Hiába volt magyar ember Neumann János, az első számitógép a „maniac” megalkotója, hiába volt magyar ember Szilárd Leó, az atomhasadás láncreakciójának, s igy az atomenergiának feltalálója, e találmányoknak a magyar nemzet hasznát nem élvezte. Azt szeretném, hogy a föld felmelegedését leállitó, az emberiség energia ellátását véglegesen és szennyezés nélkül biztositó szoláris-hidrogén technológia magyar érdeket is szolgáljon. Azt szeretném, hogy a szoláris-hidrogén erőmű kivitelezhetőségét bizonyitó kisérleti üzem, EU pénzen, de Magyarországon épüljön fel.

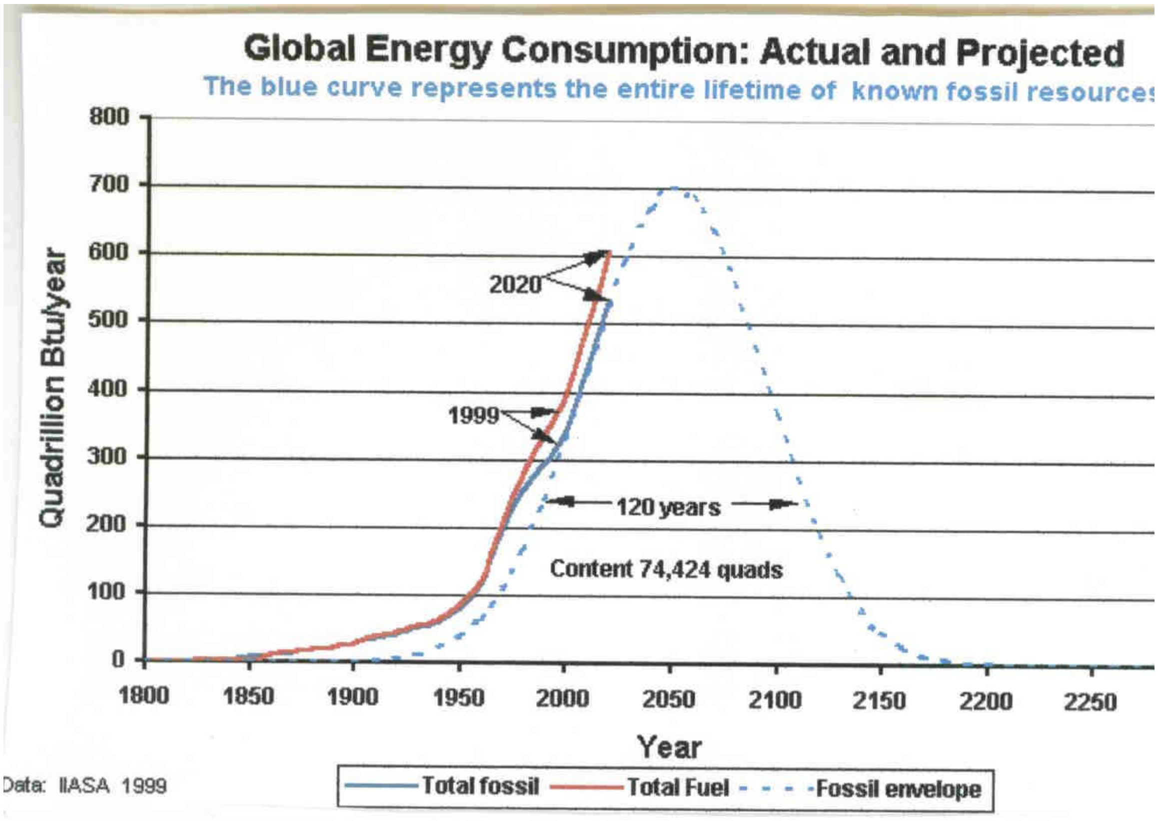
Azt szeretném, hogy túllépjünk az ujságcikkek és konferenciák vitáin, s tényekkel biznyitsuk, hogy van tiszta és kimerithetetlen alternativája az olaj vagy atomenergia forrásoknak. Azt szeretném, hogy a világ gazdasági ereje egy szép és egészséges jövő alapjainak lerakását és nem az emberiséget létében veszélyeztető energia-háborúkat szolgálná. Azt szeretném, hogy a világ első olyan kisérleti erőműve, mely elektrolizissel egybekapcsolja a napenergia gyüjtők és a már létező hidrogén technológiákat, magyar szabadalom lenne.

Ezt a javaslatot most mérlegeli a Magyar Tudományos Akadémia, de a tervről a magyar társadalom még nem tud. Kérni szeretném Önt aki e sorokat olvassa, hogy segitsen az alábbiakban részletesen ismertetett tervnek a magyarsággal való megismertetésében. Kérem, hogy segitsen úgy az alábbi angol nyelvü terv terjesztésében, mint annak magyar nyelvre való forditásában.

Lipták Béla

The Global Energy Future:
Solar-Hydrogen Demonstration Plant

During the last 50 years, the global population doubled, energy consumption quadrupled[1] and the global GDP increased 6 fold. This caused both global warming[2] and a possibility of energy wars which can turn nuclear. For these reasons and because solar energy is practically unlimited, the petroleum-based economy of the 20th century should be gradually replaced in by a solar-hydrogen economy in the 21st century. This conversion from fossil to clean and inexhaustible solar energy will require the mobilization of our scientific talent as did the Manhattan Project and must be followed by an international effort on the scale of the Marshall Plan.



Data: IIASA 1999

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[1] The global yearly consumption of fossil fuels is: coal 5.5 billion tons, oil 33 billion barrels, natural gas 100 trillion cubic foot. The yearly electricity consumption is 15 trillion kWh and the cost of electricity is much more than what we pay for it, because the environmental costs of its generation are not included. This environmental cost is paid by all mankind and Sir Nicholas Stern estimated that it will amount to 20% of the global GDP by 2020, if no changes occur. (The Cato Institute estimates that 5% to 10% is being lost as of now. http://www.cato-at-liberty.org/2006/11/03/global-warming-costs-benefits/) The global GDP today is 37 trillion dollars and is estimated to reach 50 trillion by 2020. 20% of that is 10 trillion a year, 100 trillion dollars every decade and rising.

[2] The yearly release of carbon dioxide is 27 billion tons, it has already caused 0.6 °C rise in the global temperature as the atmospheric concentration of carbon dioxide increased from 280 to 380 parts per million (ppm). If this release continues, it will reach 550 ppm by 2100. The release of methane is also rising. About 10 teratons of carbon (tera = 10^{12}) are stored in the frozen methane hydrates of the arctic regions, which will also be released, if the ice melts. The Kyoto treaty calls for greenhouse gas emissions to be reduced by 6% by 2012. Today they are still rising.

When discussing global energy consumption, the energy unit most often used is the quad[3] (Q = 10^{15} BTUs[4]). Today, the global energy consumption is between 400 and 450 Q and it is rising at a yearly rate of 20 Q. It is expected to reach 600 Q by 2020.. The presently used energy sources are: oil (35-37%), coal (25-26%), natural gas (20-25%), wood/biomass (10%), nuclear (7.5%) and renewable sources[5] such as hydro power (2.4%), solar (0.6%), geothermal (0.4%) and wind[6] (0.05%).

