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The hydrogen economy, fuel cells, and electric cars

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Abstract

Hopes have again been raised about developing a "hydrogen economy", in which hydrogen could be expected to replace oil and natural gas for most uses, including transportation and heating. It is again being claimed that hydrogen will be a widely available, clean, safe fuel. This article argues that such expectations are almost certainly illusory. Hydrogen, like electricity, is not an energy resource but an energy carrier. It takes more energy to extract hydrogen from water than burning the hydrogen can ever provide. There are also inevitable losses in storage, transmission, and final mechanical or heating applications. The question then turns on the efficiency—and safety—of the entire chain of conversion, from the energy source (fossil, solar, or other) to the final use. Moreover, energy sources (preferably renewable, for the long term) can be used for the direct creation of electricity, which can be introduced into the existing grid without requiring a vast investment in a new hydrogen distribution system. In addition, a hydrogen-based system would be unacceptably dangerous. This report will present a detailed technical and economic analysis of the problems with the proposed hydrogen economy and the advantages of some alternatives, principally electricity-based. A hypothetical case of what would be required for a hydrogen filling station serving the general public is closely examined.

Keywords: Hydrogen economy; Fuel cells; Electric cars; Energy policy; Transportation fuels

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1. Overview

There is a considerable research effort in the United States, Europe, and Japan directed towards developing a "hydrogen economy", in which hydrogen would be expected to replace oil and natural gas for most uses, including transportation fuel. Initially hydrogen would be made from fossil fuels, and later from alternative sources, such as solar, nuclear, and biomass. The US Department of Energy (DOE) has developed a project on how to achieve this goal, and the president included it in the state of the union address, presenting it as a way to energy independence. Claims about the advantages of the H_2 economy have been published which argue or assume that hydrogen will be a widely available, clean, safe fuel. The concept has received strong support from environmentalists [1].[1,2,3] This article argues that such expectations are almost certainly illusory.

Hydrogen, like electricity, is not an energy resource, but an energy carrier. Almost no hydrogen in a combustible form is available in nature. There is a vast amount of hydrogen in water, of course, but it takes more energy to extract it from the H_2O molecules than the hydrogen can provide. This is a fundamental law of thermodynamics that no research can change. There are also inevitable losses in storage, transmission, and final mechanical or heating applications. The question then turns on the efficiency of the entire chain of conversion, from the energy source (fossil, solar, or other) to the final use.

Hydrogen can be made from fossil fuels or by electrolysis of water. If other elements in the chain remain constant, hydrogen from fossil fuels would require more fossil fuel than currently used for the same purpose and would significantly increase our energy imports and global warming. If the hydrogen were to be released by electrolysis using solar- or nuclear-derived electricity, the cost would be higher. The direct use of the electricity would cost half as much as via the hydrogen route. Also, additional electricity could be slowly introduced into the existing grid, whereas it is physically and economically almost infeasible to switch to a radically new source like hydrogen that requires a new distribution system. In addition, hydrogen is the most dangerous of all known fuels and while it can, under certain conditions, burn invisibly and radiate little heat except upwards, mixed with air in a confined space it is a powerful explosive. Hydrogen cars would be a boon to terrorists.

This paper will document these widely known facts. While basic research can lead to new ideas, large-scale development cannot. Before we spend very large sums on developing a hydrogen economy, DOE should carefully rethink why we want to do so. DOE together with Germany and Japan in the 1970s spent close to 10 billion dollars in the first incarnation of the hydrogen economy, before realizing that the basis for this economy, making hydrogen by chemical processes using heat

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from high temperature nuclear reactors, made no thermodynamic or economic sense [3].

If the US really wants to reduce imports and reduce greenhouse emissions, there are many currently feasible ways to do so gradually and at lower cost. Raising corporate average fuel economy standards (CAFE), use of hybrid cars, thermal solar energy, electric cars, and several other partial solutions are cheaper and better. Another immediately available solution discussed in this paper is to utilize large amounts of hydrogen in the oil refinery processes to improve the environmental quality of transportation fuels. Either hydrocracking or hydrotreating all residual fractions increases the yield by 20%. This alone would reduce oil imports with available technology by 3 million barrels a day. These measures will cost more and sometimes are less convenient than current practices, but they are all currently feasible and are more cost-effective than direct use of hydrogen. A hydrogen economy is, for the foreseeable future, at least twice as expensive as any other solution.

