SUNRISE – A caesura after nuclear has gone: Energy in Germany (and in other potentially de-nuclearizing countries)

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Abstract
The German Bundestag decided June 30, 2011 to shut down by 2022 stepwise the complete national nuclear power plant capacity which at the time of decision generated some 22% of the nation’s electricity demand. This presentation tries to present a technology forecast of three potential compensations 1) energy and exergy efficiency gains, 2) renewable energies, and 3) hydrogen energy, thereby bearing in mind that fossil fuels such as coal, mineral oil and natural gas will by no means be gone after that short 10 year transition time. Consequently, not only the three compensations, but also fossil fuels – now efficient to the technological utmost – have to meet the obligation of reducing anthropogenic environmental and climate changing influences, and, in Germany’s case with 75% of its energy demand covered by imports of great importance, try to decrease the almost life risking high import rate by distributing suppliers all over the world and start introducing global clean renewable energies and trade in renewable hydrogen energy. Whether SUNRISE will evolve into a paragon for all those nations thinking of, planning for, or already taking the first steps towards saying farewell to nuclear is too early to determine. The four components of energy sustainability compensating for nuclear energy and exergy efficiency gains, clean fossil, solar and hydrogen – pluck up courage, make headway and leave nuclear behind. And, in particular, hydrogen energy is and will increasingly become humankind’s common cause!

Two conclusions recapitulate the findings: “Activate what lies dormant” and “Remove barriers.”

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Dedication: This paper has two dedications: It is dedicated to the political class in Germany and other countries that have decided or are inclined to decide to close their nuclear arsenal for good, and show the courage to see to it that energy efficiency gains, all sorts of renewable energies and hydrogen energy are well prepared to fill the energy gap left by de-nuclearization. And number two: After so many decades of collaboration with worldwide good engineering colleagues in the fascinating fields of novel energy research and development this paper’s author has now to leave and bid farewell. Some things have been achieved, much, much more waits for the younger generation to accomplish, and to them as well I dedicate this paper. Renewables and hydrogen energy are still not in the energy mainstream. Time and again, novel energies need time, many decades up to half centuries, for irrevocability, it seems so that it is almost always too late to start and see the matter through. Soon the environmentally and climatically irresponsible global nuclear and fossil energy trade system will have to be replaced by trade in clean renewables and hydrogen. To make that happen, fight the conversional irreversibilities and exergize energy, add to the thermodynamics of prevailing rotary and reciprocating heat engines the electrochemistry of electrolyzers and fuel cells, thereby getting more technical work from energy, more exergy! Complement the electricity grid in place with the second secondary energy grid, the hydrogen energy grid. In your thinking and acting, put technologies first, energy raw materials last!

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1. Introduction

Germany’s forthcoming energy system is de-cocooning. It compares well with a caterpillar still in its cocoon: so far it is not yet known whether a beautiful peacock butterfly or simply an ugly moth will emerge. Not much is for certain, but one thing certainly is cocksure: after Three Mile Island, Chernobyl and all the other nuclear accidents, the next Fukushima is impending! It could be anywhere in the world, only when and where is still open, as is the extent of the disaster and the human reaction.

To start with, a few facts about Germany: The country has 82 million people (2010), with a downward trend; it is situated at latitudes between 47° and 58°; with variations from year to year, its south has at most up to 1800 annual sunshine hours, its north includes a good wind regime of 8—10 m/s offshore; it is a green country, bio—technologically and — with up to some 20% of election votes for the “Greens” — politically; the country has only meagre indigenous resources besides the wisdom of its political class, the entrepreneurial ability of its managers, the scientific knowledge of its scientists and engineers and the skills of its craftsmen; its annual primary energy raw material requirements are 480 million tons of coal equivalent (tce) (2008), of which more than 75% are imported, i.e., 60% of its hard coal, 98% of its mineral oil, 84% of its natural gas, 100% of its uranium; national electricity generation amounts to 618 TWh (2008); the country converts energy at a national energy utilization efficiency rate of a modest 30% (for comparison, the world is at about 10%); it grew industrially to join today’s top ranks worldwide, and — the German Bundestag decided with a large majority on June 30, 2011 to reduce stepwise to zero by 2022, i.e., in a little more than 10 years time, its entire nuclear power capacity, which at the point in time when the decision was taken was meeting some 22% of the country’s electricity needs. In addition, the Renewable Energies Bill of 2010 (Erneuerbare Energien Gesetz) passed by the Bundestag demands that 30% of the nation’s electricity needs come from renewable sources by 2020, and up to 80% by 2050.

2. Germany’s seven energy laws

In order to maintain and perpetuate the nation’s well-being also after nuclear has gone, there are several approaches that may be taken to meet the electricity gap; they are summarized as Germany’s Seven Energy Laws:

- According to the 1990s recommendations of the Bundestag’s Enquête Commission “Protection of the Earth’s Atmosphere”: double the national energy efficiency from today’s 30 to 60% with existing or nearby technologies and without excluding any one link of the national energy conversion chain, from primary energy raw materials to primary energies, from there to secondary energies, to end energy, useful energy, and finally to the four energy services: 1) heating, cooling and air conditioning of homes and buildings, 2) energy support in production and transport, 3) lighting of rooms and city streets, and 4) communication services. — Efficient and clean energy services, the chain’s final link of national energy conversion chains, are the only indisputable reason for running through the chain; all preceding links have NO justification in themselves, they are simply means to an end! Here, where nation’s conversion chains end, untouched huge amounts of de-central distributed energies as well as great potentials of technical work lie dormant, in many cases in miniaturized (and privatised) energy conversion technologies.

- Utilize all sorts of indigenous renewable energies: of the basically eight renewable energies nature offers, namely solar, wind, biomass, hydro, ambient heat, geothermal, ocean energy and tides, the first seven are available in Germany, in absolutely unequal capacities, though, with wind the most powerful, ahead of solar, biomass and the others.

- Complete the still incomplete secondary energy scheme, incomplete even after more than two hundred years of modern anthropogenic energy, by introducing in parallel to the electricity grid a second secondary energy carrier grid, the hydrogen energy grid.

- Exergize energy up to the scientific maximum, to be realized in general, and in particular through the introduction of hydrogen and fuel cells, thereby making more technical work available from energy: energy = exergy + energy.

- Clean up and electrify transport, and make it much more efficient by replacing hydrocarbons with hydrogen and electricity, and combustion engines with fuel cells and batteries on board vehicles on land, in the air and at sea.

- Import with the help of hydrogen otherwise non-storable and non-transportable, and thereby non-tradable, renewable energies from abroad, e.g., wind from Patagonia, solar from Africa or Australia, hydro from Siberia.

- As a result: further, environmentally and climatically cleanly and securely, the ongoing low-risk electrification of the nation’s energy scheme and add to it the second secondary grid, the hydrogen energy grid. In parallel to the traditional scientific and engineering field of thermodynamics of heat engines and entire heat conversion systems, the electrochemistry of electrolyzers, liquefiers, fuel cells and batteries and are and will increasingly become the next important fields of activity for energy scientists and engineers. In this context, it may be worthwhile to recapitulate that already in 1912 in Berlin the Institute of Physical Chemistry and Electrochemistry (founding director Fritz Haber) of the Kaiser-Wilhelm-Gesellschaft, the predecessor of the Max-Planck-Gesellschaft (MPG), was inaugurated. The tradition is carried on in MPG’s Fritz Haber Institute.

Seen from a different, though deadly realistic perspective, Germany’s forthcoming energy policy is “simply” repair politics:

- Reduce nuclear risks, finally approaching zero, and this not only of nuclear reactors, but also of uranium enrichment plants, spent fuel treatment facilities and all the interim nuclear facilities of the entire nuclear processing chain.

- Complete and operate a national (international) installation for the long-term final storage of spent nuclear fuel rods.
Pessimists (or rather realists?), though, give word to their conviction that the “safest” final storage will never be able to provide the necessary geological, geo-engineering or technological barriers in any underground structure, particularly in either clay, salt or granite. Perpetuated into the future, the so far worldwide futile endeavours over many decades to find, install and operate a final, safest storage facility for radiotoxic and radioactive nuclear waste are evidence that the afore cited pessimism is not too easy to counteract.

- Stop anthropogenic climate change by reducing greenhouse gas emissions and environmental hazards; the preliminary atmospheric temperature rise of plus 2°C, considered allowable by the political class from a climate change standpoint, should not at all be exceeded.
- Stop the production of much too much useless heat and turn the heat system – arisen as the result of the two hundred years of anthropogenic energy – into a scientifically justified system following energy = exergy + anergy where exergy is the maximum of technical work from energy which can be converted into any other form of energy, whilst anergy cannot. – Regularly, anergy heat of various temperatures after completing energy conversion is released into the ambient and from there into the universe, thereby lost to mankind, once and for all.
- Introduce into the energy market the so far almost “forgotten” renewable energies of the second solar civilization and the second secondary energy carrier hydrogen and their technologies
- Introduce, in addition to the traditional and well functioning coal, oil and natural gas import systems, an import system for renewables and hydrogen, e.g., electricity from North African solar thermal power plants, or hydrogen from Patagonian wind energy.
- Raise energy and in particular exergy efficiencies to the inevitable scientific limits.
- Install high voltage transmission lines connecting the windy north of Germany to its heavy-energy-demanding west and south; likewise, install hydrogen – gaseous or liquefied – pipeline or surface transport in order to facilitate usage of northern wind-hydrogen and/or imported hydrogen disembarked from abroad.
- Store electricity, gases and heat in order to smooth out discontinuities and asymmetries in supply and usage of energy.
- Make buildings energy providers rather than energy consumers by installing “zero-energy buildings” (zero meaning almost entirely self-supplying) with (almost) no energy from the market; close the leaking thermal insulation envelope of homes and buildings.
- Add fuel cells of various temperature grades, from less than 100°C up to almost 1000°C, to the prevailing heat engines like reciprocating piston engines and gas or steam turbines – stationary or mobile – and, where applicable, finally replace them.
- Further optimize the energy appliances used in industrial and home systems.

Swiss engineering colleagues are excellent engineers; they generally stand on firm ground, and introduced into their thinking and acting the term “2 kW-society” aiming at technological means and behavioural attitudes of each citizen, including energy, industry, transport, trade and administration, to reduce energy demand to not more than 2 kW-hours and person [kWh/h-cap] without quality-of-life loss. From an engineering standpoint, that is by no means unrealistic, but, of course, it needs time — and money.

The ways to put Germany’s energy laws into operation are extraordinary and exceptional. Many around the world smile or even gibe, only some try to understand. Here, an engineering approach is used to suggest technological, economic and ecological reason why the way to go is not too grim and stony, why the procedure of changing from one paradigm technology to another is truly nothing really new, and why there is good reason for the conviction that the exemplary goal of an energy system free of nuclear can be reached in due time at tolerable cost. On the basis of the energetically and exergetically most efficient and thereby clean fossil plants, efficient up to the scientific limits, for all the aforementioned seven ways, energy and exergy efficiencies, renewable energies and hydrogen are constitutional.

Never in the history of technologies did industry stick for eternity to one technology; the same is true for energy technologies: it took some 250 years for the build-up of modern anthropogenic energy when early renewables of the first solar civilization were replaced by coal, later coal by oil and gas, still later by nuclear, step-by-step, and with growing heterogeneity of technologies and supply; now, hydrogen-energy-supported elevated energy and exergy efficiencies, the renewables of the second solar civilization and hydrogen energy are on the verge of complementing and taking over. Clearly, the trend leaves behind the dominance of primary energy raw materials such as coal, oil, gas and fissionable material, and turns to the dominance of energy conversion technologies: efficient technologies deliver energy gains, figuratively they “are” energy, you get more energy services, actually the priority purpose of all energy, from less (imported) primary energy! This is particularly true for energy-energy-materials-poor, but technologically-rich nations. Time and again, “creative destruction” (Joseph Alois Schumpeter, 1883–1950) opens ways to novel technologies, in this case to novel energy systems: centralized nuclear (and emission-heavy fossil) technologies lose, hydrogen-supported centralized and in particular decentralized, clean and renewable technologies free of polluting and climate changing operational primary energy raw materials win; adding so-far-lacking hydrogen energy, constitutional to the second solar civilization, is imperative. Hydrogen exergizes energy, it harmonizes the discontinuous offerings of wind and solar (and other renewables) with continuous electricity demand, and it helps bring exergetically efficient and clean fuel cells to market. The technologies of the forthcoming hydrogen energy economy such as electrolyzers, liquefiers, storages are key. The science of electrochemistry moves into the foreground of interest.

It’s innovations which carry forward nations’ well-being. In energy physics, electrochemistry complements the so-far prevailing thermodynamics of heat systems: heat engines, James Watt’s, Rudolf Diesel’s and Nikolaus August Otto’s (among others) heritage, get powerful competitors in William Nicholson’s or Anthony Carlisle’s electrolyzers and William Grove’s and Christian Friedrich Schönbein’s exergetically
efficient fuel cells. There is no need for detours, to first convert energy to heat and only then in a next step into electricity, as lamentably practised worldwide today: In essence, the world’s operational energy system evolved into a heat system! There is much too much heat in humans’ energy world, very often useless heat! Photovoltaic generators and fuel cells or wind turbines do it directly without a heat detour. – Big turns into small, there are differences in unit capacities of several orders of magnitude between centrally organised power stations and forthcoming de-central renewable and hydrogen technologies: The unit capacity of mass products such as low temperature fuel cells ranges from watts to a few hundred kilowatts (so far), that of wind converters from kilowatts to a few megawatts, of photovoltaic generators from watts to megawatts. In order to end up with significant macroeconomic capacities the units are combined into IT-controlled bundles. That way it’s easy to get electricity capacities which compare well with the centralized thousands of fossil and nuclear megawatts on-line today.

After some four to five decades of modern renewable and hydrogen technology research and development in the past, Fukushima seemed to have been needed – rather bitter to say – to give them a big push in policy makers’ and the public’s understanding, to market entrance, to social acceptance, to environmental and climatic responsibility. However, to avoid fooling ourselves and pulling wool over our eyes: still more decades are needed to achieve irrevocability for the paradigm change, a true peripeteia! After 2022, energy in Germany will be doable; however, no excuses, energy needs time and – conviction! Usually, market approaches of novelties are S-shaped. To date, the paradigm’s novel energies are still at the bottom of the S, with the upwards boost impending. We are not inexperienced: Regularly, many decades are spread out between start of the upward boost and asymptotically nearing market saturation; why should it be otherwise with the technologies of the Seven German Energy Laws?!