As shown in the figure above, the total fossil fuel reserves of the globe are estimated to amount to 75,000 Q and from 1950 to 2000, the global energy consumption increased from 100 to 400 Q. The figure also shows that the total energy consumption (red line) is rising at a higher rate[7] than the supply of fossil fuels (solid blue line). The difference between the curves is being provided from nuclear and renewable sources. The fossil envelope (dotted blue line) describes the likely future consumption of fossil energy (coal, oil, natural gas). The area under this curve is the total of the known fossil reserves on the planet. The curve projects a maximum yearly fossil production capability of about 700 Q, which could occur around 2050 and the exhaustion of this energy supply by the year 2200.

Naturally, the curve assumes that global warming will have no consequences and wars will not occur. In fact, besides the exhaustible nature of fossil fuels, their continued use also results in some 27 billion tons of carbon dioxide being released into the atmosphere[8]. Sir Nicholas Stern[9] estimated that by 2020 the effects of the resulting global warming will cause a 20% reduction in the global GDP. The continued reliance on fossil fuels could not only result in "energy wars" but also in the collapse of the global economy. It is for these reasons that major companies are already participating in solar related technologies[10].

Therefore the conversion to an inexhaustible and clean "solar-hydrogen" energy economy is recommended. Below, I will discuss a) the amounts of solar energy needed to meet the present

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[3] Q (Quad) equals one quadrillion (10^{15}) BTUs of energy. One Q of energy is equal to the yearly energy produced by 33 nuclear power plants, with the energy content of 10,000 supertankers of oil, 400,000 rail cars of coal or 28 billion cubic meters of natural gas. One Q also approximately equals one exajoule (eJ) or 0.293 terawatthours (tWh). FYI: kilo = 10^3, mega = 10^6, giga = 10^9, tera = 10^{12}, peta = 10^{15}, exa = 10^{18}.

[4] A British Thermal Unit (BTU) is the energy required to increase the temperature of one pound of water by one degree Fahrenheit at room temperature.

[5] Hydroelectric dams, wind turbines, solar cells, geothermal, wave/tidal power, biomass, methane from rotting trash, manure or landfills. The European Union requires that its members increase the proportion of their overall renewable energy use from 5.3% to 12% by 2010 and generate 22% of their electric energy from renewable sources by that date. The EU also requires that the biodiesel content of their diesel fuels reach 5.75% by 2010.

[6] The cost of wind turbine generated electricity is 4 to 6 cents/kWh and dropping. If fully exploited, Europe could meet 30% of its electricity needs by wind power.

[7] Reference: 2007 Solar Energy – Complete Guide to Solar Power and Photovoltaics, Practical Information on Heating, Lighting, and Concentrating, Energy Department Research (Two CD-ROM Set) (CD-ROM) by U.S. Government

[8] In addition to other pollutants such as NOx, SO_2 and particulates, the generation of each kWh releases from 270 to 1050 grams of carbon dioxide into the atmosphere.

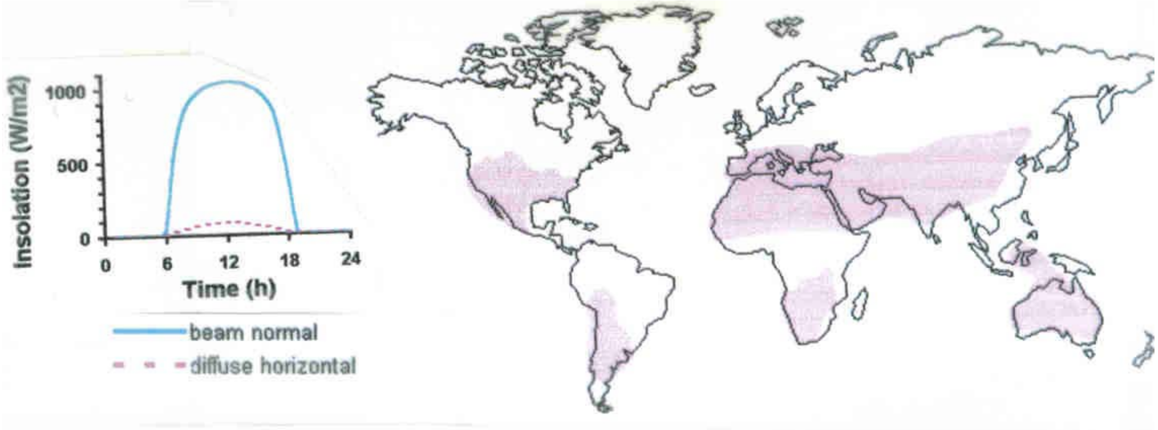
[9] Sir Nicholas Stern, a distinguished development economist and former chief economist at the World Bank

[10] British Petroleum (solar energy), Shell Oil (PV, hydrogen, wind power, biomass), Toyota (hybrid cars), General Electric (fuel cells, micro-turbines), BMW (hydrogen fueled internal combustion engine) and others.

and future global energy needs, b) the types and efficiencies of today's solar collector designs, c) the methods to convert solar generated electricity into chemical energy (hydrogen), d) the methods to store and distribute hydrogen, e) the investments and operating costs associated with the solar-hydrogen economy and e) the steps needed to fully convert to this technology by 2050.

Solar Energy Requirement and Availability

The amount of solar energy reaching a unit area of solar collector surface (m^2) is called "insolation". Insolation varies with the geographic area, with the weather, with the orientation of the collectors, and with diurnal and seasonal variations. High insolation areas of the five continents are shown on the right side of the figure below. Naturally, In addition to the continents, solar energy can also be collected on floating islands on the oceans.



Left – Variation of insolation over a full, clear day in March in Daggett California
Right - The areas of the world where insolation exceeds that of Dagget, California

An example of an insolation curve is shown on the left side of this figure, corresponding to a clear March day in Draggett, California[11]. Assuming that this is an average day for the year, the total solar energy received per square meter of collector area is slightly under 4,000 kilowatt-hours/year (kWh/yr), if the collectors are provided with tracking mechanisms which continuously points them toward the sun.

Today, the per capita energy use on the planet ranges from1,000 kWh/yr in Africa to 16,000 kWh/yr in Canada. Therefore, if the efficiency of a solar energy collection and conversion system is assumed to be 10%[12] and if the solar energy is collected in a high insolation region (such as Daggett, California), the per capita collector area required would range from 2.5 m^2 for people living in Africa to 40 m^2 for the residents of Canada.

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[11] Landolt-Börnstein – Group VIII, Volume 3C "Renewable Energy" published by Springler Berlin, Heidelberg, DOI 10.1007/b83039, 2006

[12] The efficiency of solar hot water systems is 50% to 70%, the efficiency of solar-thermal-electric generating systems (SEGS) is around 20% (DSG - direct steam generation is superior, over 30%), and future installations, such as dish concentrators driving Stirling heat engines, which are being installed in Southern California, are expected to be more efficient. The efficiencies of conventional photovoltaic (PV) collectors range from 8% to 17% (Sanyo), while Fresnel lens type PV concentrator systems have reached 26.5% (Amonix, Inc).