Unlike direct hydrogen use, for most other options, such as electricity, the existing delivery system could be gradually incremented making an easier transition and therefore a much larger impact over the next 20 years. But all options are more expensive than present practice with cheap natural gas and oil. Moreover, nobody can afford to voluntarily sequester CO_2 without profitably recovering the significant cost.

No research can change certain basic constraints. Instead, costs could be reduced by large-scale implementation of current or near-term technologies, relying on the power of competition. This requires the passing of the initial hurdle and raising the political will to distribute the cost initially over a broad consumer base. The barriers to achieving these goals are political and not technical. The same problems would be faced with hydrogen only much more so. This report will present a detailed technical analysis of the problems with the proposed hydrogen economy and the advantages of some alternatives. This paper is, however, not intended to advocate a specific energy policy, but to show that if we want to introduce alternative energy sources on a large scale other alternatives have decisive advantages over a hydrogen economy, in terms of environmental impact, feasibility, costs and safety.

2. Introduction

The concept of a hydrogen economy was introduced in the early 1970s by the Institute for Nuclear Energy in Vienna. The central idea was to generate hydrogen using high temperature nuclear reactors and to use the hydrogen to replace fossil fuels, especially crude oil, for all stationary uses. The idea resulted in a very large international research program with expenses reaching over 20 billion (1980) dollars. It was unsuccessful. The involvement of the author [3] was to show that the method proposed for hydrogen generation by thermo-chemical cycles driven by high temperature nuclear reactors was inherently inferior in cost and thermal efficiency to simply generating electricity from nuclear reactors and generating hydrogen from the electricity by electrolysis. In this case using the electricity directly was clearly preferable for most uses.

In the last 10 years the idea of a hydrogen economy has been revived [1].[4] This time the proposal is to generate the hydrogen from fossil fuels, mainly natural gas in the near term, and ultimately from solar energy via electricity and electrolysis of water. Nuclear and biomass sources are also being considered. One of the main claims or reasons for justifying manufacture of H_2 from fossil fuels is the ability to sequester the by-product CO_2. As a hydrogen economy with a national distribution system is far away, it has been proposed to initially use local small hydrogen generators to convert natural gas to hydrogen, both for smaller installation of fuel cells (distributed electricity generation) and for local service stations to fuel hydrogen-based cars.

This report will first address fallacies about the hydrogen economy and demonstrate its problems. It will also show that if we want to slowly switch to an economy based on solar or nuclear energy, direct use of the electricity is far superior, and by a factor of three cheaper as the only known way to generate hydrogen from nuclear or solar energy is via electricity. We will show that use of hydrogen from fossil fuels is the most expensive, least feasible way to decrease oil imports, and would increase global warming. As the only positive impact of hydrogen is when it is made from solar or nuclear energy, the report will compare it to an all-electric economy.

3. Common fallacies about hydrogen

There are at least six inherent fallacies of the supposed advantages of the hydrogen economy, as compared to an electric economy based on a mixture of fossil fuels, solar and nuclear energy. The ultimate stage would be in both cases an economy based on solar and nuclear energy.

3.1. Fallacy A: Hydrogen is a widely available fuel

Hydrogen atoms are widely available in nature, but only bound to other atoms, mainly oxygen (water) or carbon (hydrocarbons). It requires huge energy to separate it (Table 1); in practice much more than the energy obtained from using it.

This energy can be supplied either by fossil fuels or by solar or nuclear generated electricity. Simple thermodynamics and experience show that processes which involve such a large increase in the free energy (see Table 1) are with present technology inherently thermally very inefficient, relative to the increase in free energy. The most efficient way for generating hydrogen from water is electrolysis with an efficiency of 70%.