3. Efficiencies, energy productivity

Germany’s national energy utilization efficiency is a little more than 30%, approx. 3 kW-hours of primary energy raw materials have to be introduced into the national energy scheme in order to get 1 kW-hour of energy services (it is dramatic to reiterate that the world’s is only 10%, perhaps marginally higher!). The Enquête-Commission of the German Bundestag “Protection of the Earth’s Atmosphere” already in the 1990s decided unanimously with the votes from both sides of the aisle to recommend to the Bundestag to double the national utilization efficiency to 60%, thereby reducing with existing or near-ready technologies the needed primary energy raw materials, by three quarters to be imported from abroad. The commission stated that the necessary technologies are or will soon be available. The implementation has begun: hard coal fired power stations with heretofore unknown electrical efficiencies near 50% are in construction, and so are brown coal stations of 45% efficiency utilizing pre-dried pulverized coal; stationary gas turbines have gained 40%, in combination with steam turbines in combined cycles achieving slightly more than 60% electrical efficiency – admirable, not only for the engineer! If the exhaust heat is marketed in addition, we end up at 80–90%. – The German national electric transmission system has an overall loss of only 4%. In ten years time the nation’s primary energy consumption went down from 14,600 (1999) to 14,250 (2008) PJ; the energy-related CO₂ emissions shrank in twenty years’ time from 948 (1990) to 690 (2009) million tonnes per annum. The energy intensity of Germany’s industry as the quotient of primary energy demand over gross national product – energy productivity – went down to approx. 70% (2009; 1990 100%), with a regular annual reduction rate of 1–2%; the future downward gradient is expected to continue, since energy-intensive industrial production continuously loses importance, and the emerging energy extensive services of all kinds gain importance (likewise in more or less all industrialized countries).

Of utmost importance is putting the national energy system into balance: essentially, it so happened that the system developed prevailingly into an enormous heat system which generates quasi en passant a few exergy services, too. Consequently, the national exergy efficiency of Germany is only a miserable 15%—shameful for us engineers! The system which came down to us produces heat of varying temperatures at places where it is of no one’s use. Two examples only: the gas or light oil fired boilers of central heating systems in the basements of Germany’s homes generate flame temperatures of c. 1000 °C, whereas the room radiators require only 60–70 °C. Consequently, the exergy efficiency is very low. – By contrast, a low-temperature fuel cell replacing the boiler delivers firsthand electricity (= pure exergy) with an efficiency of 35–40%, and the remaining heat at a temperature fairly similar to that of the radiators’ needs still suffices over most of the year to heat the home (the rest of the needed heat comes from a small relief boiler). – And the other example: we admired earlier the up-and-coming modern hard coal fired power stations with their electrical efficiency of 50%. Excellent! But how about the other 50%? Again, because of nasty convolutional irreversibilities along the run through the process these plants produce high temperature exhaust heat of no one’s use, because no client is near. If we, however, stop burning the coal, gasify it instead, getting CO and H₂, shift the CO to CO₂, thereby getting more H₂, sequester the CO₂ and utilize the H₂ as a fuel in clean transportation or in a highly efficient triple high temperature fuel cell – gas turbine – steam turbine combined cycle (triple H₂-GGCCS – triple integrated gasification hydrogen fuelled combined cycle system) – then the efficiency is raised, not only for the power plant to well beyond 50%, but also for the entire energy conversion chain, since you get particularly better efficiencies also at the end of the chain when millions of highly efficient hydrogen fuelled fuel cells start operation, stationary and mobile! That, for example, is what is meant by exergizing energy! Make more technical work available from energy, less anergy which is released to the ambient and radiated into the universe, perennially lost.

Fig. 1 gives the historic efficiency development of turbines and fuel cells over 400 years between 1700 and 2100 (forecast), starting at near zero percent efficiency to today’s 40% for gas turbines and 60% for gas turbine/steam turbine combined cycles. However, again very long time periods
were necessary for the success, 300 years to date! Remarkable is that in half-logarithmical plotting (left ordinate) the development follows a straight line, which means that humans’ aiming for possible development accelerations would most probably be in vain, although, of course, a little steeper gradient would be welcome.

Now, after the 300 years, something singular begins: on principal, so far we had exclusively rotary and reciprocating heat-engines which for the first time in their history will quite likely be complemented, later replaced here and then, by a chemo-electrical converter, the fuel cell. In energy physics, prevailing thermodynamic heat engines get the addition of electrochemical electrolyses and chemo-electrical fuel cells. Triple combined cycles, e.g., HT-fuel cell – gas turbine – steam turbines are being envisaged. Electric efficiencies of an extraordinary 70 or 80% are not out of reach!

An indirect, though powerful contribution to efficiency gains is the ongoing strong trend to products of lower (sometimes zero) weight; we are on our way to the era-of-light. A few examples (Fig. 2): renewable energies have no heavyweight primary energy raw material per se, their conversion chains are shorter than those of fossil or nuclear systems; they lack the first conversion link from primary energy raw materials to primary energy and begin with primary energy; hydrogen is the lightest element in the periodic table, its ordinal number is 1. And in practice: bulky and weighty postal parcels and letters are being replaced by zero-weight telecommunications; ceramics in appropriate applications weigh much less than steel; the same applies to high-strength carbon-fibre-reinforced plastics replacing aluminium parts of aeroplanes or steel bodies of motor vehicles.

The German auto industry expects in 20 years’ time an average total fleet fuel consumption for both gasoline and diesel cars of 4–5 L/100 km (for comparison, today’s European gasoline cars consume an average of 8 L, diesel 7); modern electric vehicle designs with engines such as hybrids or plug-in hybrids further reduce the consumption; and finally, systematic building insulation drastically reduces the demand for heating fuel, in some cases down to (almost) zero, the zero-energy (from the market) home is not an illusion, even under the not too favourable climate and weather conditions of central and northern Europe! There are many, many more examples. Lightweight products save energy, in their production, their operation, their recycling and reuse. The era-of-light has just about begun favouring low-energy economies!

4. Renewable energies

Of course, renewable energies contribute to the era-of-light, too: renewable energies have no weighty operational energy raw materials per se; most renewable energies utilize directly or indirectly the “weightless” light of the sun, utilization of renewables and hydrogen as their means of transport and storage lightens the burden on environment and climate, and all the aforementioned sheds light onto what is expected to becoming a basic criterion of the 21st century: energy sustainability, “… fulfilling the needs of the present generations without sacrificing the needs of future generations” (The Brundtland Report [2]).
Germany is really not greatly blessed with renewable energies. Of the seven renewable energies mentioned above, wind is the most powerful, particularly offshore wind, second in the row is solar, then after quite a gap come all sorts of biomass, hydro and the others. Although 27,000 MW worth of wind converters and 17,000 MW of photovoltaic generators were in place in Germany as of 2010, it is, however, an illusion, a chimera, to expect the indigenous renewable sources to be able to provide the country’s complete demand in the extremely short time-span until 2022 when nuclear will have disappeared. To be reminded, it is not the megawatt capacities of renewable installations that really count, it is the work provided, the megawatt-hours or, even better, the megawatt-hours per unit of time (day, week, year), and these megawatt-hours painfully suffer from the discontinuities of the renewables’ supply. Fig. 3 [3] compares for photovoltaics, bio-energy, wind and hydro their installed capacity [kilowatts] in Germany (2010) (left) and their according technical work [kilowatt -hours] (right). The result is very clear: Even on the basis of relatively small investments, hydro and bio-energy deliver significant amounts of technical work; wind and in particular photovoltaics need a presumably non-economical high investment (and subsidies!) in order to provide rather meagre amounts of technical work!

Since energy import (and financially compensating technology export) has tradition in Germany, it is not too difficult to foresee and develop, instead of coal or oil or gas, a scheme to import hydrogen energy electrolyzed with the help of, say, Patagonian wind or Australian solar. Here is one of the centerpieces of the forthcoming hydrogen energy economy: make non-storable and non-transportable renewable energies storable and transportable via water electrolysis, hydrogen pipelines, liquefaction and LH2-cryotankers. Practise this scheme already in pre-hydrogen times by extracting hydrogen by reforming natural gas at the gas field through steam methane reforming (SMR), sequester and store the CO2 and pollutants on the spot, and ship clean hydrogen instead of the preceding links, because hydrogen energy conversion in fuel cells is so much more efficient than conversion, for example, in the combusting reciprocating piston engines, boilers or turbines handed down to us over the energy centuries. In the hydrogen energy economy the round-trip efficiency counts, not (only) the individual efficiency of one chain link or another.

“Desertec” [13], a portmanteau and logo for a project aiming at utilizing the powerful sun in North Africa or the Middle East, more powerful than in Europe by a factor of 2–3, through solar thermal power stations and shipping the electricity via high voltage direct current (HVDC) power lines or via hydrogen pipelines or cryotank vessels to Europe, is another modern example for the long experienced and well tested means of importing huge amounts of energy into energy poor countries, this time clean solar energy (www.desertec.org/atlas). The stations are reasonably efficient, more efficient than photovoltaic stations, and there is another major merit for solar thermal compared to photovoltaic stations: the daytime insolation of the sun can be stored as heat in rock, concrete, latent sodium nitrate salt or sodium heat storage facilities meeting nighttime demand, so, solar operations become feasible around-the-clock, and, decisive for the energy economist, thereby make the stations capable of delivering baseload electricity! The technology has been successfully developed over decades at the Plataforma Solar de Almeria, Spain (www.PSA.es); the first reliable operation of commercial stations in unit capacities up to some 50 MW in California, USA, and in Spain goes back to the 1980s, in the meantime to a total of not much less than c. 1000 MW – And another nice peculiarity of solar thermal power: plants, strung on a thread like a pearl necklace along the globe’s sunbelt latitude, show an attractive possibility of uniformly continuous supply of solar-electric power. When daytime for the more easterly situated plant declines to dusk and non-storage solar production fades away, the next plant west in the row starts production at dawn.

As shown in the German-Saudi Arabian HYSOLAR project (www.dlr.de/fk), an electrolyzer nicely responds to the ups and downs of the available sunshine. A number of commercial energy transport lines across the Mediterranean Sea are already in operation, others will follow. You may even use the operational natural gas pipelines, e.g., from Tunisia to Sicily, to ship pick-a-back gaseous hydrogen to an amount of some 10–15% of the total pipe capacity, and upon arrival at its destination separate it out again by means of membranes, all that without major technical modifications (www.naturalHY.net).

Fig. 3 – Renewable Energies: kilowatts, kilowatt-hours.
5. Energy storage and transport

5.1. Storage

A necessary extra word on storage: Since the renewable primary (solar, wind) or secondary (heat, electricity, cryo-hydrogen \([\text{LH}_2]\)) energies are principally not, or at least only to an extremely limited extent, storable according to the requirements of the energy economy of an industrialised nation, storability of renewable energy is an extraordinary challenge for the engineer and the economist. It so happened that nature provides excellent storage capabilities for chemical energy carriers (coal, oil, natural gas) or for uranium. The capabilities of man-made physical, electrical or mechanical storage, however, are comparatively rather meagre. The following list gives characteristics of the major technologies, in shorthand style notes only:

5.2. Mechanical

- Pumped-storage hydropower stations: Surplus electricity is used to pump water uphill with hydro pump-turbine-motor-generator sets, this water flows downhill when surplus electricity is needed; in reliable operation around the world, units up to several hundreds of megawatts; high investment, extended construction times (many decades), reasonable kilowatt-hour cost, topologically depending on not too numerous mountain areas of the earth with elevations above ground of hundreds of metres, appreciably high efficiency.
- High pressure air storage: With the help of surplus electricity pressurized air flows into an underground space with an impermeable overhead rock cover, and flows out of it through a turbine-motor-generator set at times of electricity shortage; in two commercial examples in operation in the U.S. and Germany, unit capacity is a few hundred megawatts, storage space is caverns in leached-out salt domes or excavated rock, high investment, extended construction times, reasonable kilowatt-hour cost, depends on favourable underground conditions, efficiency low. – Two thermodynamic rules are distinguished: adiabatic or diabatic. The one uses as turbine inlet conditions the airflow temperature and pressure available in the cavern, the other gets an outflow energy boost in a natural-gas-fuelled combustion chamber; of course, the electricity capacities in both cases vary, but because of the number of the consecutive conversion steps – inflow, compression, storage, outflow, electricity generation – both efficiencies are not overwhelming.
  - Tidal stations: Sea water flows at high tide into an elevated natural bight, and at low tide out of it through hydro-turbines; worldwide only operational in two commercial applications, one at the Atlantic coast of France and another at the West–coast of Korea near Seoul, unit capacity of both a few hundred megawatts, high investment, topologically depending on not too often found coastal areas with reasonable height differences between low and high tide (metres to tens of metres) and favourable bight geography with a small opening to the sea where the floodgates and the hydro-turbines are built in, extended construction time, kilowatt-hour cost reasonable.
  - Flywheels: In comparison to all aforementioned designs very small capacities (up to tens (one hundred) of kilowatts), low cost, short-time activation (seconds), de-centrally applied in trolley busses for short term start-up support, rather quick involuntary discharge if not operated in vacuum chambers.
  - Solar thermal power stations use the direct insolation of the global irradiance. Two types of stations are in operation with a total capacity of some hundred, altogether perhaps 1000 MW, particularly in the USA since the 1980s and in
Spain: the parabolic trough type where the high reflectivity mirror surface of the trough reflects the incoming solar beam onto the heat-carrying medium, a thermo-oil-containing, vacuum insulated focal line, and heats it up to 400 °C (up to which temperature the thermo-oil is stable), and the tower type where flat, large (up to c. 100 m² each) heliostats reflect the solar light onto a heat exchanging receiver on top of a hundred meter (or higher) tower and heats it up to appropriate turbine inlet temperatures (c. 700 °C for steam turbines, up to 1,000 °C and more for gas (air) turbines). In the first case the sun’s daily travel is mimicked by rotating the mirror-trough around its focal line (one axis tracking), in the other case the heliostats follow IT-controlled, depending on the latitude of the power stations’ locations, the sun’s daily journey (two-axis control in azimuth and elevation). In either case more or less conventional water steam or compressed air cycles convert the solar heat into electricity (sodium in the primary cycle of the tower receiver in research). Surplus produced heat is stored using concrete, water, sodium or latent salt storage media. In principle, solar thermal stations can be operated a full 24 hours a day (this is the principal advantage over photovoltaic stations, which are restricted to daytime operation). Consequently, solar thermal power stations do not need extra storage facilities, their design contains storage capability in itself. The disadvantage: solar thermal stations need water, which providing in adequate amounts may be a hard task in desert locations; utilizing groundwater or even fossil water is not a long-term solution, shipping-in sweet water from abroad or desalinating water from nearby North African or Atlantic coasts is costly.