Using conservative insolation values (less than in Daggett, California) as the basis of the calculation, the collector area required to meet today's global energy needs is 3% to 5% of the area of the Sahara[13] (a large dot on the map above). Naturally the total area of high insolation on earth is much larger[14] than that of the Sahara and solar energy can also be collected in areas of lower insolation[15] or on floating islands in the oceans.

Thermal Solar Collector Designs

The thermal collectors on the roofs of private homes[16] usually serve to provide the residence with heat and/or hot water. The larger sized thermal power plant designs on the market[17] are either concentrating[18] or flat, their operation is either stationary or tracking[19] and their methods of conversion is either to convert the solar energy (photons) to thermal energy (heat) or directly to electricity (photons to electrons) by the photovoltaic process.

Here, the thermal designs will be described first. These designs are often referred to as the solar-thermal-electric generating systems (SEGS). An example of that design is a 354 MW plant that has been in operation at Kramer Junction and Harper Valley in California since 1985. The main components and operation of that design is described in the figure below. In this design, parabolic mirror reflectors (troughs) are used to track the trajectory of the sun and to concentrate the sunlight onto absorber tubes that are located at the focal line of the parabolic mirrors. Inside the absorber tubes, heat resistant oil is circulated and serves to transport the collected heat into steam boilers, which provide the steam to drive the turbine generators[20].

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[13] Assuming that the collector efficiency is 15%, the yearly solar energy reaching each square meter of collector area is 3,000 kWh, knowing that a square kilometer (km^2) is a million square meters and that each kWh of energy equals 3413 BTUs, the collector area needed to generate each Q of electric energy is about 666 km^2. Therefore, to collect the 400 Q, 266,000 km^2 needs to be covered by solar collectors. Because the area of the Sahara's is 9 million km^2, about 3% of it's area would need to be covered to supply the Global energy need today, if the energy was not converted to hydrogen (was used when generated) and 5% if it was stored in the form of chemical energy (hydrogen).

[14] The Sahara covers 1.6% of the total surface area of the globe (land on the planet occupies 150 million km^2, the oceans occupy 361million km^2). Therefore, including the oceans, the total high insolation area on the planet is more than 25 times that of the Sahara and more than 500 times the total available area of high insolation.

[15] In the north central USA, the yearly insolation is between 1000 and 1500 $kW/h\text{-}m^2$. The efficiency at which this energy can be collected today varies. Flat water heaters convert that energy at an efficiency of 60%-70% efficiency, while photovoltaic (PV) convert it with an efficiency of 10% to 17%.

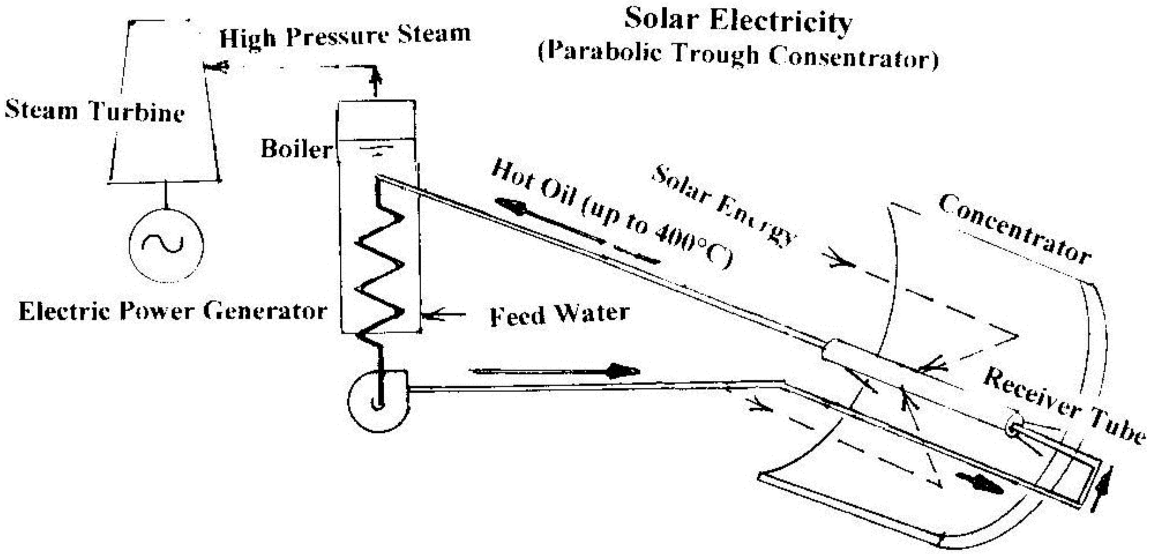
[16] A well insulated house in the north east United States uses about 1000 gallons of oil (150 million BTUs = 44,000 kWh) a year for the purposes of heating and hot water.

[17] The nations with the largest installed capacity of solar collectors are: China (36 gW - gigawatt), Japan (9 gW), Turkey (7 gW), Germany (3.5 gW), Greece (3.5 gW),….USA (1.5 gW). On a per capita basis, the leading users of solar energy are Cipus, Izrael and Greece.

[18] The concentrator designs (among many others) include parabolic troughs, parabolic dishes, central receivers and Fresnel lenses. This last design uses refraction instead of reflection,

[19] Tracking increases the amount of energy collected by 30% to 40%.

[20] One of nine solar electric energy generating plants at Kramer Junction, California. The individual plant sizes vary from 30 mWs and up having a total capavity of 354 MWe. (photo courtesy Kramer Junction Operating Company)



In this particular installation, the hot oil circulates at 400 °C (752 °F), but there are higher temperature installations also. One advantage of the SEGS design is that the solar energy can be conveniently stored in thermal storage and used as needed to compensate for diurnal, seasonal and weather related changes as insolation changed. Several computerized control systems are in operation. These serve to optimize the positioning of thousands of mirrors to accurately track the trajectory of the sun and thereby maximize the collected energy. One such early installation was controlled by a Beckman model MV-8000 DCS system (Beckman today is Fisher-Rosemount).

In some of the more recent SEGS designs, the circulating fluid temperature has been more than doubled, while in others direct steam generation (DSG) has been achieved, which increases the power production by some 15%.

Photovoltaic (PV) Collectors

Sunlight is composed of photons containing various amounts of energy corresponding to the range of wavelengths within the solar spectrum. In the photovoltaic (PV) collectors[21], when photons strike the cell, they may be reflected, pass through, or be absorbed, but only the absorbed photons generate electricity. This is because the construction material (the silicon atom in the crystal) has to receive 1.1 electron volts in order to cause its valence electron (electron in the outermost shell) to move into the conduction zone.