Table 1
Production of hydrogen

Reaction	ΔH_R° (kcal/g-mole)	ΔG_R° (kcal/g-mole)	$\Delta G_R^\circ/\Delta H_R^\circ$
$H_2O \rightarrow H_2 + 1/2O_2$	+57.8	+54.6	0.94
$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$	+39.4	+27.1	0.69

Heat and free energy of reaction at standard conditions (state, ideal gas; T, 298 K; P, 1 atm).

3.2. Fallacy B: It is easier and more efficient to transport hydrogen than natural gas over large distances

We have available numbers based on long-term experience for both electricity and natural gas, which are given in Table 2.

The energy losses for transportation of hydrogen in pipelines depend on the design and cost. It has been proposed to use present pipelines designed for natural gas, although there remain severe questions whether it is safe to do so because of the potential leaking of hydrogen though the valves. For H_2 we need to triple the volume to supply the same energy as natural gas. Therefore, if we were to use existing pipelines, the velocity in the pipe would have to be tripled (pressure drop increases by a factor of nine), which makes H_2 transport much less efficient than either electricity or natural gas in the national distribution system. The transport losses of methane and electricity over large distances are fairly equal at 5–7% (with electricity having a slight advantage for long distances). With hydrogen, using the same pipelines for hydrogen could increase the losses to 20% (see Table 3). In reality, it is very doubtful that we would use natural gas pipelines or local distribution systems for H_2. Hydrogen requires various different fittings and pipe specifications. It would also require installation of much more powerful compressors. We would probably need a totally new distribution system both nationally and into the houses, a very high cost. Additional electricity can be gradually introduced and the grid can be expanded as needed.

While it is true that H_2 could be shipped in a liquid form, this is prohibitively expensive and energy intensive (based on available cost of shipping methane)[5] as H_2 is more expensive to liquefy and much more expensive to ship.

3.3. Fallacy C: H_2 is safe. It diffuses faster into the air than it can ignite. The Hindenburg disaster was not caused by hydrogen

While H_2, like nitroglycerin, can be safely handled, it is the most dangerous of all fossil fuels known to man. It is true that H_2 did not self-ignite to cause the burning of the Hindenburg, and that some of what burned was the aircraft fuel aboard and the cabin and skin of the dirigible. It is also true that some of the hydrogen may have burned without exploding and sent heat mainly upwards. But if the Hindenburg had been filled with helium, nothing so rapid or serious would

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Table 2
Distribution losses for natural gas and electricity in grid

	Distribution losses in grid (% of total distribution)
Natural gas (from gas companies)	5–7%
Long distance electricity (from Keystone)	1.5–2.1%
Local electricity (from Keystone)	3–5%

Table 3
Distribution losses for hydrogen vs. methane basis using natural gas distribution system for hydrogen

	Ratio H_2/CH_4
Density	2/16
Moles	3
Velocity (three times)	9
Loss	3.4

Loss ≅ density × velocity squared/number of moles.

have happened. Like nitroglycerin, hydrogen does not explode by itself. It needs an energy release (a spark, for example) to ignite or explode a hydrogen–oxygen mixture. However, for hydrogen the minimum energy required is very small. All fuels mixed with air can cause explosions or large fires and have done so. The question is the likelihood and the severity of the safety measures that have to be taken to prevent a fire or explosion. The flammability or explosion limits of H_2 are much wider than for any other fuel, and the minimum energy required for ignition or explosions is by a magnitude lower than for methane (see Table 4). This limits the maximum amount that can be safely stored and demands special expertise of the personnel handling it. Safety instructions for handling compressed hydrogen are distributed by Air Products, Inc.[6]