- Comparing the cost [€/MWh] of all the aforementioned electricity storage types, the most cost effective designs are big pumped-hydro and compressed air storages, both of daily and weekly storage times. If, however, extended storage times are envisaged (weekly or longer), central hydrogen cavern storage follows closely.

5.2.1. Chemo-electrical (Fig. 4) [4]

- Accumulators in a billion units worldwide commercially in operation in small electric/electronic appliances and as batteries in autos, e-bikes and trolleys; purchase cost high, cost of the kilowatt-hour very high, re-chargeability depending on specific designs. – Lithium ion batteries, the core technology in BEV – battery electric vehicles with a limited number of recharges and, consequently, with drastically reduced mileage compared with the usual gasoline-fuelled car (<100 km against 500 km and more); to date, battery development progress is annoyingly incremental, so far, convincing breakthroughs with respect to capacity, durability, re-chargeability and cost, truly not the least decisive parameter, are not yet in sight (Fig. 5a).

- High pressure (700 bar for c. 500 km mileage) gaseous, tank-derived, hydrogen-fuelled fuel cells for mobile (and stationary) applications in autos and home heating systems, high energy density, hydrogen-specific safety standards, not really commercially available yet, in lots of some thousand copies worldwide in demonstration; high cost because mass production has not yet started, fuel cell stack life compatible with vehicle life not yet assured, more than one stack per auto life still needed. – The fuel cell is not at all unescorted, not left all by itself: It is a component, admittedly the core component, of the complete hydrogen energy economy, meaning that in parallel more or less all components of the conversion chain have to be improved, such as the
production of hydrogen, its transport, its storage, finally its utilization in the fuel cells. (The obvious advantage of the mobile electric battery system compared with the hydrogen system is clearly visible: the “fuel” system electricity grid is commercially fully established, the hydrogen system grid on the other hand is still more or less in its infant stage and on the verge of being installed, not just from scratch, but billions are still needed to achieve unrestricted reliability).

When hydrogen-fuelled fuel cell vehicles and BEVs are compared, one item is worth explicitly pointing out: The latter gets its “fuel” from the outside after it is plugged into the socket of the electricity grid; fuelling time is much longer than the accustomed time for fuelling gasoline vehicles (hours vs. minutes), and the capacity of the on-board batteries limits the vehicle’s range. – The former generates its electricity inside the vehicle via on-board fuel cells, the range of the vehicle depends on the hydrogen storage capacity (700 bar GH₂ storage guarantees the vehicle’s usual 500 km range), the hydrogen dispensing time at the filling station compares rather well with the few minutes at the gas station.

5.2.2. Electrical

• Double-layer capacitor for extremely short electricity delivery times (from under a second to seconds), commercially available, possible application in electric vehicles as short-time booster, low cost, high efficiency, small capacity.
• Super-conductivity coil, for stationary applications, expensive, needs continuous supply of (very) low-temperature cooling media, not yet market ready, high capacity density.

5.2.3. Systems (not really genuine “storages”, but with interesting storage capabilities)

• Interruptible heat or electricity consumers, such as big cooling stores or bigger, well-insulated heating complexes or aluminium or zinc smelters which can be cut off from the supply for a limited period of time when supply shortages are expected and re-connected at times when surplus energy is again available.
• Combined solar/wind systems: Nature occasionally provides heavy winds when solar is low or even zero, e.g., at night or with cloud coverage, and they deliver significant insolation yields when the wind is dead calm. Both wind and solar “help” each other, smoothing out the combined renewable offer, though at lower than combined nameplate capacities.
• Production of methane from electrolytic wind/hydrogen and atmospheric CO₂ following the Sabatier process (Paul Sabatier, 1912 Nobel Laureate in chemistry), a process so far utilized nowhere in the world commercially. A difficult and costly, however highly interested chemical process, since the CO₂ taken from the atmosphere or from exhausts of much higher CO₂ density (e.g., stacks) is circulated and given back to the atmosphere at the end of the process – there is no addition to the anthropogenic greenhouse gas emissions – and the produced methane finds a fully operable, market-ready quasi-storage in the worldwide installed natural gas infrastructure grid.

• For a transitional period, injecting up to 10–15% hydrogen into the natural gas grid, where one gets another quasi-storage period for hydrogen whilst it is being transported along with the natural gas up to the point where it is separated out through membranes for further use; at medium inner pipeline pressure (a few 10 s of bars) only minor technology modification necessary. (www.naturalHY.net).
• When the forthcoming second secondary energy grid – the hydrogen energy grid – will be fully established, the pipeline system, the hydrogen supply trucks, the filling station tanks, and not least the numerous (millions, billions at full swing) mobile hydrogen tanks aboard vehicles, all these components of the hydrogen energy grid bundled together make up a storage system, comparable to the storage system of the natural gas grid now in place. Example: Since the 1930s a 30 bar hydrogen pipeline system has been in operation over some 200 km connecting the German chemical industries of the Ruhr and the Rhineland; industries with a temporary hydrogen surplus production feed it into the pipeline, whilst industries with a temporary need take it out. The system demonstrated its safety standard even in wartime, major incidents were not reported.

6. Transport

All three transport branches on land, in the air, and at sea need two things: hydrogenation of the fuel in order to become cleaner and more efficient, and specifically lightweight structures for the reduction of acceleration energy and thereby the reduction of fuel demand. – Prevailing aims at sea are generating the ship’s electricity needs by means of on-board fuel cells, in particular when mooring in harbours in order to avoid fumes and pollutants near high density habitats, and taking clean liquefied hydrogen (LH₂) on board cryotankers linking heavy, in particular renewable, energy supply zones with globally distant heavy demand zones, say, sunny Australia with Japan, or windy Patagonia with Europe or North America. Although the temperatures of LNG and LH₂ (minus ~161 °C and minus ~253 °C, respectively) are dissimilar, liquefied hydrogen transport benefits from the ongoing well established liquefied LNG transport system which went on duty (and for the time being is being vigorously extended) whenever installing gaseous natural gas (NG) pipelines was not possible, e.g., over transoceanic distances.

Air transportation suffers under one principal peculiarity: In order to reduce drag intercontinental airliners regularly travel above the atmospheric tropopause, i.e., depending on where you are above some 10 km altitude, where humans are the only environmental polluters and contributors to climate change. Ongoing and almost never ending aircraft development is following two goals: Reducing aircraft weight and cutting fuel consumption and thereby exhaust constituents which influence the environment and add to climate change. From 1960 via 1980 to the present we see a remarkably successful development of aircraft and in particular of their power plants: The early turbojets of the 1960s had a specific kerosene consumption of c. 1 kg/daNh (da = deca = 10), the turbofans of the 1980s reduced the consumption to as low as 0.6, and the present generation of mantel-turbofans arrived at...
and controls! Hydrogen tanks, the fuel cell, the electric front wheel motor, and biomass in order to gather experience under performance conditions.

Hydrogen in air transportation has two facets: Hydrogen at the airport and hydrogen aboard the plane. Airport authorities aim at installing hydrogen fuelled fuel cells as a reliable, clean means of uninterruptible electricity supply for airport towers, supplementing and eventually replacing the present noisy, polluting and comparatively inefficient diesel gensets with continuously rotating flywheels in order to be prepared on the second for affordable power demand when the public supply fails. And the authorities are interested in all sorts of clean hydrogen fuel cell service vehicles on the airfield and at the ramp.

Hydrogen on board the aeroplane comprises a variety of technologies: One of the earlier installations may become the undercarriage electric nose wheel, its electric motor powered by an on board hydrogen fuelled fuel cell [www.dlr.de]. The installation enables forward, backward and sideward motion of the plane without the need for a towing vehicle and its cumbersome coupling and decoupling, for which the plane regularly has to wait; the main engines are cut, no noise, no fumes, no pollutants bother passengers and airport staff and surroundings — although (nothing in the world has advantages only) the plane has to carry the additional weight of the hydrogen tanks, the fuel cell, the electric front wheel motor, and controls! — The other medium-term project brings liquefied hydrogen aboard, re-gasifies it by cooling the surfaces of wings and empennage, thereby shifting the more efficient laminar flow zone further along the wing’s cord and getting lower drag by avoiding the early onset of turbulent flow; the re-gasified hydrogen serves as the fuel for fuel cells meeting the overall electricity demand of the plane. The fuel cell’s hydrogen/oxygen (air) recombination provides potable water for crew and passengers, and for the pantry and toilets. The major advantage of this medium-term project is the removal of the jet turbine as auxiliary power unit (APU) at the rear of the plane, the cause of so much unpleasant noise and exhaust pollutants and greenhouse gases from the plane when taxing or waiting at the ramp.

Using hydrogen as the jet propellant for the main engines is not in sight yet, although it has been studied intensively for a number of past decades. It is a longer term project, since it involves the adaptation of entire fleets and the ability of airports to refuel planes at the ramp with large amounts of liquid hydrogen fuel, securely safe. It may, however, become the forerunner of the up and coming hydrogen energy economy, since airports and aviation are entirely in the hands of professionals, and, no doubt, that will remain so.

6.1. Individual surface transport

Truly dominating modern, clean, safe, reliable and efficient transport developments are the numerous engineering aims at producing lightweight autos with the steadily further developed traditional reciprocating piston engine on board, the hydrogen fuelled fuel cell, and/or the electric battery. In the following paragraphs we first try to compare the reciprocating piston engine vehicle with the up and coming fuel cell vehicle (FCV), and after that the fuel cell vehicle with the pure battery electric vehicle (BEV).

6.2. Reciprocating piston engine vs. fuel cell

In order to reduce fuel consumption, steel as the prevailing material of autos since the early days of Gottlieb Daimler and Karl Benz more than hundred years ago, and of Henry Ford later, is being complemented (and here and there replaced) piece-by-piece by lighter weight aluminium, magnesium, fibre-reinforced plastics, or ceramics, without safety losses and sometimes with even higher design strengths and stiffness; without exceptions engine and gear box casings have developed into aluminium foundry constructions.

On a longer run it so seems that the reciprocating piston engine will be replaced by the hydrogen fuelled fuel cell, the piston engine which since the very beginning of individual automobile surface transport has so wonderfully and reliably powered the vehicle (Bertha Benz, the wife of Karl Benz, undertook together with her two sons (13 and 15 years of age) and without the knowledge of her husband in 1888 the first-of-its-kind automobile excursion with a three-wheeler “Benz” over c. 100 km from Mannheim to Pforzheim, Germany — for a lady in those times a brave and bold experiment, but also an advertisement promoting the early products of her husband’s workshop!).

The transfer process from piston engine to fuel cell will not be a jump-type of process, but a longer term parallelism of both prime movers, and “longer term” means decades rather than years, because the piston engine is by no means at its life’s end, waiting for its death blow, development potential is still in store, and its hundred years of experience is an additional powerful argument not to be lightheartedly ignored! As in many earlier cases of technology replacements the price is, and will most probably be in the future, the decisive parameter: not easy to meet for the fuel cell will be the appreciable relatively low price of the piston engine of a few 10 s of euros/kilowatt; however, let us not lose hope, the cost of fuel cell mass production is by far not yet known!

Consequently, the reciprocating piston engine will no doubt be with us for many decades to come; it is therefore only wise to clean it up to the utmost, thereby minimizing its influences on environment and climate. The environmental cleanliness of modern engines has already been achieved at almost zero exhaust pollutants, we even speak of engines as “washing machines” for the ambient air in highly polluted inner city areas (not quite without reason!). What remains is the greenhouse gas carbon dioxide (CO₂) (and small amounts of CH₄ and N₂O) which is a direct consequence of the engine’s hydrocarbon fuel consumption, of the relative carbon content of the fuel, of the vehicle’s weight, the aerodynamics of the car’s body and chassis, the engine’s thermodynamic efficiency and the driver’s operation habits (speed and speed variations, acceleration/deceleration, ...); in addition, very small though continuous amounts of greenhouse gases stem
from burnt lubrication oil which creeps through the ring room between piston and cylinder if the sealing piston rings are not doing what they ought to do.

For illustration a few numbers: 1 kg C burns to 3.67 kg CO₂, 1 L of diesel delivers 2.62 kg CO₂, 1 L of gasoline 2.32 kg CO₂, the difference of 14% is explained by the higher C-content and the higher specific weight of diesel, so, if the consumption of gasoline is 14% higher than that of diesel (which in practice it generally is), both fuels will have the same CO₂ emissions.

The European Commission has released an EU directive specifying CO₂ fleet emissions (for one brand) of 130 g CO₂/km (2012: 129.92 g/km), which is easily met and even fallen short of by smaller cars, but by far not by sedans, SUVs and the like. The 130 g are not out of reach, but further intensive, fundamental chemo-aero-thermodynamic research of the complex situation during the burning process inside the engine cylinder is needed in order to meet the directive. 130 g CO₂/km correlate to 5 L of diesel/100 km or 5.6 L of gasoline/100 km (today’s average figures for German cars are 8 and 7 L for gasoline and diesel vehicles, respectively).