A typical silicon PV cell is composed of a wafer consisting of an ultra-thin layer of phosphorus-doped silicon (N-layer with a negative character), which is placed on top of a thicker layer of boron-doped silicon (P-layer with positive character). These layers are connected by the P-N junction. When sunlight strikes the surface of the PV cell, an electrical field is generated, which provides momentum and direction to the light-stimulated electrons, resulting in a flow of current when the solar cell is connected to an electrical load.

Flat-plate PV collectors contain an array of individual cells, connected in a series/parallel circuit and encapsulated within a sandwich structure, the front of which is glass or plastic. Unlike thermal collectors, the backside of the collectors is not insulated, because for best performance, they need to be cooled by the atmosphere. If this energy loss can be eliminated in new designs, the conversion efficiency could be much improved. Flat PV collectors can also track the sun by being tilted about their axis.

Today the energy payback period[22] of PV collectors for thin-film PV systems is 3 years and for multi-crystalline silicon PV systems is 4 years. As manufacturing techniques improve these payback periods are likely to drop to 1 to 2 years. With a minimum life span of 25 years, the ratio of energy obtained to energy invested is 10:1 for solar energy. This compares favorably to oil shale for example, which has a ratio of only 4:1.

The carbon dioxide emission payback period[23] is 3 years. Because, solar collectors have already operated for over 25 years and their life span is likely to increase, this ration is also about 10:1.

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[21] As to the present use of PV collectors in the world, according to the International Energy Agency (IEA) 40% of all the PV installations today are in Germany and 13% in the United States. In Germany, the power companies buy back the generated electric power at a rate secured for 20 years. This is called a Feed in Tariff (FiT) program. The magazine Solar Generation reports (Sept. 2006 pp.24), that the total solar energy generation commitment in the USA by 2020 is 7.3 GW. Of this total, California is committed to 3 GW and New Jersey to 1.5 GW.

[22] The energy required for manufacturing, expressed as the time period required to collect the equivalent amount of solar energy to the energy that was needed to produce and assemble the particular PV collector and its support structure.

[23] This is the time required to compensate for the carbon dioxide emission that occurs during the manufacturing of the collectors,- if the PV collector is manufactured by the use of fossil fuel generated energy (400 kg CO_2 per square meter of collector) - by the emission avoidance, which in that time period the use of PV collector generated energy will result in.

Storing and Transporting Solar Energy

The storage of solar energy is an important consideration, because storage is required to compensate for the diurnal, seasonal and weather-related variations in insolation. Therefore, in order to supply continuous users without power interruptions, the generated electricity must be stored. On small installations, such storage can be provided by hot water tanks or high density batteries. On mid-sized installations pumped hydro storage can be considered. For larger installations, the compressing of air into underground caverns is one of the methods being evaluated.

A better option is to eliminate the need for storage. This need can be eliminated if an electric grid is available to can take the excess solar electricity when not needed and supply the shortage when needed. For example, if the solar power plant is located close to a hydroelectric or fossil power plant, it is possible to increase or decrease their rate of generation to match the variation in the availability of solar energy.

The favored method of storage is to convert solar energy into a chemical energy form (convert it into a fuel) and to store/distribute it as chemical energy. The carriers of this chemical energy can be gases, liquids or solids. In one process, high temperature solar chemistry is used, where mirrors concentrate the sun’s rays on zinc oxide and vaporize it at a temperature of 1200 °C. The vaporized zinc is later condensed into a powder. This zinc can be transported and when reacted with water vapor, will produce hydrogen fuel, while recombining with oxygen back into zinc oxide[24]. This method of solar energy storage is not yet available commercially.

Chemical energy can also be stored in hydrogen, which can be generated from ammonia, from the reforming of fossil fuels or by the electrolysis of water. Naturally, when made from fossil fuels, the carbon is exhausted into the atmosphere in the form of carbon dioxide.

Hydrogen can be stored as high pressure gas, as cryogenic liquid or can be absorbed in solids such as in metal hydrides (sodium borohydride) and in metallic “sponges” (zirconium, platinum, lanthanum). As of today, hydrogen is the favored means of storing solar energy in the chemical form.

Before discussing the generation of solar-hydrogen (electrolysis), first I will discuss the properties of hydrogen and its suitability as a transportation[25] fuel.

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[24] A pilot plant funded by the EU, the Paul Scherrer Institute (PSI) and the Swiss Federal Institute of Technology of Zurich (ETHZ) has successfully demonstrated this process in a 300 kW pilot plant at the Weizmann Institute of Science (WIS) in Rehovot near Tel Aviv and produced 45 kilograms of zinc per hour.

[25] Hydrogen filling stations are already in operation in California, hydrogen buses operate in Montreal and Bavaria, a hydrogen powered passenger ship sails in Italy. BMW is marketing its 7 Series, 12-cylinder, 260 horsepower car using liquid hydrogen to fuel its internal combustion engine, which can also run on gasoline. In Japan, as part of their national hydrogen program a 200,000 m^3 tanker ship been designed.

Hydrogen as a Transportation Fuel

Hydrogen is stored in both as a liquid (cryogenic) or as a gas compressed to some 800 atmospheres pressure (12,000 pounds per square inch). On a weight basis, hydrogen contains 3.4 times more energy than gasoline[26]. On a volume basis, hydrogen requires 3 times the volume of gasoline to store the same amount of energy. Hydrogen can also be stored in solids and these "reversible solid" storage method of storage are probably the safest, but their development is still in the experimental stage and today they are capable only of storing small amounts of energy.

Because of its lower volumetric energy density, when hydrogen is used as fuel for transportation, the volume of the hydrogen tanks need to be 3 times the size of today's gasoline[27] tanks to provide the same driving range. Actually, the volume of the hydrogen tanks can be somewhat smaller than 3 times, because hydrogen engines are more efficient[28] than the gasoline burning ones.

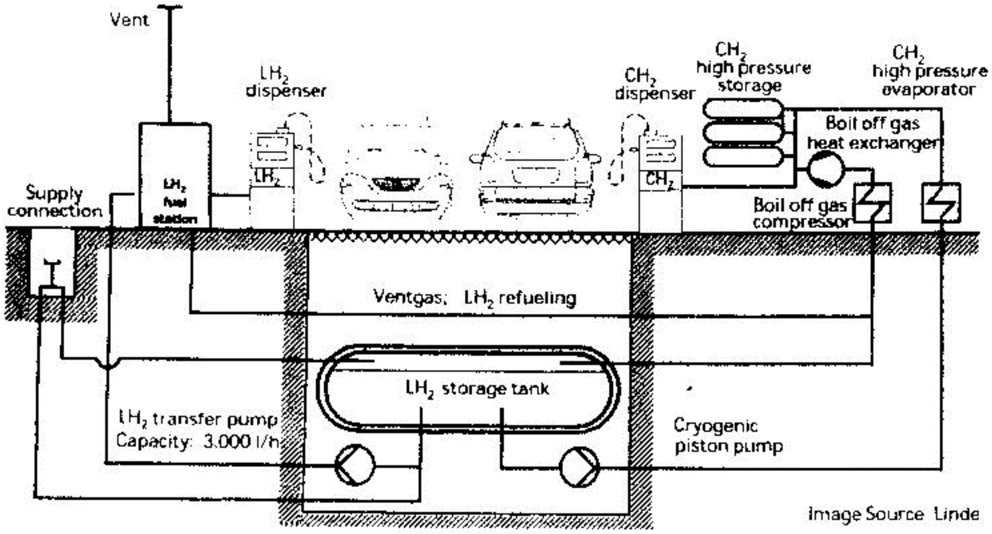

Image Source Linde

High pressure hydrogen tanks are made of carbon fiber. Cryogenic (liquid) hydrogen tanks are double walled with the space between the walls evacuated to provide good thermal insulation. If electric cars[29] with battery storage are used, the batteries can be refilled at electric filling stations. In the future, these filling stations are likely to be combined with the capability for also providing

