeable and experienced in hydrogen and its technologies. Large amounts of captive hydrogen are in use in crude oil refining, for the production of reformulated gasoline or de-sulphurized diesel. But again, no champion has evolved yet.

Having said all this, can a hydrogen energy tycoon realistically be expected? Most probably not. Let's see: Most of the hydrogen energy technologies along their complete conversion chain from production of hydrogen via storage and transport to dissemination and finally utilization go back to inventors who have lived and researched over the past two centuries and a half starting in the later 18th century. Mostly as late as in the second half of the 20th century, their inventions were taken over by developers in national labs or universities, and their results are now under the control of the appropriate industries who simply buy what has left the labs, approaches market readiness and promises profitable return (see Tables 1–3). The coal, oil and gas industries are familiar with all aspects of hydrogen production in gasifiers, reformers, partial oxidizers, and other approaches. The electrochemical industry builds and operates electrolyzers. Pipelines hundreds of kilometers long for gaseous hydrogen and liquefied hydrogen (much shorter) are day-to-day practice. Storage on the ground and underneath are fully operable, taken care of by the technical gases or industrial chemistry industries, or by space launching companies.

In the final link of the hydrogen conversion chain, the utilization link, we see a different picture: The hydrogen-fueled portable mini-to-micro fuel cells are clearly in the domain of the electronics' industries. Small-to-medium size companies have specialized on portable fuel cells in the kilowatt range for military applications or leisure activities. Deliverers of central heating systems for residential homes or office buildings are active in low-to-medium temperature fuel cell replacements of the traditional boiler/burner combinations. Here a challenging controversy is to be expected between central heating system companies and electricity utilities. Because with their fuel cells the system companies no longer deliver only heat devices, but devices which simultaneously generate heat and electricity. In a country like Germany, to take that example, with some 15 million boilers/burners replaced by fuel cells à 5–10 kW electric, the distributed power easily sums up to today's full-electric power on line! Since this newly evolving competition in the electric power market competes with the traditional power business of the electricity utility companies on line, the matter will become rather touchy! An exciting development is foreseen, as its result one or two matadors may evolve.

The auto manufacturers deserve special attention: It may be that the present major challenges—cost reduction, fuel consumption reduction, change of fuel to carbon poor/hydrogen richer compounds—will be mastered by further-developed ICE vehicles, natural gas or biofuels, and hybridized electric vehicles of various designs. In the longer run when the traditional fossil fuels get scarcer and scarcer (and ever more expensive), the ICE's development potential approaches its limit, and the land surface area dedicated to the production of biofuels is completely exploited, then hydrogen energy, in particular renewable hydrogen, gets to its tipping point.

Let's return to our question: Will we see ''A Hydrogen Energy Tycoon?'' It seems not too realistic to expect one, at least not in an early period of time. The energy-related industry branches appear to be well prepared to add to their portfolio hydrogen energy and all sorts of hydrogen technologies, as soon as indications of forthcoming profitability favor investments. One thing, however, should not be forgotten: energy is a highly political matter, and so will be hydrogen energy! We said it earlier: ''The laws of parliaments and the laws of nature have developed increasingly divergent, and it is unreasonable to expect that the laws of nature will yield!''

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