For American readers, the correspondence between liters/100 km and miles per gallon (mpg) reads: 1 L/100 km = 235 mpg, e.g., 8 L/100 km = 235/8 = 29.4 mpg. – And for both Europeans and Americans a final correspondence: 1 L fuel/100 km = 23.2 and 26.2 kg CO₂/10 L for gasoline and diesel, respectively, e.g., 5.6 L gasoline/100 km multiplied by 23.2 kg CO₂/10 L = 129.92 g CO₂/km.

In a serious comparison of the two prime movers, piston engines and fuel cells, three undisputable characteristics favour the low temperature hydrogen fuelled fuel cell over the engine: 1) it is so much more efficient (rough estimates: fuel cell >60%, gasoline engine 25–30%, diesel 45–48%), and, consequently, its fuel consumption is so much lower. 2) its operational environmental and climatic cleanliness is absolute; that applies not only to the individual vehicle, but to the complete energy conversion chain when the primary energy is renewable; when hydrogen, however, is produced from non-renewable energies, their environmental and climatic relevance have to be taken into account! And 3) at part load (which is so often the regular load in the typical, particularly inner city, driving cycle) the fuel cell’s efficiency goes up, quite different from the engine’s decreasing efficiency at part load.

It so happened that occasionally the gallon prices at filling stations in certain locations of the U.S. climbed up to $4 per gallon of gasoline. Knowing that the energy content of one gallon of gasoline is about equal to that of 1 kg of hydrogen, a price of $4/kg hydrogen nears commercial viability; not to speak of present prices of €1.50/liter of gasoline (2011) at German dispensers = 5.988 $/gallon, exorbitant for Americans, even for Europeans ($/€ = 1.4; US-gallon/liter = 3.785). Without question = $6/kg hydrogen already exceeds by far commercial viability and incidentally meets the earlier U.S. Department of Energy’s goal of exactly $6/kg hydrogen! —

The result: Since the fuel cell’s drive train is about two times more efficient than that of the gasoline internal combustion engine’s, the price of the fuel cell’s fuel hydrogen at the dispenser may be higher by a factor of two than the price of gasoline fuel for the piston engine, and still the fuel cell will walk ahead to success! — However, let us stick to the customary solidity of engineers: we do not see a race, the development of both routes is highly challenging, and the finish is not yet in sight; time and again, it needs a good period of time for the completion of both prime movers’ technological development and, perhaps almost more important, for the education and conviction of the political class and the public.

6.3. Fuel cell vs. battery electric vehicle

Two types of electric vehicles are distinguished: The battery electric car gets its electricity from the outside grid; the hydrogen fuelled low temperature (c. 80 °C PMFC polymer membrane fuel cell) fuel cell car generates its electricity inside the vehicle through recombination of hydrogen and oxygen (from air). Both designs have advantages and disadvantages, and commonalities and differences:

- **Commonalities:** Both designs utilize the extremely efficient (typically 85–95% efficient) electric motor, both benefit from the generic high acceleration of the electric drive train, both are operationally environmentally and climatically clean, clean over their complete respective energy conversion chain, however, only if both their fuel grids, electricity and hydrogen, respectively, are supplied by renewable energies; the operation of both is nearly quiet. — In both cases full commercial viability is not yet achieved. The battery’s life is much shorter than the vehicle’s life, so, more than one battery set is needed over the vehicle’s lifetime; and likewise, fuel cell stack durability still does not yet match the car’s total life.
- **And the differences:** Fuelling time of the fuel cell car compares reasonably well with the few minutes fuelling time of the gasoline or diesel car, the battery electric car on the other hand needs hours, if high voltage quick charge is not foreseen, that however causes harm to the battery and reduces its life. The battery’s weight is much higher than the fuel cell’s including the hydrogen filled tank and consequently needs stronger (and heavier!) structural construction of the vehicle’s chassis, which means more acceleration energy and thereby higher fuel consumption. For illustration a few numbers: For a vehicle with on board 50 kWh fuel energy storage the estimated weights are
  - Li-ion accumulator ~ 300 kg
  - Diesel incl. tank ~ 70 kg
  - Gasoline incl. tank ~ 80 kg
  - CGH₂ incl. 700 bar tank ~ 130 kg
- **The volume of the fuel cell including all auxiliaries fits nicely into the engine compartment of a typical gasoline-fuelled car,** whereas the battery volume reduces the car’s seating capacity to two seats, if the dimensions of the car’s body and chassis are not widened which, however, is poison for the car’s aerodynamic drag and acceleration losses. Of course, the hydrogen storage tank, even at 700 bar, has a much higher volume compared to the usual gasoline tank and requires additional space underneath the vehicle’s body in locations that meet the specific safety requirements, i.e., above the rear axle, or benefiting from the empty cardan shaft tunnel space for front wheel drive.
- **The 700 bar hydrogen tank fuel cell car’s range meets comparatively well the usual 500 km of the gasoline car.**
battery electric vehicle of present technology status still suffers under a reduced range of less than 100 km. It may be operated as a niche product for inner city short range travels. (A word of caution: 700 bar hydrogen pressure is by no means trivial, even for engineers, a fortiori for millions of future lay drivers! Consequently, a foolproof filling procedure is mandatory!)

The result: With the experience of the past few decades of research and development on both the hydrogen-fuelled fuel cell vehicle and the battery electric vehicle, it appears that the fuel cell vehicle has the mid-term ability to replace the common gasoline or diesel vehicle with respect to operability, purchase price and operation cost, and that the battery electric vehicle, as long as the battery development does not offer a real breakthrough with respect to price, durability and weight, remains a short range niche product, highly priced, but operated at very low electricity cost.

As long as renewable energies have not replaced the customary electricity mix (in Germany in 2010 consisting of 43% coal, 13% natural gas, 22% nuclear, 19% renewables, other), and as long as the second secondary renewable energy grid, the hydrogen grid, is not in place yet, both the locally clean hydrogen for the fuel cell vehicle and the electricity for the battery electric vehicle suffer under the emissions of the early links of their respective energy conversion chains, the links from primary energy raw materials to primary energies and further to secondary energies, end energies and useful energies prior to the final chain link, the electricity and hydrogen energy services.

In the meantime, the steadily further developed gasoline and diesel cars will continue to dominate the market. Their sophisticated emission understanding makes them as environmentally clean as battery electric or hydrogen fuel cell vehicles, and their ongoing fuel consumption reduction copes with the presumably never ending increasing price growth of crude oil barrels and reduces the anthropogenic influence on climate change. Combinations of the venerable reciprocating piston engine and electric technologies such as the hybrid and plug-in vehicles or range extenders help on that way. Nothing is finally decided yet, it is clear that versatility and heterogeneity of technologies will further increase!

The following three tables [5] give the development status for hydrogen technologies and an outlook for 2020 and 2030: Remarkable is how many technologies along the entire hydrogen conversion chain are already on the market or nearing it, the more so when the further developments of the next 10 year time period are taken into account, which in energy categories is considered to be “tomorrow.” — Under the longer term perspective, technologies are listed whose appearance on the market may well be later than the indicated 20 years’ time span, e.g., hydrogen thermolysis, or the LH2 cooled super-conducting “supergrid” with integrated hydrogen transport, or hydrogen jet fuel in civil aviation. As always in the energy field, politics will have an influence too, and particularly when the installation of the novel hydrogen energy grid is forthcoming. Since politics are regularly much slower than technologies, technologies are already present when politics start to run. — And another thought: Energy without hydrogen is absolutely functional, there is no urgency to replace reliable technologies people are accustomed to. “Better is the enemy of good” is common parlance. The good, e.g., fossil energy technologies, are well known to everyone, and their potential of further upgrading improvement is still not zero. Consequently, as long as the novelties have not yet delivered convincing proof of being outstanding, it will be not too easy for a changeover. That renewable and hydrogen energy technologies are environmentally and climatically clean is a powerful help, but do not forget, fossil technologies are still not yet at their final level of environmental cleanness.

7. Residences and buildings

End energy demand in Germany is rather evenly distributed through 3: areas 1) industry and power, 2) transport, and 3) homes and buildings; only small remainders go to trade and the military. The first two areas are in the hands of professionals; for number 3, only bigger buildings such as hospitals, office complexes, computer centers or large apartment houses are also managed by professionals; single family or detached dwellings are typically run by amateurs.

In all three areas two energy services are demanded: 1) heating/cooling/air-conditioning, and 2) electricity. In general, electricity comes from the central grid, increasingly also from distributed photovoltaic generators on roofs or walls as well as from nearby wind converters and biomass stations. The demand for heating or cooling and air-conditioning is a direct function of the insulation quality of the house’s envelope; historically, roofs, walls with windows and doors, and basement ceilings are poorly insulated: thermostats of building surfaces speak volumes! The requested heat is supplied by district heating, by gas or light oil fuelled boilers in the basement, and more and more by solar thermal collectors, electrical heat pumps or stationary fuel cells.

Let us take a look at the house of the future: its insulation envelope is closed, more or less, heat losses are very small, if any; windows have double or triple glazing, the panes’ coating has solar conversion capability (“solar-chrome”); if the windows are hermetically shut, a silent laminar air supply system in combination with heat exchange is installed. Electricity comes from photovoltaic generators on the roofs and walls, surplus electricity is fed into the central grid. The house nears the criterion of a zero-energy house for which only a minimum amount of energy is purchased from the market, if any, or surplus electricity may even be sold to it. The future energy-self-supplying family dwelling is two things: as customary, it provides home and shelter, and in addition it is an active part of a distributed district energy system. The end link of nations’ energy conversion chains where historically useful energy is converted to energy services increasingly changes its character, adding to its traditional role of consuming what regularly has been supplied by far away central energy converters (e.g., power plants, refineries) the novel role of consuming what is self-supplied (photovoltaics, stationary hydrogen fuelled fuel cells or mobile ones in autos parked in the house’s garage), selling the overrun to the central grid, and providing temporary electricity storage. Since, however, the inhabitants
of these “distributed energy providers” are typically non-energy-professionals, the idea is that several of these providers are bundled in a district system controlled by IT and run by professionals. — All this sounds a little futuristic, admittedly. However, futuristic or not, for the time being and certainly for the near future, too, the individual components of the house’s energy system (photovoltaics, fuel cells, heat pumps, solar-chrome window panes, etc.) go their way, without much concern for overall systems control. But, with rising numbers of these components (in Germany for the time being rather fast-rising numbers) an inbuilt promotion of efficient, distributed energy plants in the energy economy of nations can quite certainly be expected!

7.1. **SUNRISE industries**

Do we see a Friedrich Krupp, Henry Ford, Werner von Siemens, Cornelius Vanderbilt, Bill Gates of renewable energy and hydrogen technologies, of energy-systems-of-change? 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 renewable energy and hydrogen technology markets? To markets for the various sorts of renewable energies, such as solar, wind, biomass, ambient heat or hydro, and for clean hydrogen production, different types of hydrogen storage, hydrogen transport and trade, and for hydrogen utilization technologies? Are we expecting well-known companies to start or at least be on the verge of becoming forerunners in renewable and hydrogen energy businesses? Yes we do, and no we don’t (yet); both answers have some truth.

In the following two chapters on energy efficiencies, on renewable and hydrogen energy technologies, we try to explore where we can expect market developments to SUNRISE industries that aim at opening, after the first solar civilization to today’s remnants in the developing world who are devoting their thinking and acting, their skills, their financial capital, and their organizational talent to evolving renewable energy and hydrogen technology markets? To markets for the various sorts of renewable energies, such as solar, wind, biomass, ambient heat or hydro, and for clean hydrogen production, different types of hydrogen storage, hydrogen transport and trade, and for hydrogen utilization technologies? Are we expecting well-known companies to start or at least be on the verge of becoming forerunners in renewable and hydrogen energy businesses? Yes we do, and no we don’t (yet); both answers have some truth.

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**Solar-passive buildings**: southern orientation (in the northern hemisphere), geometrically optimized windows/walls ratio, active solar-chrome glazing, excellently insulated north (east, west) walls, roofs and ceilings, passive inside ventilation utilizing intelligent ancient architectural designs still in use in Arabia.

**Solar thermal collectors**: mostly rooftop assemblies, perpendicularly oriented to the direct solar radiation, which is converted into heat in a meandering copper, steel or plastic pipe or flat board for warm water production and supports the building’s central heating system, the board’s surface with a high absorptivity and heat conduction/low reflectivity coating, the collector protected by a glass sheet of high transmissivity, not or only moderately concentrating the solar light, here and there a minimum vacuum inside in order to minimize convection losses. To date, thermal collectors are a more or less well developed and successfully marketed product covering millions of square metres in many countries of the world.

**Photovoltaic generators**: generating plants in open spaces, and also assembled on rooftops or walls, here competing with thermal collectors for surface area, flat board, converting the sun’s global radiation (direct and diffuse) directly into electricity by means of semiconductors, after DC/AC conversion mostly fed into the public grid, efficiency some 15%, noticeably higher yields are under development, electricity output following the sun’s course throughout the day, no (or rare) battery-storage capability, at present uncompetitive without subsidies.

**Heat pumps**: predominantly electrically operated, they “pump-up” the heat equivalent of the input electricity by factors of 3–5, utilizing the heat of the ambient, viz. the atmosphere, near earth surface, the water table, or underground aquifers; enjoy a certain amount of storage capability due to the storage abilities of the surrounding space from which the heat pump removes the heat; to date a fully commercially viable product; one thermodynamic counter-argument: pure exergy (= electricity) should not be converted down to low temperature heat!

**Wind energy converters**: with the ancient milling or sawing “windmills” probably one of the oldest renewable energy technologies, modern wind energy converters worldwide with more than 100,000 MW on line (2010), fast market
growth, unit capacities from kilowatts to a few megawatts, prevailing three-blade rotor design, rotor diameters up to 100 m and more, fibre-reinforced plastic blades of 50 m length each, horizontal axis, electronically controlled self-starting free rotation, automatic shut-down at preset storm limits, tower heights 100 m and higher; in order to keep the tower tall, operation beyond resonance of the tower’s first bending mode, onshore as well as more and more offshore locations (here higher wind regimes, but much costlier installation, operation and maintenance), offshore wind electricity either transported onshore by HVDC cables or producing hydrogen electrolyzed offshore; ongoing R&D aims to forecast harnessed wind energy potentials in minute, hour, and week regimes, in locations of acceptable wind prospects wind electricity sells well and the converters are profitably operated. – A severe problem: Existing overhead line capacity is incapable of transporting fast growing additional quantities of wind electricity from wind heavy zones to the demand heavy zones of national economies. The consequence is that in certain high wind periods the production of wind electricity must be stopped because the overhead lines are already “full” – certainly technological, ecological and economical nonsense! The obvious solution is twofold: Upgrade the electric transport system or temporarily store electrolytic hydrogen.