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[26] Liquid hydrogen weighs 0.59 pounds/gallon and the energy content of one gallon of gasoline equals the heating value of 3.58 gallons of hydrogen. The heating value of one pound of gasoline is about 18,000 BTU (19 mJ) which corresponds to 39,600 BTU/kg (41.8 mJ/kg), while the heating value of a kilogram of hydrogen is 134,616 BTU (142 mJ).

[27] A typical passenger car has a range of 575 miles and is provided with an 18 gallon tank, while an 18 wheeled semi-truck has a 750 mile range and requires two 90 gallon tanks.

[28] At cruising speed, the efficiency of gasoline engines is 25%, of diesel engines 35%, while the internal combustion type hydrogen engine is 35% efficient and the fuel cell type 45%.

[29] Ford Motor leased some 300, 150 mile range electric cars in California, where electric refilling stations are available, but later, without a clear reason, recalled these cars and sold them in Norway.

gasoline and hydrogen fuels, as the automobile fleet of the next couple of decades is likely to be a mixed one.

The energy consumption of compressing hydrogen is about 16% of the energy content of the gas, if a single stage compressor is used and 12% if multistage units with intercoolers are utilized. The energy cost of liquefying hydrogen is about 30% of its energy content. In addition, when storing liquid hydrogen, some of the liquid in the tank will vaporize due to heat infiltration (hydrogen boil-off), which will reduce the volume available for storing the liquid.

Because of its lower density, the transportation of hydrogen through pipeline requires about 4 times more energy than does the transportation of natural gas. Transportation of compressed hydrogen gas by trucks is inefficient, because the weight of an empty truck (capable of holding several hundred atmospheres of pressure) will weigh almost as much as a full one, because the volume of its tank is sufficient for only 400 kilograms of hydrogen. For this reason, a busy gas station could require 10-20 deliveries of hydrogen gas a day, while if liquid hydrogen is used, a single daily delivery would suffice. This is a consideration in favor of liquefying, although liquefying hydrogen requires more energy than does the pressurization of the gas.

Hydrogen generation, storage and bulk distribution systems (Praxair, Inc)

Safety is another important consideration. During the last decades, hydrogen has been used extensively in the petrochemical, food and space exploration industries[30]. This experience has made hydrogen storage, transportation and handling reasonably safe. The design of hydrogen tankers and trucks are similar to their LNG counterparts. From the point of view of safety, the low molecular weight of hydrogen has an advantage over LNG, because in case of a leakage, the high molecular weight gases, such as propane, will accumulate on the ground, while hydrogen will quickly escape into the atmosphere. This was tested by crash tests of automobiles with hydrogen tanks.

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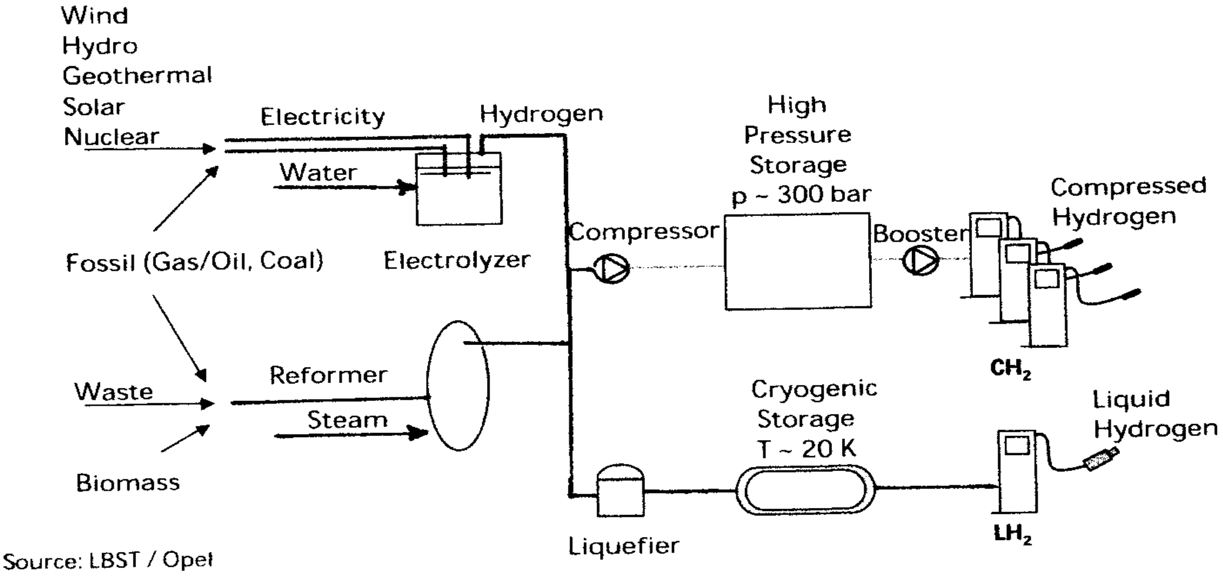
[30] Today, the United States is safely using 9 billion cubic feet of hydrogen a day in the petrochemical, food and rocket propulsion industries.

Hydrogen Generation, Electrolysis

Some 98% of the bulk hydrogen that is produced today is generated from steam reformation of natural gas (methane, CH4) where methane is reacted with water vapor over a catalyst to form carbon monoxide (CO) and hydrogen. Actually, one can use ethanol (alcohol), biomass, fossil fuels or organic waste to produce hydrogen by the process of "reforming", but this process also releases large quantities of greenhouse gases into the atmosphere. Vegetation, including algae, also produces hydrogen from water while absorbing sunshine and combining the hydrogen with carbon dioxide to produce glucose. As shown in the figure below, multiple energy sources and a variety of chemicals can be used to generate hydrogen, but solar based electrolysis of water is the only process that is nonpolluting.