Diesel is a safer fuel than gasoline, which is safer than natural gas, which is safer than propane, which is safer than H_2, notwithstanding some assertions to the contrary. All of these, especially natural gas and propane, have caused explosions, some catastrophic. Because of the hazard, we strongly limit the size of propane tanks and also their transportation. One is not allowed to transport even a reasonably small propane cylinder for a camping stove through a tunnel despite the fact that the maximum explosive force of a propane cylinder for a camping stove is between 40 to 100 lb of TNT. By comparison, the explosive force of a H_2 container as proposed by the car companies is 220 lb of TNT (equal to five suicide bombers). Furthermore, the probability of a fuel tank for a hydrogen car to explode is an order of magnitude larger than that of a propane tank. A bus has a much larger potential explosive force than a propane tank. For a H_2 storage tank of the size

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Table 4
Flammability (explosion) limits for H_2 and methane and propane% H_2 (methane) in air, and minimum ignition energy (at 1 atm total pressure)

Gas	Lower limit	Upper limit	Minimum ignition energy (MI)
Hydrogen	2.0	75.0	0.03
Methane	5.0	15.0	0.29
Propane	2.1	9.5	0.15

used in a bus, one would normally recommend a protected special room with a blow out wall into a safe area with no people or any combustibles (see footnote 5). In a bus this blowout wall is into the bus itself. An accident in one bus in a tunnel would put the tunnel out of use for months. There is also a critical post-September 11 problem. H_2 cars can be easily modified to become an undetectable bomb for a suicide bomber. All one has to do is to equip the hydrogen tank with a release valve and a delayed detonator. If 10% of the cars were H_2 cars, less than five cars exploding at the same time in rush hour in a confined space, such as the Lincoln Tunnel in New York, might kill more people than on September 11, and make the tunnel unusable for a year.

Whenever accidents can happen they will ultimately happen regardless of safety measures. Therefore one has to limit the impact of the largest reasonably possible accident even if it has a low probability to occur. No safety measures can compensate for the physical properties of hydrogen (very wide combustion limits of H_2 air mixtures and low minimum ignition energy) nor can safety measures compensate for the fact that H_2 is the most dangerous fuel known to man. The question is, why introduce it, especially as it is not an energy resource, only an energy carrier? And if it were introduced, the public outcry after the first few catastrophic explosions would shut down any large-scale use of hydrogen.

3.4. Fallacy D: Hydrogen is storable, electricity is not

Actually both H_2 and electricity are storable. The question is efficiency and cost. Electricity has several options for storage. For a thermal solar plant, there is an option to store the heat transfer fluid. While this is relatively cheaper and involves no efficiency losses, cost limits storage to 1 day for load following. The cheapest storage is hydraulic, but it still has an efficiency of at best 80%. The same is true for batteries. Hydrogen storage by liquefaction is even more expensive and has larger efficiency losses. But if we include the efficiency losses of making the hydrogen from electricity, it is clearly more costly and much less efficient.

H_2 storage has one advantage. It requires much less weight, which is important for cars. However, in a car with present fuel cells, H_2 would require three times as much electricity to manufacture the vehicle compared to an electric car. The best hope for the future is to reduce this by a factor of two (H_2 generation from electricity including compression has very optimistically an efficiency of 70%, but 55% at present), and the fuel cell itself 60% (40% at present) [4,8].

3.5. Fallacy E: Hydrogen is a clean fuel widely available and environmentally beneficial

As said before, hydrogen is not an energy resource, but an energy delivery system. Therefore, while hydrogen just like electricity is clean, the impact on the environment in both cases depends on the primary energy source used. If H_2 were made from a fossil fuel such as natural gas, the inherent loss of efficiency would cause a large increase in greenhouse gases compared to direct use of the fossil fuel (double or higher). Furthermore, if the hydrogen is generated in small-distributed generators, instead of a large central plant, the increase in greenhouse emissions could be much larger. Small units are hard to tightly supervise, and as the catalyst ages the unit could have significant emissions of methane, which has a 20 times larger global warming effect than carbon dioxide. Therefore, the hydrogen economy could have a strong negative impact on the environment especially if distributed energy is used.