- **Biomass conversion**: biomass is a collective term, biomass comes from vacant lands, from agriculture, forestry, human and animal residue; since the production of human food and animal fodder always has absolute priority, the amount of earth’s surface area availability for energy production is finite (since the fast growing bio-energy business utilizes more and more agricultural land, Germany for the first time in recent decades had to import grain from the world market!); versatile utilization of biomass, e.g., burned for heat production, gasified and as “bio-natural gas” fed into the natural gas grid for combined heat and electricity production, liquefied to transport fuel; biomass may be an energy solution under certain conditions in certain areas of the world (e.g., sugar cane ethanol in Brazil), the undisputed energy solution for mankind, however, is not biomass! Biomass acts as a natural CO\textsubscript{2} sink – an extremely important attribute; biomass is a circular CO\textsubscript{2} agent, the CO\textsubscript{2} amounts taken up during growth and given back during decay or utilization of biomass are the same. Biomass does not contribute to anthropogenic climate change, but a word of caution: environmentally, biomass is not absolutely clean.

- **Hydropower**: hydropower plants deliver electricity, they are in full swing around the world providing up to thousands of unit-megawatts wherever potential above-ground river head or mountain region elevations allow, very high efficiency, very long construction periods (decades), very high investment, very long life (half centuries and longer); nowadays more and more intelligent small- to medium-size plants are under consideration, with limited capacity, though.

- **Ocean energy**: experiments are under way around the world to harness the immense hydrodynamic energy potential of ocean waves or currents at shelving sea shores, on the sea’s surface or submerged; a wealth of ideas under demonstration, mostly in small unit capacities (tens of kilowatts) under rough sea conditions, e.g., salt water and haze, storms, surf surges and breakers; the final outcome of the experiments hardly predictable yet. – A concept to harness the temperature difference over the ocean’s depth is OTEC – Ocean Thermal Energy Conversion. Particularly in warmer zones around the equator temperature differences between surface water and water at some hundred metres depth reach a few tens of degrees, which allows for low temperature thermodynamic conversion in ORC – Organic Rankine Cycles. Besides a few experiments here and there in Japan, in the Caribbean or in Hawaii, so far only on paper in the literature.

- Solar thermal power stations come into play for those world regions in the earth’s solar belt which enjoy high direct insolation, e.g., in Australia, northern India, the Arabian Peninsula, North and South Africa and the Southwest of the United States. The first commercial plants of 50 MW each (altogether up to c. 1000 MW) have been in operation since the 1980s in California, USA, and nowadays in Spain, and are in the planning stage in the North African Maghreb. The experienced efficiencies are higher than those of photovoltaic power plants of similar size and under similar conditions, and the cost is lower! The most important major difference, however, is the ability of solar thermal power plants to store surplus daytime heat for nighttime use, thereby making feasible around-the-clock operations.

- Two dissimilar plant design types are distinguished: The trough type solar collector and the tower type; the former heats up thermo-oil to 400 °C in the trough’s focal pipeline which gives over its heat in a water steam heat exchanger, a more or less conventional steam cycle follows; the latter has a quasi-elliptical field of numerous up to 100 m\textsuperscript{2} surface area heliostats around a radiation receiver atop a tower, here the heat-carrying medium may be air, or water steam or another appropriate medium (sodium); gas turbine or steam turbine generator sets follow. In order to track the sun’s daily journey, the trough turns around the focal line (one axis tracking) and the heliostats are controlled over two axes (elevation and azimuth), guaranteeing that the sun’s beams always meet the trough’s or heliostat’s surface perpendicularly.

- “Desertec,” a European initiative to erect solar thermal plants in North Africa and pipe the electricity via HVDC or electrolyzed hydrogen underneath the Mediterranean Sea to Europe, is still in its planning stage. Experience with operational power lines from Morocco to Spain and natural gas pipelines from Tunisia to Sicily is useful.

Now, let us return to our question: whether we already see an outstanding renewable energy industry matador. Yes, we see quite a number of wind technology companies all over the industrial world where in the meantime even fierce competition has evolved, but a matador? Likewise numerous photovoltaic firms around the world deliver machinery for the production of PV generators, manufacture the cells themselves, or construct PV plants, smaller ones on roofs, wider ones in the open fields; also here appreciable competition has resulted in ongoing price reductions (and the failure of inefficient and incapable companies), but once again, no outstanding matador is seen. Altogether, after only a few
decades of market experience it might be too early to expect already a sorting of the wheat from the chaff. One thing, however, is clearly visible: the big electric firms, Siemens, GE, and Alsthom, among others, are deeply involved, and they may someday be among those that take the lead. Ever so often, the big shots simply buy from smaller companies or national labs what has demonstrated technological reliability and market potential.

7.3. Hydrogen energy industries: the build-up of the hydrogen energy grid

Where are we? Where are we in the build-up of the forthcoming hydrogen energy grid? – Of course, there are the space rocket launching companies, which would not 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 there are the Seven Sisters running their refineries, and there are the methanol or ammonia manufacturers producing hydrogen from fossil fuels and captively utilizing it in the amounts they need for their products.

All these hydrogen businesses have something in common, they belong to “old” well established markets: hydrogen as a space launching propellant began more than a good half century ago, the space business would not even exist without hydrogen, and neither would liquefied free-flowing gasoline and diesel fluids without their hydrogenation in refineries. Hydrogen chemistry and the technical gas trade are much older still. No, what is meant with our question about the hydrogen industries refers to those technologies which can serve the novel markets-to-come of the foreseen hydrogen energy economy, and here the answer is still rather modest!

If we look at summaries of novel hydrogen energy technologies already marketed in small quantities, or in a waiting position, or still in R&D labs and development shops, is there a hydrogen industry proponent among them? One whose key technology can be 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 created a global industrial empire; or like Werner von Siemens, whose electrical generator provided the core solution for generating power at one place and using it at another, the still valid solution of geographically disconnected power 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, a fuel cell manufacturing company of world rank; and we have almost all the big world auto makers, who are developing fuel cell vehicles – a little hystically, though, since they are in parallel also devoting their talents to other electric vehicles that get their electricity not on board from fuel cells but from the outside grid, like the plug-ins, the plug-in hybrids, or the pure battery electric vehicles. For the industry’s policy makers the final developments are still not too clearly seen, as reflected by the frequent changes in electric vehicle (fuel cell and/or battery) market entrance dates which automobile companies are used to predicting.

For tiny to small 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 often live off risk capital with interest rates of 30% or even higher. Similar things are true for mobile hydrogen storage developers.

An exception to this general observation were, temporarily, the big players in electronic devices who were devoted to developing 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 highly efficient fuel cell supported combined cycle power plants simultaneously delivering both electricity and hydrogen? No, they are still on their usual pathways, constructing and operating exergetically excellently efficient (relatively) coal fired power plants of nearly 50% efficiency or even a little bit higher. No doubt, the engineer and the energy economist admire that, but let’s be realistic, the remaining 50% of the coal’s energy content is still being converted irreversibly 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 find a market – perhaps.

Electrolytic wind-hydrogen and solar-hydrogen (“power-to-gas”) are even farther away from the market. Still, wind energy converters and solar generators “only” deliver electricity, and when, say, an offshore wind park needs efficient and reliable electricity transport to its far away onshore users, high voltage direct current (HVDC) solutions enjoy priority (if the distance and nasty sea floor conditions allow this). The situation changes when very large amounts of wind or solar electricity are planned to contribute to the world energy scene, for example, solar thermal power from the “desertec” project delivered from Africa’s Sahara to the southern shores of Europe, or wind from Patagonia in the far away south of Argentina, or solar from Australia, all three commissioned to supply Europe or Japan or the United States. In such cases hydrogen is unavoidable as the transportation means. But, far and wide, no major energy company in the world is following up that idea as yet, not to speak of a proponent. Only DII, the Desertec Industrial Initiative, assembles some 50 industries mostly from Germany (Europe) following up the grand idea of bringing solar power from North Africa to Europe (www.dii-eumenen.com); the state-of-affairs, however, is that it has not really left the paper and discussion stage, yet.

The technical gas industry is well prepared to play an important role in the hydrogen energy field. The major companies—Air Liquide, Air Products, Linde, Praxair and perhaps a few others—are experts in electrolyzers, steam methane reformers (SMRs), liquefiers, hydrogen dispensers, and hydrogen service stations. None of them, however, plays 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-sulfurized diesel. But again, no champion has evolved, yet.

Having said all this, can a hydrogen energy forerunner realistically be expected? One who evolves eventually into a champion? Most probably not. — Let’s see: most hydrogen energy technologies along their complete conversion chain from production of hydrogen via storage and transport to distribution and finally utilization go back to inventors who lived and researched during the past two centuries and a half starting in the late 18th century, after Henry Cavendish (1731–1810) and Antoine Lavoisier (1743–1794) (their earlier name for hydrogen was “inflammable air”) had written their papers on hydrogen experiments. Much later 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 usually simply buy what has left the labs, what approaches market readiness and promises profitable returns. The coal, oil, and gas industries are familiar with all aspects of hydrogen production in coal or biomass gasifiers, natural gas reformers, partial oxidizers, and other approaches. The electrochemical industry builds and operates electrolyzers and liquefiers. Pipelines hundreds of kilometres long for $\text{H}_2$ and (much shorter) for $\text{LH}_2$ are in day-to-day use.

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In the final link of the hydrogen conversion chain, the utilization link, we see a different picture: The hydrogen-fuelled portable mini-to-micro fuel cells are clearly the domain of the electronic industries. Small- to medium-size companies have specialized in portable fuel cells in the kilowatt range for military applications or leisure activities. Manufacturers of central home heating systems are active in low-to-medium-temperature fuel cells, replacing the energetically inefficient 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 systems companies no longer only deliver heat devices, but devices which simultaneously generate electricity and heat. In a country like Germany, to take that example, with some 15 million home boilers/burners supposedly replaced by fuel cells at 5–10 kW electric, the distributed power easily sums up to today’s full central electric on-line power! Since these newly evolving competitors in the electric power market compete with the traditional power business of the big central electricity utility companies, the matter will become rather touchy! An exciting development towards distributed power is foreseen, and as its result one or two proponents may evolve. — After Germany has decided to cut back its nuclear power generation, replacing this lacking power amount by fuel cells seems absolutely feasible, and, a welcome side effect, in an environmentally and climatically absolutely appropriate way, since fuel cells are exergetically highly efficient and deliver the maximum of technical work from energy.

The auto manufacturers deserve special attention: It may be that their 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, fuelled with 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 hydrogen energy industry proponents soon, even matadors? It seems not too realistic to expect one, at least not in an early period of time. The energy 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 favour investment. One thing, however, should not be forgotten: energy is a highly political matter, and so is and will be hydrogen energy.

We quoted it earlier: “The laws of parliaments and the laws of nature have developed increasingly divergently, and it is unreasonable to expect that the laws of nature will yield!” [7]. (B. McKibben, Natural Capitalism, Boston, New York, London, 1999, paraphrased).

Here and there you heard said, quizzically and cynically, or even maliciously, “Better change politicians rather than light bulbs!” — not quite without reason, since the light bulbs’ effect on energy consumption is not much more than 1–2%, politicians influence, however, on sealing a nation’s energy fate can be dramatic, positively or negatively! In Germany, to take that example, photovoltaics subsidies, to be paid for by the general electricity consumer, are bursting through the roof, they grow dramatically into tens of billions of euros the faster the more PV generators are marketed — what a waste of national financial capital, and what a waste of talents of physicists and engineers who devoted their intellect and skill for so many years to clean solar to come true! Not to speak of a clear identification with non-sustainability!

7.4 Hydrogen completes the energy constitution (www.itsHYtime.de)

Fig. 6 [8, 9] depicts the anthropogenic energy history of the last two centuries and a half, and offers a look into the future: The three sides of the triangle are associated with coal (left), the two fluid hydrocarbons oil and gas (right), and the operationally carbon-free renewable and nuclear energies (bottom); isoshow share lines bring the shares [%] of the three components from upper to lower left for coal, horizontally from lower to upper right for oil and gas, and on the bottom from left to right for the carbon-free energies. The development starts outside the lower right triangle corner with the renewables of the first solar civilization which exclusively accompanied the energy history of humans from their first advent on earth until far into the 18th century when coal started consecutively to replace them. The 19th century was the century of coal; it grew through the century from (nearly) zero to a c. 75% share. In the later half of the century oil and gas started to replace coal, which shrunk during the course of the 20th century, arriving at around 20% at the turn of the 20th to the 21st century, and consequently in parallel the share of oil and gas increased to today’s 60%. During that entire process lasting over c. 250 years the operationally carbon-free energies went
down from 100% (renewable energies) to some 15–20% (renewable and nuclear), where they stand now. From the middle of the 20th century on, the reduction of renewable energies of the first solar civilization was only marginally compensated by limited growth of nuclear, and the influence of the technologies of the second solar civilization had only just begun.

The question arises where to go from here. In the upper corner of the triangle only a narrow room is left for what is called “business as usual” (BAU). However, from an anthropogenic climate change standpoint it would be disastrous to further expand carbon-containing energies, particularly coal. Further growth of nuclear may be a solution for a limited number of countries where it is societally accepted. What has a chance over the entire 21st century of nearly unlimited growth back to their great ancient importance are renewable energy technologies, of course now of the second solar civilization. Since, however, the renewable potentials are quite unevenly distributed over the globe’s surface, hydrogen as a storage and transport medium is imperative in order to supply also those regions where renewable energies are not available, or at least not available in appropriate quality and quantity.

If we close our eyes and try to imagine the energy situation at the end of the 21st century (half centuries to almost centuries are a typical measure for world energy developments, as seen during the development of the last 250 years), we discover the final phase of a circular development of humans’ energy over a period of three centuries and a half inscribed in the energy triangle of Fig. 6. It started with the renewables of the first solar civilization and ended again with renewables, now of the second solar civilization, with coal, oil and gas as interims and nuclear as a small addition — if any.