Source: LBST / Opel

In 1820, Faraday discovered electrolysis by passing electricity through water and thereby generated hydrogen at the negative electrode (cathode)[31] and oxygen at the positive electrode (anode). Thus, electrolysis can be used to produce hydrogen from water while consuming electricity. Plants and vegetation use a similar process. They use chlorophyll as a catalyst and the energy of the sun to decompose water into diatomic oxygen gas and hydrogen that is reacted with carbon dioxide to form glucose. Electrolysis is an endothermic reaction that requires energy for its operation (blue arrow in the figure below):

$$H_2O + (286 \text{ kJ of ENERGY}) \leftrightarrow H_2 + 1/2O_2$$

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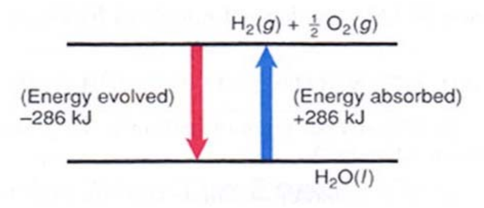
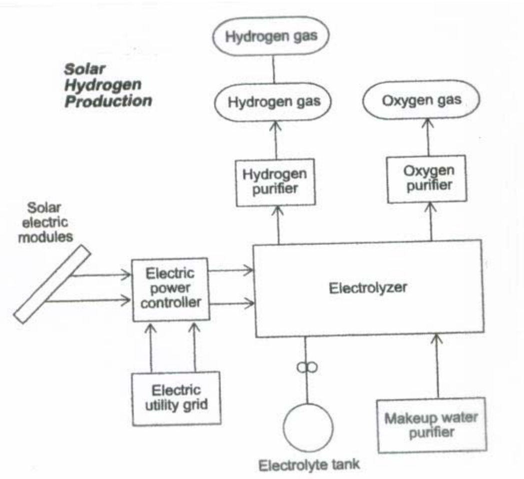
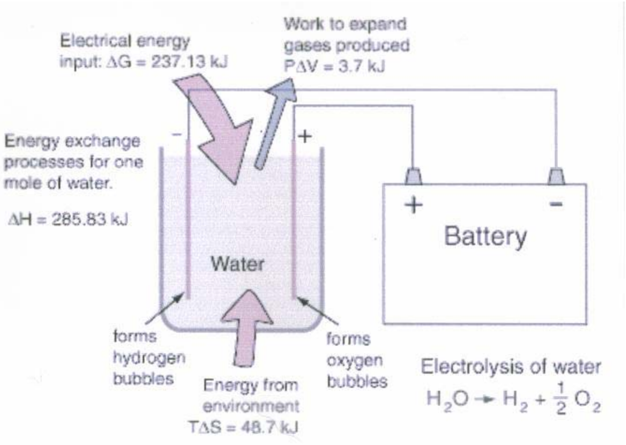
[31] 96,484 coulombs (Faraday's constant) are required to deposit one mole of any material at the cathode of an electrolytic cell. Therefore it takes 237.13 kJ of electricity to synthesize one mole of hydrogen (kJ = 0.948 BTU). At typical ambient temperatures, the environment contributes 48.7 kJ of thermal energy per mole of hydrogen to this process for a total of 286 kJ. The weight of one mole of hydrogen is 2 grams and the energy content of one gallon of gasoline equals about that of 500 moles of hydrogen. The electricity needed to obtain the amount of hydrogen that has the same energy content as one gallon of gasoline [(237.13 x 500 x 0.948)/3,413)] = 32.9 kWh



As it is illustrated above, it takes the same amount of energy to split water into hydrogen and oxygen as the amount of energy that is generated by oxidizing hydrogen into water. The only difference is that because electrolysis increases entropy, not all the energy need to be supplied in the form of electricity. Therefore, the surrounding environment will thermally contribute 48.7 kJ and therefore only 237.1 kJ of electrical energy is needed to make a mole of hydrogen.

Water can be converted into hydrogen and oxygen by using electricity from a battery or any other electricity source, including solar. (In nuclear submarines, the electricity is provided from nuclear power, while the main reason for operating the electrolysis equipment is to produce oxygen.) When the electricity from a battery is replaced by electricity from solar collectors, "solar-hydrogen" is produced. One mole of water produces one mole of hydrogen gas plus a half-mole of oxygen gas, both in their normal diatomic forms[32].





The target set by the US Department of Energy (DOE) is to increase the efficiency of electrolysis (presently around 66%) to 75%, while eliminating the need for platinum electrodes. (Efficiency is defined as the ratio of the energy contained in the hydrogen produced, divided by the energy it

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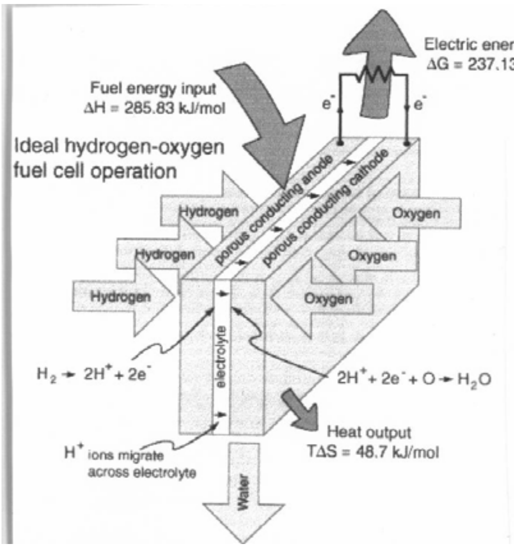
[32] IMAGE SOURCE: "Chemistry in Context" Wm C Brown Publishers, Dubuque Iowa, 2nd edition, A project of the American Chemical Society, ed: A. Truman Schwartz et al., 1997, Chapter 5 "The Wonder of Water"

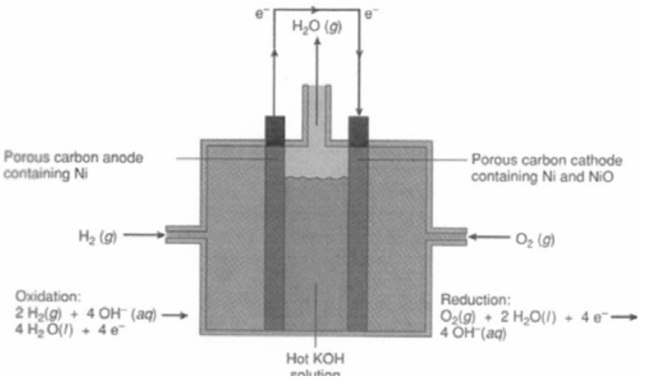
takes to produce that hydrogen). The DOE efficiency target has already been reached by some electrolysis designs using new porous electrode materials.

Fuel Cells

When hydrogen fuel is burned, it emits no carbon dioxide, no carbon monoxide, no sulfur dioxide, no volatile organic compounds, nor fine particles. The only by-product of the combustion of hydrogen is water vapor. This formation of a mole of water (2 grams) also produces, 286 kJ[33] of energy. If this combustion takes place in a fuel cell (illustrated below), only 237.3 kJ of this energy can be recovered as electric energy output, while 48.7 kJ will heat the environment. Viewing the electrolysis and fuel cell reactions as a pair, the enthalpy change is 286 kJ in both reactions, but in case of electrolysis the environment contributes 48.7 kJ heat energy while in case of the fuel cell reaction 48.7 kJ has to be dumped in the form of heat into the environment.

In an ideal (theoretically perfect) fuel cell, the energy content of the fuel is converted into electrical energy at an efficiency of 237/286 = 83%. This efficiency is much greater than the efficiency of hydrogen burning power plant generators. Although real fuel cell efficiencies are lower than this ideal value (about 66%), they are much greater than the efficiency of fossil electric power plants[34] or internal combustion engines (25%).