It is claimed that if we build large H_2 plants from fossil fuels, we could sequester the CO_2. But the same is true for electricity generation. We could even sequester CO_2 from some of the existing coal power plants. However, it is by no means sure that we have the capability to safely sequester such tremendous amounts of CO_2 for ever. At present we already recover about 50 million tons of CO_2 from hydrogen plants and another hundred million tons a year from natural gas and ammonia plants, and release this CO_2 with no attempt to sequester it. If we were to introduce solar power plants, we could have an immediate impact on greenhouse emissions; whereas a hydrogen economy would not only cost more than three times as much, but any significant impact on CO_2 emissions would have to wait until we have built a national distribution system.

3.6. Fallacy F: There is an advantage for distributed electricity generation to save the cost and problems of long-range distribution on the grid

This is partially true, but neither hydrogen nor fuel cells have any potential role. Today, many natural gas fueled combined cycle power plants of 500 MW are built all over the country based on local needs. These are real distributed electricity generation reducing the load in the national grid. Small-distributed units are only useful for remote locations and in under-developed countries and even for such uses fuel cells have to compete against small turbines and diesel generators. A reliable electric grid is an essential infrastructure for a modern economy. Present trends for all small-scale distributed electricity generators are based on back up by the grid to keep the size and the cost of the unit reasonable. Compared to combined cycle power plants, distributed electricity generators have a smaller impact on the required carrying capacity of the grid, and no impact on the cost of the power company to maintain the local distribution system, almost half the cost of the power.

One advantage of the grid is that, because electricity use in homes is highly fluctuating, it provides an averaging mechanism. A private house has an average consumption of 1–2 kW, but the maximum may at times exceed 20 kW. The grid allows a substantial averaging. True there is a penalty. Over 50% of the cost of electricity is for the distribution. For a given customer distribution costs are independent of the amount of electricity consumed. The present pricing system, which includes the distribution cost in the price per kWh, provides a large subsidy for the small user just as long distance service used to subsidize the small telephone user. This is now slowly changing, and in several areas, users are already charged separately for the connection and the electricity. By comparing the local generation cost of a fuel cell (or solar cell) to the full cost of electricity to the user, one can obscure the fact that those technologies are inherently non-competitive.

But there are two additional problems. If the distributed unit is designed to be large enough to meet the peak demand of the user, it is excessively expensive. Storage devices for electricity are also expensive. In a remote location, using a local generator, there is no choice and one reduces electricity use to the essential. The only cheap solution is back up from the grid. To further reduce costs legislative bodies have passed laws that force the power companies to buy back the electricity from solar cells or other sources generated by the home owner whenever he does not need it. This actually forces power companies to give a large subsidy at the expense of other users.

The electric company still has to maintain its generating capacity and maintain the distribution grid. All the fuel cell saves is the cost of the electricity itself. The argument that it is cheaper than extending the natural grid is perhaps partially correct, but it is much cheaper to reduce the requirements of the national grid by local combined cycle power plants, which have only half the greenhouse emissions, compared to local fuel cells. Furthermore, it gives the power company the electricity

Table 5
Impact of fuel cells for apartment building and private homes: six cases providing 1 gigawatt power in a major city (present fuel cells)

Case	I	II	Disadvantages of case II
Investment cost (billion dollars)	0.5	2–3	1.5–2.5 (higher cost)
Reduction of load on National Grid (gigawatt)	1	Smaller impact especially for private homes	
Thermal efficiency (%)	56–60	30–35	25–30 (lower efficiency)
Fuel requirements for 10 years (million equivalent barrels of oil)	80	140	60 (higher requirements)
Cost of fuel for 10 years (billion dollars) ($4.00 a million BTU for power plant, $5.00 for distributed fuel cells)	1.9	4.2	2.3 (higher cost)
CO_2 emission over 10 years (billion tons equivalent green house gases)	26	50–75	24–49 (larger emission)

Case I, Building a new 1 gigawatt gas fired combined cycle power plant.
Case II, Installing 1 gigawatt present fuel cells with steam reformers for natural gas.
Column III, Disadvantages of fuel cell compared to combined cycle power plant.

whenever it needs it. The subsidy required for fuel cells and the increase in greenhouse emissions caused by them is given in Table 5. When we ultimately go to solar energy, then transferring it to hydrogen and back to electricity makes no sense as we will get less than half the electricity back and a hydrogen distribution network would cost more than increasing grid capacity.