The circle starts with no fossil energy raw material energy technologies (muscle power of humans and animals, wood, flowing water, …) and will be ending with no fossil energy raw material energy technologies, but with modern hydrogen-supported energy technologies (solar collectors, photovoltaics, hydropower stations, wind converters, electrolyzers, fuel cells, …), with the energy-raw-materials-dependent fossil and nuclear energy technologies in between. A massive build-up of raw material flowing around the globe was (and still is being) observed which, however, must be expected to fade away when approaching the end phase of the circle. Operationally no-carbon energies via high carbon/low hydrogen to no-carbon/high hydrogen energies have been and are being experienced: The atomic hydrogen/carbon H/C ratios of coal, oil, gas and hydrogen energy are \(< 1 : 2 : 4 : \infty\); already these days two thirds of the atoms routinely burnt are hydrogen atoms. — All this seen and compared with the long time period humans were, are and will be present on earth, the relatively short period of fossil energy usage of a few centuries is considered a stumbling block on humans’ energy path from environmental and climate cleanness back to environmental and climate cleanness, from no-energy (raw materials) energy to no-energy (raw materials) energy, from technologies only to (almost) technologies only, from “technologies compete, not fuels” (D. S. Scott) to technologies compete, not fuels — all these developments of course accompanied by highly appreciable energy and exergy efficiency gains to the utmost energy science can provide.

At the end of this section let us come back to its heading which states that hydrogen is on the way to becoming a constitutional component of humans’ energy system: yes, without the installation of the second (after electricity) secondary energy grid, the hydrogen energy grid, the second

![Energy Triangle – Shares in Primary Energy](image-url)
solar civilization will not be, or, to be correct, will be restricted to regional importance where storability and transportability of renewable energy in macroeconomic terms are of minor (almost no) importance. Then, the above mentioned triangle inscribed circle will not be closed. Closing it means completing humans’ still incomplete energy system through hydrogen energy: truly, a syllogism! In one word: hydrogen energy is our common cause! And when the majority of the commons is indifferent, it leaves the future of energy policy to experts and to those who have particular interests. What hydrogen energy needs is vigour, not fikkleness; major capital, not small change; continuity, not ups and downs, and, perhaps the most important, conviction, not ambivalence.

In this context, a highly interesting decision was made by the World Energy Council at its annual meeting in September 2011 in Rio de Janeiro, Brazil, titled “2011 Global Energy Issue Survey” (Fig. 7). Major energy-related parameters are depicted in a diagram with “uncertainties” on the y-axis and “impacts” on the x-axis, with six statements:

1. Fossil energies do not appear or at best appear indirectly in the climate framework, Middle East dynamics, energy prices, CCS, Russia and EU and US politics
2. Energy efficiency and renewable energies have succeeded in having the highest impact with only moderate uncertainties – for the rather conservative attitude of the Council in earlier decades a most remarkable finding!
3. Nuclear energy has the highest uncertainty, although the highest impact, too
4. The four encircled (emphasized) electricity components smart grid, electric storage, sustainable cities and electric vehicles are in the midfield of uncertainties and impact
5. Big hydro and bio-energy have a rather small impact at moderate uncertainties, and
6. The hydrogen energy economy is far away with almost no impact at moderate uncertainty (which is in clear contradiction to the mission of this paper and ignores hydrogen as the fuel for fuel cell electric vehicles and as the storage and transport medium for otherwise globally non-tradable renewable energies. But, no fear, it is well remembered that the World Energy Council took decades to make the statement on renewable energies mentioned above; now it may well work on its attitude towards hydrogen energy over the next decades, when hydrogen will long have been fuelling millions of on-road electric cars and transporting far away offshore wind-electricity to onshore users!)

7.5. On investive and operational influences

Energy passes through energy conversion chains, link-by-link. The classical five links of the chain are: from primary energy raw materials via conversion technologies to primary energies, further to secondary energies, end energies, useful energy, and finally to the energy services, which are the only reason for passing through the chain, all aforementioned links have no reason in themselves, they are means to an end! Renewable energies lack the first link of the chain, primary energy raw materials are inexistent, they start with primary energies such as the kinetic energy of wind, the thermal or photonic energy of insolation, and hydro’s upper level height above the turbine/generator set. At each link-to-link joint a specific conversion technology is deployed, all link-to-link joints suffer from conversion losses, on principle, loss-free efficiencies of 100% are impossible, although the efficiencies may vary significantly in one link joint or another; a few examples:

- Coal in power stations: from primary energy raw material to primary energy, and further to heat and electricity
- Mineral oil in refineries: from crude to gasoline or diesel

Fig. 7 – The World Energy Council’s 2011 Global Energy Issue Survey.
- Natural gas in fuel cells: from desulferized gas through reformers to electricity and heat
- Insolation in photovoltaic generators: from solar irradiance to electricity
- Wind in wind energy converters: from kinetic wind energy to electricity
- Nuclear in gas ultracentrifuges or in nuclear power stations: from uranium-hexafluoride to uranium enrichment, or from nuclear fuel rods to heat, and further to electricity
- Hydrogen energy in electrolyzers or liquefiers: from electricity to hydrogen, or from gaseous hydrogen to liquid hydrogen
- ...

Both energy-carrying materials and conversion technologies influence the environment and anthropogenic climate change. We distinguish investive and operational influences. Investive influences are all those occurring during exploration and production of the conversion technologies, putting them in place, their refurbishment, their demolition at life’s end, and their recycling; operational influences of the technologies are very small, if any. – It is otherwise with the energy-carrying materials, here the influences are the other way round: investive influences are small, operational influences dominate! Also here a few examples:

- Coal: emissions of CO₂ and other greenhouse gases when burnt, gasified or otherwise treated
- Mineral oil: emissions when refined, hydrogen-treated and desulferized, emissions when burnt in combustion engines or burners or boilers
- Natural gas: emissions when burnt or converted in burners or fuel cells
- Since renewable energies are without primary energy raw materials per se, their operational influence is nil; only the invested technology has an influence. — Caution, though: Also technologies may have (small) operational influence, e.g., through wear or friction of catalysts, at membranes of fuel cells, through hydrogen embrittlement, etc. An indication of operational influence is often the early exchange rate of detail technologies prior to the general technologies’ end of life, e.g., of catalysts, fuel cell stacks, or degraded photovoltaic cells.

7.6. **On energy and miniaturization**

Historically, big and small energy installations are unevenly distributed along the energy conversion chains: big governs the front-end of the chains, small their back-end, by and large. Overhead lines, natural gas pipelines and other transport means connect the two ends, thereby, in a figurative sense, “diluting” the transported energy by orders of magnitude. Coal mines, oil fields, power stations and refineries at the chains’ front-end have capacities of hundreds of megawatts to (many) gigawatts, whilst the household appliances, the road vehicles, the planes, even the smaller companies’ demand are counted in watts, kilowatts to a few megawatts only.

It so happens now that at the energy chain’s back-end a miniaturization of energy converters is observed, a miniaturization and in parallel a privatization and individualization of energy and its technology, thereby shifting the energy center point downstream where people live:

- The central power station gets more and more competition from smaller distributed suppliers such as biomass plants, wind turbines, roof-mounted photovoltaics, fuel cells in home heating systems, etc.
- The railway companies face hard times, since the number of individual vehicles grows and grows.
- The modern high-speed train has lost its front-end locomotive, which was replaced by electric motors at each railcar’s axis.
- It is long ago when the manufacturing company’s steam engine with its kilometer-long leather driving belts was replaced by numerous individual electric motors at each spot of power support for machine tools.
- The big cooling food locker is no more in use, since people use their home “fridges” to keep food fresh
- The washhouse closed down after people purchased home washing machines
- The downtown motion picture theatre got heavy competition from home television sets
- The central computer center looks like a dinosaur in light of the billions of individual personal computers at home or on the road
- The library faces hard times, with e-books now starting to be introduced into the market.
- ... and many, many other examples, present and upcoming.

What does all this mean? There are four consequences; the development is still in full swing:

- The rule: “front-end = energy production in big facilities, back-end = energy utilization in small to very small converters” is no longer valid. Increasingly, distributed energy production at the chain’s back-end competes with the front-end producers. What is locally available is converted: solar when the sun shines, wind when it blows, hydro where its potential is not yet utilized, geothermal where underground temperature anomalies allow, biomass turns ordinary farmers into energy farmers, stationary or mobile fuel cells simultaneously produce heat and electricity locally. Both chain ends produce energy. It so happens that distributed back-end energy is environmentally and climatically cleaner than centralized front-end energy.
- Distributed back-end energy encounters lay people, “you and me,” who will not become energy experts the moment the PV generator on our roof starts generating electricity, or the fuel cell has replaced the combustion engine in our new-generation motor vehicle. Consequently, to use the full potential of back-end energy, simultaneously producing and consuming energy, it is mandatory to combine the individual technologies into bundles run by local or regional authorities. City utilities may become the proper unit to face the extremely difficult task of optimizing local and central influences, time dependencies of solar, wind and other renewables, without ever forgetting economic viability, environmental and climate change consequences, and reliability of supply.
And the third consequence? We said it earlier, end energy demand in Germany (and comparatively in other countries) is rather equally distributed among three areas (1): energy, industry and power (2), transport, and (3) households and buildings. We have understood that the miniaturization process massively influences number (3) and partly number (2), too: Theoretically, household and building energy demands from central suppliers goes down to zero (the “zero-market-energy home”) because the miniaturized system not only covers all its own needs autonomously, but under certain conditions also feeds electricity into the public grid. It goes without saying, there is no need to centrally produce what is not asked for to be delivered by overhead lines: the turnover of central big power plants, refineries and natural gas installations shrinks! A similar development is seen in the transport area: the fuel demand of modern fleets decreases and so does the turnover of Big Oil; a similar effect is decarbonization of fuels (ethanol, liquefied natural gas, hydrogen); hydrogen can even be produced locally with the help of surplus electricity generated on roofs, walls or nearby open spaces.

Finally the fourth consequence: generally, the not too numerous front-end “big” facilities are more expensive than the mass-produced millions of smaller back-end items. Think of the vehicle’s internal combustion engine with a few tens to a few hundred kilowatts with its unit price of some tens of euros per kilowatt. Similarly, one may imagine that the unit prices of heat pumps, wind generator sets, PV units, etc. will drastically go down the moment they are mass produced. It is well remembered that in the early days of PV generators for aerospace applications in the 1960s the watt was priced at US$ 50,000 to 100,000; these days, you may purchase a watt for $1 (even though not space proof)! Although the time required for the decrease was almost half a century.

7.7. On energy and time

Energy and politics are closely related! Hardly any other industrial branch depends to such an extent on national and increasingly international policy makers and political operations than does energy and its technologies. Self-evidently, politics has to take responsibility in questions of foreign policy and safety matters. In addition, supply security, trade terms, long-term research, environmental and anthropogenic climate-change-related energy influences are further items for political consideration. Take Germany’s farewell to nuclear, or America’s nay to a pipeline connection from Canada’s Athabasca tar sands across the USA to its southeast, or the USA’s permitting, after BPs recent Deep Water Horizon disaster, deep water drilling in the Gulf of Mexico only under certain harsh stipulations, or the numerous and difficult intergovernmental obligations involved in the forthcoming “desertec” project, generating solar electricity in North Africa and piping it to Europe — questions of that calibre, of course, have to be handled or at least co-handled together with industry by the political class. Here politics cannot disavow responsibility!

Dissimilar time periods forming a time gap of regularly many decades between policy making and political operations on the one side and technology development and technology strategies in industry on the other come into play: the typical time periods of energy technologies are long, not seldom many decades long, whilst legislative periods are short, depending on the country only four to seven years. Consequently, many generations of elected politicians are involved in decades-long technology developments. A few examples: coal mines and oil fields need 20–30 years for their exploration, their build-up, and installation before the first ton of coal or barrel of oil leaves the gate, and their following service life is counted in decades, up to half centuries (and longer); the power station is designed and erected in 10–15 years and generates electricity for up to half a century; a novel auto generation remains for 10 years in research labs and development shops before the first handful of demonstration copies appears on the road, and if all goes right, the novel, commercially market-ready vehicle will be operated for more than another 10 years; based on an Israeli/U.S. initiative the start of solar thermal power stations was around the 1980s when some 350 MW began operation in the Mojave desert in California, USA, and now, after 30 years of thinking, calculating, evaluating and lobbying, the first European stations of together c. 250 MW generate power in Andalusia, Spain; and as a last example (of many more), components of the hydrogen fuelled fuel cell vehicle, e.g., the fuel cell stack or on board high pressure filament-wound hydrogen storage, started their laboratory life in the 1970s to 80s, and still after 30–40 years’ time only a small fleet of perhaps altogether 1000 demonstration vehicles worldwide are in operation around the globe, admittedly vehicles of each and every brand, after all; no auto maker is not involved.

What is said is that the technologies’ inherent long time periods require an engineering and entrepreneurial continuity which the political class is unable to provide, since its individual political life is so short and sometimes gets even shorter with fluctuations of governmental responsibility from one side of the parliamentary aisle to the other. The timely and factually proper collaboration of the two is inconsistent: regularly, the political class needs time to catch up to where science and engineering already are!

The enormous challenge of the next decades (the next half century?!) is and will become ever more urgent: the relation of energy to anthropogenic climate change. The usual mix of coal, oil, gas, and nuclear fission has no future, even if the policy goal of an additional two degrees of atmospheric temperature, considered “allowable” by the political class, is met, or better, undercut. Energy supply is one of three major contributors to anthropogenic climate change (the other two are industry and households). The fossil fuels emit more greenhouse gases (CO₂, CH₄, N₂O and fluorine gases) than they ought to, and the compensatory operationally carbon-free nuclear and renewable energies do not develop as fast as would be necessary climatically.