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[33] One kJ (kilojoule) equals 0.948 BTU, 0.239 kCalories or 0.278 Wh.

[34] Sub-critical fossil fuel power plants can achieve 36–38% efficiency. Super critical designs have efficiencies in the low to mid 40% range, with new "ultra critical" designs using pressures of 30 MPa and dual stage reheat, the efficiency can reach about 48%. An important class of fossil power plant uses a gas turbine, sometimes in conjunction with a steam boiler "bottoming" cycle. The efficiency of a combined cycle plant can approach 60% in large (500+ mWe) units. Nuclear power plants generally cannot reheat process steam due to safety requirements for isolation from the reactor core. This limits their thermodynamic efficiency to the order of 34–36%.

The various fuel cell designs are categorized according to their operating temperatures, electrode designs, electrolytes and the type of fuel used. Electrolytes can be acidic or alkaline liquids, solids or solid-liquid composites. Low temperature alkaline fuel cells (AFCs) were one of the first designs used in the US space program to produce water and electricity on spacecraft. They are subject to carbon monoxide poisoning, are expensive and have short operating times.

Phosphoric acid fuel cells (PAFC) are considered to be “first generation” mature designs that are used in larger vehicles and buses. They can be 85% efficient when used to generate both electricity and heat, but not much over 40% when generating electricity only. They are large, heavy and cost around $4000/kW.

Polymer electrolyte membrane (PEM) fuel cells (also called proton exchange cells) are suited for passenger vehicles. They provide high power density and are low in weight. They use a solid polymer electrolyte, porous carbon electrodes and platinum catalyst. Developers are currently exploring other catalysts that are more resistant to carbon monoxide poisoning. Another area of development in progress is the design of high pressure hydrogen tanks that would provide a range of 400 miles between refuelings.

In addition, the development of many new designs is still in progress. Once lightweight and low cost fuel cells are available, they can generate electricity or power electrically driven automobiles without causing any pollution. In electric cars, it is likely that they will outperform today’s heavy and large storage batteries. Yet we do not yet know the final outcome of the battery vs. fuel cell race, because the energy density of batteries is rising, they are getting smaller while fuel cells are still expensive.

Efficiencies and Costs

The solar collectors are the first links in the chain of equipment that is required for the functioning of the solar-hydrogen economy. The efficiency of photovoltaic (PV) cell’s range from about 8% for the amorphous silicon versions to 14%-17% for crystalline silicon designs. The efficiency of concentrating and reflected PV designs are 25% to 30%.

The first cost of crystalline PV collectors is about $3,500/kWp, while their installed cost is about $7000/kWp. When used in residential installations, the solar installation costs for an average home range from $40,000 to $60,000. The average capacity of these installations is 5 to 8 kWp[35]. Such an installation pays for itself in about 12 years, if it is partially financed by state support[36] and if the state requires the power companies to allow these installations to be connected to the

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[35] These numbers increase if swimming pool or waterfall pumps and similar equipment are to be also supplied. The amount of solar electricity generated in most of Europe and most of the USA is about 90% of the amount generated in the southern regions. Therefore the capacity needed is 10% less in the South. The installations are usually sized to cover the total yearly electricity use of the home, so that the electricity bill will “zero out” at the end of the year. The yearly energy bill of an “average” household in the north central United States is about $4,500 ($2,500 for heat and hot water, $2,000 for electricity.)

[36] The highest amount of support in Europe is paid in Germany and in California (USA), about $25,000/household installation. In New York the state pays 49% to 70% of the cost, in New Jersey the support is $3,800/kWp and in Connecticut $25,000 per installation.

grid, so that the excess power need not be stored in batteries, but can be sold to and will be credited by the power company.

The unit cost of electricity generated by larger PV installations is about $0.2/kWh[37]. When generated by higher efficiency thermal solar plants, the electricity cost drops to $0.08 to $0.17 per kWh[38] . This cost is competitive with the price paid for fossil generated electricity in some areas, but it is 1.5 times that in other areas. In case of large solar power plants, the energy supply of the area is usually coordinated among the power companies and state authorities. Both Israel[39] and China[40] are building large solar power plants at investments of about $7,000/kW capacity or about $2,500/m^2 of collector area.

Solar collector systems in the past were priced on the basis of their capacity in $/Wp. Recently the first cost involved in their purchasing has been eliminated. In case of buying these systems on a Power Purchase Agreement (PPA) basis, there is no up front cost for the purchaser, only an agreement is signed that the electricity generated by the system will be purchased for a negotiated price in the range (between 6 to 30 cents/kWh[41]) for an agreed upon time period (5 to 25 years).

After the solar collectors, electrolysis is the next link in the chain of equipment used in the solar-hydrogen process. It's efficiency is around 66% and the target set by the United States Department of Energy is to increase electrolysis efficiency to 75%. The installed cost of smaller electrolysis equipment is around $3,000/kW and this cost drops substantially as the size increases. The efficiency of compressing the generated hydrogen is 84% to 88%. It takes about 16% of the energy content of the gas to compress it, if a single stage compressor is used and 12% if multistage units with intercoolers are utilized. The efficiency of the equipment used in liquefying the compressed gas is about 70%.

In addition to the above listed expenses and losses, there are also transportation, storage and infrastructure expenses. Today, the cost of liquid hydrogen, made from natural gas is about $8/kg while hydrogen in the high pressure gas form is $25/kg. As a kilogram of hydrogen has the same energy content as a gallon of gasoline, which in Europe is around $7 to $8 and in the USA between $2 and $3, this price is not yet competitive. Hydrogen made by electrolysis from water, using fossil fuel generated electricity costs about $4.50/kg.

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[37] The cost of 20 cents per kEh is based on an installed collector cost of $2/kWh. This number is reasonable for a 100 kWp unit with a life expectancy of 20 years and 5% interest on investment.

[38] At Kramer Junction, California, some 9 solar power plants, 30 mW and larger are in operation today. Their combined capacity is 354 mW. The yearly insolation in the area is 2940 kWh/m^2. Plant efficiencies range from 10% to 17% and their capital costs range from $2500 to $3500 per kWp. The cost of generated electricity drops as the size of the plants increase from 17 cents to 7.7 cents per kWh.

[39] The initial capacity of the thermal solar power plant in the Negev is planned to be 150 mW and it is estimated to cost $350 million. The plants is planned to expand to 500 mW at a cost of $1 billion.

[40] In Dunhuang City (Gansu Province in China) the construction of a $765 million solar power plant been approved. The plant will have 31,200 square meters of solar collectors at an installed cost of $2451/m^2. Because in tha area, the sun is shining for 3,362 hours a year, assuming that the plant will run fully loaded when the sun is out and assuming that the electricity will be sold at $0.1/kWh, the value of the produced electricity is $33.6 million/year.

[41] This way, solar power is able to directly compete with grid based power. SunEdison in California, SkyPower in Ontario and New Mexico are selling their systems on this basis. Their clients include Staples, Whole Food Markets, California State University and the city of San Diego.