4. Phasing in an alternative energy supply system

One problem with all radically new alternative energy systems is how to switch to a new source, which requires a new distribution system. This is prohibitively difficult in a developed economy in which there are large investments in the infrastructure of delivery for natural gas, electricity, gasoline and diesel. While ultimately one could think of using the natural gas pipelines (at high conversion costs) for hydrogen it could not be done while natural gas is still in use. Since hydrogen may leak out of natural gas pipelines, and requires different fittings and compressors, they might never be used for hydrogen. The same is true for all alternative liquid fuels. Unless they mix with gasoline or diesel, a dedicated distribution system is needed. Therefore, switching is impractical unless one designs the new energy source to be so compatible that it can simultaneously use the existing distribution system. Localized generation of hydrogen by alternative energy is impractical. If the hydrogen is generated from methane or electricity, this is thermally inefficient and involves a large penalty, not only in thermal efficiency and cost, but possibly also in global warming. There is no way to sequester CO_2 from small local plants.

Electricity is the only energy form that can be generated from alternative energy sources on a large scale and that can be phased in to slowly replace fossil fuels. It can be directly used replacing fossil fuels, which is such a decisive advantage that it overshadows all other arguments even for mobile uses, especially as direct use of alternative electricity is much cheaper. The ability to phase in slowly is essential, as we do not have the resources to switch such large critical systems in a reasonably short time. It also allows society to learn from its mistakes, which radically reduces the cost. The hydrogen economy has no advantages to compensate for this major difficulty.

5. Thermal efficiency

Any large-scale use of H_2 is not only costly but involves large penalties in cost and thermal efficiency. Consider for example a hydrogen economy in which the hydrogen is made by solar electricity. The car could use the electricity directly with a loss of 5% in the grid. The car is driven by the same electric motor and does not know if the electricity comes from the grid or from a fuel cell. For hydrogen, we first have to generate the electricity and lose at least 30% in the production and compression of the hydrogen. Present proven technology, including compression, has an efficiency of 55% [3,8]. Second, the fuel cell has at present an efficiency of

45% and hopefully in the future of 60% [4,8]. This results in a large penalty on efficiency and cost. Not only do we need twice as much electricity, but also hydrogen plants, and compressors. Furthermore, fuel cells are expensive. This at least doubles the cost of the electricity fed to the motor. Any large-scale use of hydrogen to replace methane for fuel use or generation of electricity will have a significant cost penalty compared to direct use of electricity generated from alternative sources. In a home direct use of electricity for heating is, based on the heat equivalent of electricity, thermally more efficient than use of fuel. If one includes the efficiency of electricity generation, this comparison depends on the efficiency of the power plant. Electric heating is much easier to control and adjust to the need of different rooms. An electric hot water system is cheaper to install and thermally more efficient than a gas heater. At present the high cost of electricity makes it much more expensive. But if it would eliminate the subsidy to the small user, electric heating may become competitive. Compared to heating by using hydrogen, especially hydrogen produced from electricity, direct heating by electricity is thermodynamically more efficient by a factor of two. For this purpose as for others, to convert electricity to H_2 makes no economic, thermodynamic or technical sense. The same is true for stationary fuel cells or hydrogen use in houses or other stationary uses. Furthermore, a large fraction of the natural gas is used for power generation, where direct use of electricity has an additional advantage of a factor of two. If the feed to the H_2 plant is natural gas the thermodynamic and cost penalty is less, but it is still large. The LHV efficiency of H_2 generation is 65–70% in the best large units. In a small unit for generating hydrogen for a fuel cell in a home or gas station the efficiency is even lower, as one cannot afford all the measures one takes in a large plant to increase efficiency.