The decarbonization process of the past decades accompanying the transfer from the high carbon/low hydrogen ratio of coal via lesser carbon/higher hydrogen of oil to low-carbon/high hydrogen of natural gas has slowed down because of the tremendously fast economic development of developing
countries, some of them utilizing coal in unforeseeably large amounts. The almost traditional downward decarbonization slope has practically come to a halt; recarbonization is on the verge of taking over, which is obviously counterproductive with respect to climate change.

The “Decarbonization Triangle” (DT), recently proposed by Nazim Muradov, [10] (Fig. 8) depicts the relations of its no-carbon or low-carbon components electricity \( e^- \), hydrogen \( H_2 \) and methane \( \text{CH}_4 \). On the triangle’s right arm the fuel cell’s recombination of hydrogen and oxygen to water generates electricity, or the other way around, water is electrolytically split into hydrogen and oxygen; the bottom arm shows steam methane reforming (SMR) to hydrogen and \( \text{CO}_2 \), or otherwise hydrogen and atmospheric carbon dioxide form methane (the Sabatier process, Paul Sabatier, 1912 Nobel Laureate in chemistry); finally the left arm closes the triangle and shows electricity generation in gas turbine generator sets by burning methane and thereby releasing water steam and carbon dioxide, or otherwise water steam and atmospheric carbon dioxide with the help of electricity form methane electrochemically at high temperature. With electrolyzers and fuel cells the right arm is completely commercially available and so are the bottom arm’s SMR and the left arm’s gas turbine processes; the remaining two processes are still in their development phase, more or less. One thing becomes very clear, in order to end up with continuous energy decarbonization the presently prevailing anthropogenic heat system is to be complemented, in parts radically replaced, by electrochemical systems; both aero-thermodynamics and electrochemistry will be the two scientific fundaments of future decarbonized and thereby climatically clean(er) energy. From a scientific standpoint, utilizing the processes along the arms of the triangle, what will have been achieved is exergyizing energy, making more exergy available from energy, i.e., aiming at the maximum of achievable technical work, less energy, which is of very limited anthropogenic worth, simply waiting for its release into the ambient and its radiation into the open space, leaving the anthropogenic energy system for good.

The processes forming the basis for DT have remarkable efficiencies. However, appreciating that, let us not forget time and — money!

We get a realistic appreciation of the time periods involved by recalling that electrolysis goes back to 1800 with the work of William Nicholson and Anthony Carlisle, and Henry Cavendish published in 1766 his work on hydrogen, which he named “inflammable air”! And it was two friends, the German Christian Friedrich Schönbein and the Welshman William Grove, who published for the first time on fuel cell research in 1839 and 1845, respectively. These inventions of the late 18th and the 19th century form the bases of modern technologies whose renaissance appeared so much later. The major difference between the 18th and 21st centuries, however, is that the former conducted their research not overwhelmingly as a step to market, while today’s engineers are clearly market oriented. The market, however, is not just waiting for the novel research and development results, regularly the novel technology encounters “old” technologies that have long been on the market, reliable, cost effective, and by no means expecting their final death blow. They still have potential for elevated efficiencies, decreased fuel consumption and thereby better cleanliness, and, due to fierce international competition, reasonable price stability. Meeting these parameters will not be easy for the novel technologies. Common parlance says (paraphrased): “The old is the enemy of the (assumed) better”! Humans do not like to change habits they are used to, unless in the end the better has really overcome the old; a change in collective consciousness takes time, much time.

All the aforesaid on energy and time is nicely summarized in a quotation:

“It takes about 50 years for an idea to breakthrough and become vogue; no one likes an intruder, particularly when he is upsetting the commonplace!” [12] Sorry for the impatient!

### 7.8. Energy and globalization

To start a few definitions: there are three categories of nations, 1) those with an abundant wealth of energy supplied by indigenous coal, oil, natural gas (and/or fissionable material) for their own use and in addition for supplying other nations (e.g., Australia, Canada, OPEC, Russia, South Africa), 2) those indigenously poorly blessed with energy resources of any kind and depending on global energy trade (more or less all EU countries, e.g., France, Germany, Italy, the UK), and (3) those mostly highly industrialized nations providing the world with energy conversion technologies and entire systems (Germany, USA, others); all three categories (1) to (3) are interdependent in one way or another.

It so seems that on a longer run, the energy technologies walk ahead, for three reasons: number one, technologies are key to energy efficiency gains, with the consequence of less need for energy raw materials for the same or even a greater amount of energy services; number two, while coal is coal, oil is oil, etc., the conversion technologies are by far not yet at the end of their development, e.g., modern power plant efficiencies are continuously increasing, photovoltaics offer higher outputs at lower cost, deep sea platforms allow for tapping sources thousands of metres underneath the sea floor, solar thermal power plants tap the sun in world regions of highest insolation and send generated electricity to far away clients, hydrogen-fuelled stationary fuel cells deliver highly efficient combined power and heat, and start competing with central on-line power, etc., etc.; and number three, renewable energies know no operationally primary energy raw material per se, their conversion chain is always one link shorter, fortunately also “shorter” in link-joint associated losses of course; it begins with primary energy. — It so happened that the

![Fig. 8 – The de-carbonization triangle DT.](image_url)
predominant energy suppliers of the world, mainly of oil and gas (in cases coal), are concentrated in the “energy strategic ellipse” spread out from the Persian gulf via Iraq, Iran, Central Asian states to as far as Siberia; deplorable for the energy world is that one state or another in this ellipse is of not too convincing political stability. A comparable concentration of technology is not seen, worldwide technology competition, sometimes fierce competition, furthers the markets’ best, technologically, economically, ecologically, and societally.

Of course, nations firsthand strive to utilize indigenous energies and technologies of national production. Regularly underestimated is the national potential of efficiency gains which, in its importance recently rediscovered, is of much higher potential than thought earlier; there is much room beyond today’s meagre 10% world efficiency. France installed its massive nuclear capacity of c. 87% of the nation’s electricity in order to decouple the grid from foreign dependence; likewise, Germany tries to loosen its almost life risking dependence on more than 75% energy import by increasing national energy utilization efficiency above today’s 30% and significantly raising the renewable energy share, although the renewable offer, under the insolation and topology conditions of Central Europe, is not too convincing; sources to meet 35% of the electricity demand from renewables by 2020 have been located (predominantly wind and solar). Both countries (and many others) are not really helped much in the end by their aim of indigenous (and highly expensive) sources; the import figures still remain perceptibly high, e.g., Germany’s imports are 60% hard coal, a little less than 100% oil, 84% natural gas (2008); particularly gas import is expected to further expand!

The country pays for its energy import with its technology export income.

No doubt, indigenous energy utilization by countries is welcome, even under sometimes not really favouring conditions (which increases costs!). However, the general trend of globalization is towards worldwide international trade of energy and appropriate technologies, especially efficient technologies increasingly win over energy raw material. That development explicitly started after WW II and its end is not yet seen. US$200 billion (≈ US$ 2 x 1016) were traded in world energy in 2004. Even with peak oil production probably seen in a few decades to come, conventional oil nota bene, non-conventional production methods are still in store. Production methods like injecting water steam or CO2 or detergents into the bore hole in order to overcome underground viscosities and get out more oil. Comparably, novel methods of gas production in deep layers, dubbed “fracking” (horizontal fracturing), are under way; in both cases ecological and safety precautions are indisputable! It happened here and then that the groundwater table was methanized and potable tap water including methane caught fire; a mixture of re-surfaced chemically laden production water stored in open ponds is obviously not the final solution!

Clearly, for many reasons future energy is global:

- Industrialization proceeds. The industrialized countries deliver a paragon of wealth which the developing countries try to copy under consideration of their specific national conditions. Regardless of the usual ups and downs the world economy grows, and so does energy demand and consequently its transport around the globe.
- Energy raw materials are not evenly distributed on the globe, and neither are renewable sources. Those countries blessed with energy raw materials and high insolation sell, the others buy and often pay with income from their exported technologies and energy services. Those unable to pay are not crushed by globalization, however; they are simply ignored – bitter to say.
- As can be learnt by the number and importance of granted patents, scientific and technology knowledge is dominated by the north of the globe, by and large. That may change in time, but as long as the industrializing countries have not yet joined up, knowledge flows from north to south. Generally, intellectual property rights rise in importance.
- For global, transoceanic distances renewable energy trade needs hydrogen as the storable and transportable energy carrier, thereby influencing the global energy mainstream.

In order to put Germany’s seven energy laws into operation, Conclusions I and II summarize strategic steps:

8. Conclusion I: activate what lies dormant

- Utilize indigenous and/or traded renewable energies, disembarked from abroad
- The first and second solar civilizations are, of course, of no difference as to their global solar input, perhaps at best there are some local or regional insolation differences between the two; the distinction rather lies in the conversion technologies and in particular in those man-made technologies which on principle did not exist in the first civilization, e.g., photovoltaic generators and fuel cells and modern wind turbines and hydropower plants
- With the aggressive employment of modern technologies, strive to exploit the immense dormant potential of energy and exergy efficiency gains, thermodynamics shows us how to reduce energetically extremely painful energy irreversibilities
- Fight exergy destruction by avoiding irreversibilities, particularly in boilers, combustion chambers, heat exchangers and the entire conversion facility’s chemo-aero-thermodynamic throughput, thereby making more exergy and less anergy available from energy: energy = exergy + anergy [11]
- Make more services available from less energy raw material by always putting efficient technologies first, energy raw materials second
- Turn the gigantic heat system now existing, which evolved over the centuries and which in parallel provides in addition only a small amount of technical work = exergy, into a technical work system which in parallel also provides the demanded heat, now at user-appropriate temperatures
- Foster the energies-of-light: supposedly non-energy-related technologies strongly influence the energy system, e.g., lightweight moving structures need less energy for acceleration and deceleration, closed insulation envelopes of buildings and their southerly orientation diminish their need for energy from the market
- Follow-up the historical development line from coal via oil and natural gas to hydrogen, i.e., from high carbon/low
hydrogen via de-carbonization/hydrogenation finally to high hydrogen/low carbon, i.e., the atomic relation H/C for coal, oil, natural gas and hydrogen varies from $<1:2:4:\infty$. Keep in mind that already to date two thirds of all atoms burnt are hydrogen atoms: Consequently, we are on our way, where to go with no aberrations is well defined

- In parallel to the first secondary energy grid, the electricity grid, install the second secondary energy grid, the hydrogen energy grid
- With the help of electrolytic hydrogen store and transport otherwise non-storable and non-transportable renewable energies such as wind and solar, and thereby enable them to become the media of the world’s future clean energy trade system
- Fuel with hydrogen energetically efficient low temperature fuel cells for transport and for industrial and residential usage
- Expand scientific energy knowledge by adding the science of electrochemistry of electrolyzers, fuel cells and batteries to the science of thermodynamics of heat engines.

9. Conclusion II: remove barriers

- Convince German compatriots (and the inhabitants of other countries that are inclined to de-nuclearize their energy system) that energy without nuclear is doable and affordable; it is not a tightrope walk, but – not unusual for energy in general – needs time, decades, even half centuries are not uncommon when striving for irrevocability!
- Strive for nuclear-free energy without negatively affecting anthropogenic climate change
- Get agreement for wind-electricity high voltage north/south overhead transmission lines near people’s backyards
- Obtain public approval for energetically highly efficient new gas or coal plants including gasification plants as well as hydro and underground hydrogen or compressed air storage
- Tell people that there is no absolute safety, never, nowhere and under no condition, and that hydrogen, like any other energy, is to be operated responsibly under secured hydrogen-specific safety standards
- Install and finance the national hydrogen grid, including LH$_2$ from abroad
- As a showcase, engineer, build and operate the first “desertec” plant in North Africa and bring the product, HVDC electricity or renewable hydrogen, to Europe
- Alter the energy supplier/customer relationship, thereby shifting the responsibility for removing greenhouse gases and pollutants from energy demanders to energy suppliers, with the consequence of circulating clean hydrogen instead of dirty fossil material around the globe.

10. Epilogue: on de-nuclearizing conditions

Since the majority of the world’s nations never expressed its will to acquire any nuclear capacity, and after some even excluded the acquisition by law, and after Germany has deliberately and voluntarily decided to close down its entire nuclear reactor capacity by 2022, the question arises whether there are more nations tending to at least reduce their nuclear arsenal, if not give it up. What are favouring or hindering conditions? – Let’s see:

One thing is obvious without much exploration: The “nukes,” those eight nations possessing the bomb and those two striving for that possession, will never have even the slightest thought about reducing their nuclear capacity, much less abandoning it! All links of the nuclear conversion chain are needed to maintain the quantity and quality of the military threat (the justification is not discussed here), from the chain’s front-end with exploration and mining of natural fissionable nuclear material to the very back-end of the chain where bomb-quality plutonium is extracted from the spent nuclear reactor rods after they have left the reactor, via nuclear chemistry and highly enriched uranium (HEU), and where special reactors and the associated rods (among other things) are manufactured. That in parallel electricity for civil use is also generated in reactors dedicated to producing bomb material, is only minor welcome extra income.