Economics on the Global Scale

It has been calculated that to meet today's global energy consumption by solar energy, 3% to 5% of the Sahara would need to be covered with solar collectors. The cost of that, plus the cost of the equipment associated with the generation and handling of hydrogen, at today's costs is prohibitive[42]. Yet, the cost of inaction by 2020 is estimated by Sir Nicholas Stern, former chief economist at the World Bank to be 20% of the global GDP[43] and it is rising.

On the brighter side, it is known that that as new technologies mature and enter mass production, their prices drop. In past years, computer performance improved by orders of magnitude and continues to do so every decade. Similarly, over the last decades, the cost of wind power generated electricity been reduced to one quarter. Therefore, it is not unrealistic to expect that costs of modular energy devices will also drop as mass production is started and their markets expand. In addition, the cost of transition to a solar-hydrogen economy will be spread out over several decades.

The implications of a shift to the solar-hydrogen economy are profound. The world would be freed from dependence on fossil fuels, thereby ending not only global warming but also the geopolitical nightmare that has preoccupied national security planners for the last 50 years. This systematic change can begin slowly, but can gain momentum quickly. The pace and direction of the energy transition are determined not just by technological developments, but also by social, economic and environmental forces and by the response of industries, governments and society as a whole. The response of societies and the enlightenment of the general public can only be gained by providing reliable facts and proved data.

Conclusion

The time for holding conferences and for writing articles is over. It is time for action. It is time to build a complete solar-hydrogen demonstration plant. Once built, it will provide reliable cost and efficiency data so that the operation of the equipment chain can be optimized until it is reliable and cost-effective. The figure below identifies the equipment components of a solar-hydrogen demonstration plant. The complete chain comprises the solar-hydrogen generator unit, which can be mass produced in various sizes[44] .

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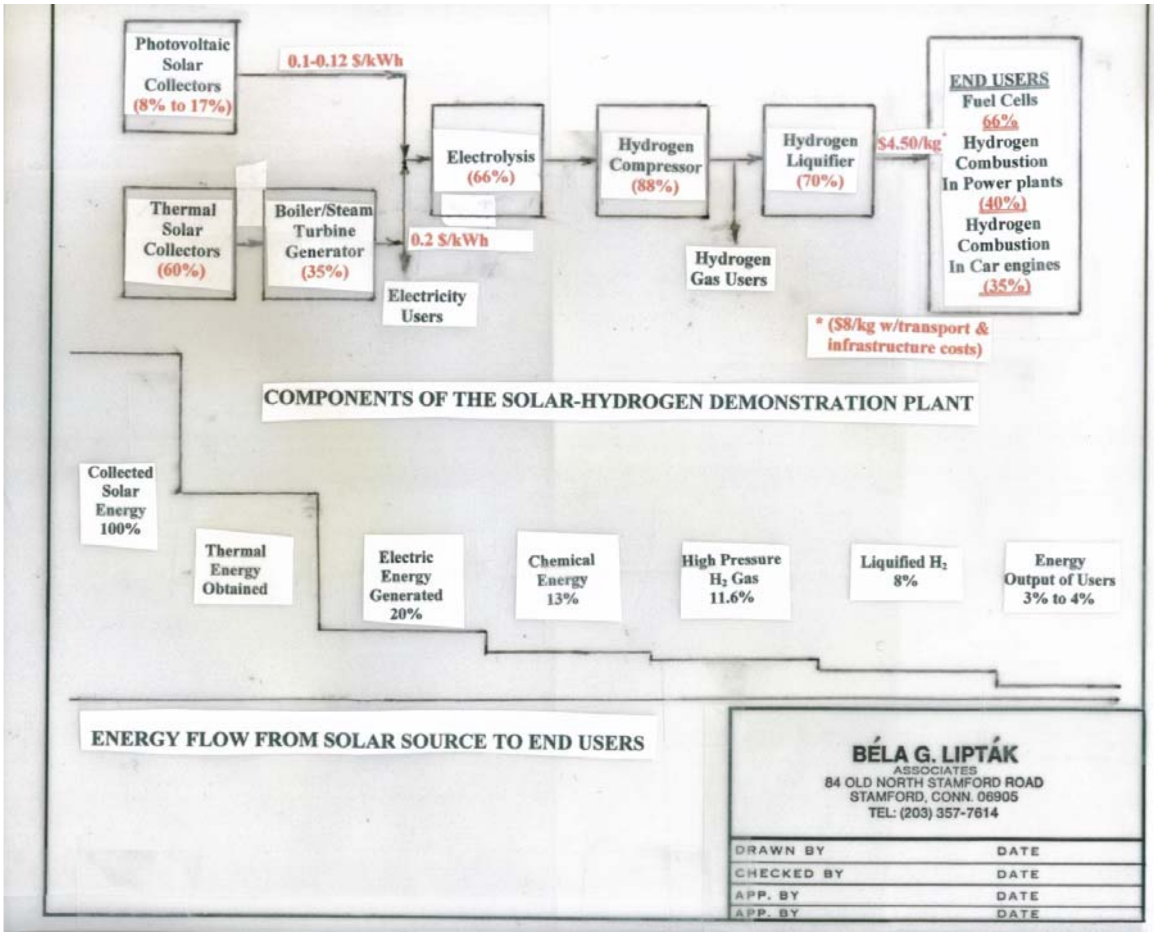
[42] It could amount to several years of today's global GDP. Naturally, this would be spread out over a transition period of 50 years or so and during that time period, the cost is likely to drop by orders of magnitude.

[43] The global GDP today is 37 trillion dollars and may reach 50 trillion by 2020. 20% of the GDP of 2020 means a yearly loss of 10 trillion dollars, which is 100 trillion dollars every decade and rising.

[44] From 10 kW units for private homes to 1 gW sized power plants.



This figure lists the present efficiencies of the equipment blocks and gives the costs of hydrogen and electricity produced today. The cost of solar electricity is between $0.1/kWh and $0.2/kWh. The hydrogen equivalent of a gallon of gasoline costs $4.50. One of the goals of the demonstration plant is to cut both of these numbers in half.

The figure also shows that, with today's technology, at the end of the chain only 3% to 4% of the solar energy is converted to useful purposes in our homes and industry. This is because of the low efficiencies of the energy conversion equipment blocks as the solar energy is first converted to thermal, then to electric, then to chemical forms and finally applied to useful purposes.

The goal of demonstrating this technology is to obtain hard numbers, so that the debate over the costs of the solar-hydrogen economy can be closed. The other goal is to identify and eliminate the bottlenecks, optimize the processes and generate standardized international specifications for the mass production of the required equipment components. To do this, the best scientific talent of the world should be mobilized, similarly to what was done in the Manhattan project.

When the technical problems are resolved and the specifications for the various size solar-hydrogen generator units are available, an international effort should be initiated to minimize the generator costs through mass production and free market competition. Once the generator units are on the market and the coordinated transition from oil to solar energy is in progress, mankind's confidence in its future will be rebuilt, just as Europe was rebuilt by the Marshall Plan.

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