Now to non-nukes: When one component of a nation’s electricity supply is cut out, which replacements are available under the condition that the level of supply be maintained? Four of them are in stock (1): raising utilization efficiencies, chain link by chain link of the national energy conversion chain, thereby gaining more energy services from less primary energy raw material input (2), striving for environmentally and climatically clean and most efficient fossil power plants, and switching via decarbonization from high carbon/low hydrogen to low-carbon/high hydrogen, i.e., from coal via oil to finally natural gas, – here with predominant methane (CH$_4$) only one carbon atom is oxidized to CO$_2$ when burnt, but four hydrogen atoms to H$_2$O (3), utilizing indigenous renewable energies, and (4) with the help of hydrogen as a storage and transport means importing renewable energies from those world regions where solar, wind, hydro etc. potentials are highest. Almost exclusively, all aforementioned four replacements are dependent on technologies that might not be routinely at hand in de-nuclearizing countries. A nation which has thought, acted, and trusted, often for many decades, in nuclear energy categories, politically, economically, ecologically and from an engineering standpoint, might quite likely have neglected its duty to look for alternatives in due time. Exemplarily, the World Energy Council (www.worldenergycouncil.org), the world assembly representing more than 90 countries with delegates from politics, economics and engineering, at its annual meeting in September 2011 in Brazil issued an “Uncertainty vs. Impact” plot on energy and related questions where for the first time in the almost half century long history of the Council its world experts ranked “Efficiency” and “Renewable Energies” as having the highest impact of all energies and only moderate uncertainty! Fossil energies are not even mentioned, or indirectly mentioned at best, and nuclear is “encircled,” meaning that particular attention ought to be drawn to future continuance, societal acceptance, safety and cost. Here a movement is under way among the mostly conservative members of the Council, and, not otherwise expected, the movement took almost half a century – so far.
A further aspect: “Nuclearized countries,” so far without much interest in the mentioned replacements, have economically almost sealed the country away from the up and coming world energy technology market — truly, a not too farsighted attitude! Because, never in the history of humans’ energy (and, of course, of market items in general) did market development stay with one singular technology, continuous replacements are the rule. For decades J. A. Schumpeter’s “creative destruction” supported humans’ well-being and will further do so. The question only arises, when will that happen, at what appropriate time should one move from one technology to the next? A wedge-shaped fading out of the “old” technology and in parallel a building-up of the novel one seems the suitable modus procedendi, since the wedges provide the possibility to alter their gradient according to market conditions, thereby shortening or extending the transition period. Since novel energy technologies need time, much time, before they are well developed, it seems, we said it, that it is always too late to begin the wedge procedure. The wedges avoid the necessity, perhaps the dire necessity, to decide under the coercion of disasters.

An example from everyone’s day-to-day experience shows what is meant: for more than one hundred years an on board small (and miserably inefficient) electric generator, an auxiliary of the automobile’s engine, has provided the electricity the vehicle needs. Now a more general and principal electrification of the auto is under way with electrically supplementing plug-ins, hybrids, pure battery electrics or hydrogen fuelled fuel cells under the hood. And it may be envisaged that in the near future the combustion engine may even be completely removed from the vehicle and replaced by exclusively electric drive trains: here we have a prototype example of a “creatively destructed” wedge-shaped replacement of an “old” technology by a novel one. The result is an affordable exergetically efficient transport means, with much lower fuel demand, low noise, impressive acceleration, operationally environmentally and climatically absolutely clean.

Said time and again, novel energies need time, many decades rather than years. The worldwide nuclear complex was erected over a good half century: To date, 434 reactors are in operation, generating some 387 GW in 31 countries (2008); in 14 countries 62 more reactors for 63 GW are in a planning stage. – After Germany decided to abandon its 17 reactors, its 17 reactors, the question arose how many years would be needed for the demolition of the reactors, the recycling of the technology and the final safe storage of “hot” components. A first estimate says that from the proverbial “green meadow” prior to reactor erection to the green meadow after completion of its demolition, a century will not have come full circle. The consequence: planning and erecting a reactor including all its auxiliaries and its demolition after its end of life extends over two or three human generations. – Not included in that period is the operation and maintenance of a safe storage facility for radioactive and radiotoxic waste with up to almost eons-long half-lives; to date literally not one storage facility is in place worldwide to regularly take up the waste of the operated nuclear reactor park, not to speak of further reactors to come.

For the production engineer nuclear reactors are individual, customized items each manufactured on a “first and only” basis. – It is otherwise with the technologies of the post-nuclear replacements: PV cells, wind turbines and their rotor blades, heliostats and mirror troughs of solar thermal plants, heat pumps, fuel cells on board autos or in distributed district energy supplies are mass products, marketed in millions, if not billions (e.g., solar cells or fuel cell stack membranes). Their appropriate design, their production facilities, their transport requirements call for low cost, for longevity and high efficiency. Heliostat fields of tens of thousands of reflecting mirrors with the highest reflectivity, a production lot of hundreds of thousands of fuel cell engines with tens of millions of stack membranes, gigawatts per annum of PV cells among other things experience fierce competition and as a consequence low (and ever lower) cost. Think of the traditional auto engine with its market price of a few tens of €/kW – that price serves as a benchmark for alternatives that may come, not only for fuel cells. Obvious for the engineer and the economist, a few tens of €/kW for a mass product is something absolutely different from a few thousand €/kW for a nuclear reactor. On principal, it is not too easy for the engineer to design a low(est)-cost product produced in millions and serving for many decades at no or low operation and maintenance (O&M) costs.

The conclusion: replacing the electricity output of an abandoned nuclear reactor with four replacements (1) energy and exergy efficiency gains (2), clean fossil (3), renewables and (4) hydrogen energy is well prepared. The time for their implementation is well covered by the reactor’s operation and subsequent demolition period of two or three human generations. The specific cost (purchase, operation and demolition) of the replacements may even be lower than the nuclear equivalent. – If all goes well, key to the nuclear/non-nuclear replacements changeover will most probably be the collective anticipatory consciousness of the political class and their voters.

Asking the nuclear engineer to leave his nuclear business (and his conviction) and switch over to the four mentioned replacements should be avoided. With all due respect to the professional technical achievement of the nuclear engineer: “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.” (Max Planck).

Acknowledgement

The graph of figure 1 is courtesy of Nazim Muradov who created it based on data from reference (1); the author thanks Nazim for his generous understanding.

Annex. On nuclear energy and sustainability

Can nuclear survive? Does it have a future after the recurrent painful disasters around the world, e.g., of Three Mile Island in the USA, of Windscale in Britain, Chernobyl in the former Soviet Union, and now Fukushima in Japan? Do people (the responsible) know their stuff, are they able to control what ordinarily happens and above all what is hidden as potential disasters? Is nuclear-specific education and training of those in the front line of operations — regular and irregular operations — appropriately covering all contingencies? The thinkable contingencies and the unthinkable ones?
Most of the world’s nuclear reactor operators would have positively answered most of the aforementioned questions — even after Fukushima! Only Germany took the radical decision to close down all their nuclear reactors within 10 years’ time; a few other nations give it consideration, after all. What, however, is mandatory for all installations, present ones and those in planning and under construction, is the unmistakable elaboration of their sustainability status, and that not only for the reactor, but for all other installations of the nuclear conversion chain, the installations preceding the reactor and those that are subsequent. The following paragraphs give it a try. One thing is clear without much thinking: As long as those nations in possession of the bomb, the so-called “nukes”, remain just “nukes,” they do not even give the slightest thought to abandoning their nuclear reactor capacity, since their nuclear reactors provide them not only with electricity but also with bomb-appropriate plutonium. In this respect Germany’s situation is easy, because the country is no “nuke” and it is bound by law not to become one.

After the German Bundestag decided in June 2011 that Germany’s complete nuclear reactor capacity is to be closed down by 2022 (by the way, only around half a century after Otto Hahn split a uranium atom for the first time in his lab in Göttingen, Germany, and after Enrico Fermi’s first reasonably sized demonstration reactor started operation underneath stadium terraces in Chicago, USA in the 1940s), the question of nuclear energy and sustainability was, still is, and most probably will further be, queried. — On cursory sight, no really serious reason is seen why the Bundestag took that drastic decision after the rather long time period of Germany’s operating 17 national reactors without really significant technological safety risks (usual minor failings not counted). The more so as the reactors provided some 22% (at the point in time when the decision was taken) of the country’s electricity demand and were over decades always among those reactors worldwide heading the listing of highest production rates, year-by-year, and in particular, as only months before the Bundestag decided to extend the operation periods of one or the other reactor installation.

Two relevant and typically German national problem areas supplied decision support. Number one is obvious: the 2011 catastrophic disaster of the four nuclear reactors of Fukushima-Daiichi, Japan had happened only weeks earlier, confirming the “German angel” a large part of the country’s population had (and still has) that a similar severe accident might occur in its neighbourhood. And number two, also of typical German provenance: for the first time in the nation’s history the right-wing government’s opposition, the “Greens,” obtained 24% of the votes in regional elections, i.e., a seriously taken novel parliamentary opposition had evolved, almost “overnight,” in Germany’s parliamentary history absolutely unusual! The government thought it had to react, and a great majority of parliamentarians followed suit.

However, and that is much more important: The zeitgeist questioned ever louder the sustainability of nuclear energy! Not only the sustainability of electricity generation in nuclear reactors, but also the urgently required decision about the worldwide (and likewise in Germany) lacking solution of how to store away for good radioactive and radiotoxic waste. So far, the spent nuclear fuel rods are temporarily stored in cooling basins on the reactor’s premises coping with the radioactive decay heat of the rods, “temporarily” meaning for years, decades or, probably more realistic, for an even longer period, until some final “safest storage” will have been established and operable — and accepted by the political class and society! Radiotoxic plutonium and radioactive nuclear fission products (some) are extracted in the nuclear facility of La Hague, France prior to returning the rods into the longer term interim underground salt storage facilities in Gorleben, Germany. Whenever the train transporting the nuclear waste containers nears Gorleben, fierce donnybrooks between demonstrators and the police take place, not seldom at the edge of legality.

Nuclear energy is non-sustainable not only for one reason:

- Starting a novel energy regime with the investment of intellectual skill and billions of financial resources (mostly tax money) and only one or two generations later giving it up again, is not sustainable. Nuclear energy with its inherent characteristics is nothing for the interim, it is a long-term venture. The nuclear energy conversion chain is long and has many links all around the globe, from exploration of fissionable material and its mining, via yellow cake and hexafluoride production, uranium enrichment in gas ultracentrifuges, nuclear fuel rod production, electricity generation in reactors, extracting of plutonium and fission products from spent fuel rods, long-term storage of nuclear waste, and further, decommissioning of depreciated installations and their final recycling. If one link in this chain is cut out (e.g. the reactor), many of the other links lose their purpose — what a waste of engineering efforts, what futile industrial identification, what an investment of no avail! In the case of Germany’s reactors what remains is the decades long demolition of the installations and the securely safe recycling of the contaminated material — an unexpectedly “welcome” business for many decades!

- It seems to be increasingly insufficient to follow good democratic-parliamentarian tradition, handling national investments of outstanding importance under the laws and rules of legislative and executive bodies. Regularly, ordinary mortals, “you and I”, assume the right to influence the decision process directly. That’s by no means illegal, but it is sometimes extremely time and money consuming with no rational result guaranteed. There is good reason for national constitutions not providing formal plebiscitary referenda (like in Germany). If, however, it is in the national interest to get people’s views incorporated into the decision making process, then sustainability requires rules and standards.

- The half-life of nuclear fission products can be extraordinarily long, e.g., 24,000 years for plutonium. Obviously, the sustainability key is violated, “fulfilling the needs of the present generation without sacrificing the needs of future generations” [2]; 24,000 years is much longer than modern humans have been on earth! Safety precautions, rules, standards, etc. introduced by the living generation, may not be regarded as likely and plausible (or even be understood) by future generations.

- The potentials of renewable energies, the indigenous ones and those imported from abroad with the help of the energy...
carrier hydrogen, such as the potential of insolation, of national onshore and offshore wind sources, of still non-utilized hydropower sources, of biomass, of geothermal resources, justify the expectation to fill the gap after all German reactors are gone (8 of the 17 reactors are already closed by 2012). Also refurbished or newly built fossil-fuelled plants (in particular much cleaner and highly efficient gas combined cycles including high temperature fuel cells as the first conversion means prior to gas turbines and steam turbines) with noticeably raised efficiencies will be making contributions, and so will numerous electric appliances in industry and households: overall, the potential to replace the vanished nuclear capacity is not doubted.

However, will the replacement be taking place in the extremely short (in energy categories) time of 10 years, will it be finalized by 2022? Here the answer is not at all in doubt! On the contrary, novel energies have never been successful in such a short time period, all the more so as conditions of urgency are not given. No fear, energy exporters around Germany only wait for supply contracts, Russia sits on surplus oil and gas, Poland on coal, France and the Czech Republic on nuclear (sic!). But caution: France, in hot summers when the nation’s rivers are at the low water mark, has to throttle nuclear (sic!)! But caution: France, in hot summers when the nation’s rivers are at the low water mark, has to throttle nuclear production and import electricity from abroad, hitherto also from Germany! And the other way around, in harsh winter times France "squeezes out" its power plant capacity to 100 percent for its own purposes, since many houses in the country are electrically heated (by the way, an exergetically dubious solution!)

Altogether, we are not flying blind, we can be confident that in 2022 lights in Germany will not go out after nuclear has gone; one thing helps to boost courage: so far, the nation’s specific energy demand has declined year-by-year by some 1–2%, and it is not illusory to expect the same thing for the future. But hastening to meet the goal, ill-considered activity without proper engineering solidity, is not sustainable. Time and again, energy needs time! After all we know, certainly the nation’s 22% electricity demand gap will be closed one way and the other, but certainly later than 2022.

- Two nuclear energy development paths are distinguished: one leads to electricity for peaceful purposes, and the other aims at the atom bomb. As far as nuclear fuel is concerned there are almost no technological differences between the two paths, either path leads through all links of the nuclear conversion chain, admitting though that the reactor not only delivers electricity but also plutonium in spent fuel rods, and that gas ultracentrifuge cascades need many more steps in order to end up with highly enriched uranium (HEU, 90% of fissionable $^{235}\text{U}$), which is unnecessary for mere electricity generation (3–4% $^{235}\text{U}$), but indispensable for the bomb. For technologically fairly advanced nations the construction of the bomb is not a major challenge. It depends on the will of the nation’s political class with or without the accordance of its people and global society. Historically, eight nations have evolved into "nukes" and two are in developing stages (as far as the world is aware of).

Whether the bomb contributes to sustainable development or violates it, is, and most probably will further be, controversially discussed. Never again was a nuclear bomb dropped after Hiroshima and Nagasaki, Japan in 1945; quite a number of experiments and development demonstrations were pursued above ground and underground worldwide, at present less frequently than in the past. Regardless of the (probably never ending) controversy, two facts make nuclear clearly non-sustainable 1) the above elaborated deficit of securely safe final storage of radiotoxic and radioactive waste material for eons, and 2) living under the threat of the Damocles sword of the nuclear bomb!

All in all: If we take as standard of proof Klaus Töpfer’s words, “Sustainability is the novel perception of peace,” nuclear will never be sustainable! On the contrary, it increasingly entertains an illusion which will be biting the dust – hopefully prior of the next Fukushima. The responsibility nuclear imposes has developed into a burden humans seem incapable to take on.

REFERENCES