The investment cost of a process with standard design assumptions is strongly related to the inherent efficiency of a process. One can increase this efficiency by lowering the ΔT (increasing the heat transfer surfaces), but it requires higher investment. On the other hand, one can also lower investment by decreasing efficiency. Smaller units for distributed use are more expensive because of the reduced size. One can reduce the differential by mass production, but one cannot reverse it.

The lower efficiency in addition to the switching problem makes the H_2 economy very seriously non-competitive with the electric economy. For the same investment we could double the beneficial impact of alternative energy sources on the environment. Table 5 shows that distributed fuel cells based on hydrogen have a strong negative impact on the environment.

Interestingly, fuel cells were initially developed to achieve higher efficiency using natural gas. They lost this potential advantage when they switched to H_2. Thus they became obsolete for power 15 years ago. This fact is obscured by publishing numbers giving thermal efficiency including heat recovery, which can reach 85%. This is not how one normally reports efficiency. The first law of thermodynamics states that energy is always conserved. So efficiency including heat recovery is always 100%. It is the actual free energy value of the heat or its practical value that counts.

Normally, the efficiency of a peaking turbine is quoted as 32 to 35%. The heat in the exhaust gas of a gas turbine has a higher thermodynamic value than that of exhaust gas from a regular fuel cell. Unlike the heat of a fuel cell, the heat from the exhaust gas of a gas turbine can be used in a steam turbine. There is another problem with including the heat of a fuel cell in the thermal efficiency. Even for water heating, the fuel cell does not necessarily operate when we need the water. In the summer electricity consumption goes up, but heat and hot water use go down. Nor are the heat requirements of a house matched to the low-grade heat of the fuel cell.

In a refinery, use of electricity and steam is reasonably constant, and co-generation makes sense. When fuel cells came in, power plants from natural gas had an efficiency of 35–38%. Fuel cells promised more. Today operating combined cycle power plants have an efficiency of 56%. New production models have reached 60%, and 40% of the energy coming out as low-grade heat has the same thermodynamic value as that from a standard fuel cell. Regrettably, many promising technologies in development lose the race, as better technologies come in, and if fuel cells had not had such large government support, they would have had to face this sad fact long ago, and the effort would have focused on those limited uses where they have unique advantages.

6. Hydrogen cars

There has been tremendous publicity about use of hydrogen in cars. It is true that a car driven by H_2 and a fuel cell has no emissions, unless the H_2 is generated in the car itself, where it could be worse than gasoline, especially for global warming and CO_2 emissions, due to control and inspection problems. Using compressed hydrogen, H_2 cars have a significant advantage in weight of the fuel tank compared to a battery. Prototypes have been built that drive quite well, but at a very high cost.

Electric cars, which inherently have a much higher efficiency than hydrogen cars, also have zero emissions. Still GM phased out its electric cars, as the market was too limited. Electric cars are not as convenient and powerful as gasoline cars and are more expensive. H_2 cars are at present far more expensive than electric cars. For the $120,000–150,000 that a small H_2 car is presently projected to cost, one could build a very efficient electric car. It is claimed that by research and by mass production of hydrogen cars, prices can be lowered. But the same principle should hold for electric cars. Even if it is true, how do we subsidize the first hundred thousand or the first 8 million cars, to get to the lower prices? As long as gasoline is cheap and one can get a powerful gasoline powered car, very few people are going to buy electric or hydrogen cars or even a hybrid car. Hybrid cars inherently have a much better efficiency than a H_2 car and are a much better way to reduce oil imports. If we want to preserve the environment and become independent in our energy supply we will have to make some sacrifices, and for most uses even present electric cars are fully sufficient.

In addition to electric cars that ultimately could use alternative electricity, there are other cheaper ways to reduce oil requirements and lower global emissions. All of those are not competitive or economically attractive with the present gasoline prices. This will be discussed in Section 8. Here we limit ourselves to the potential ultimate goal, switching partially to a non-fossil fuel economy, as in all other cases hydrogen would clearly have a negative impact on global warming.

Hydrogen cars have several obstacles. The safety problems are practically insurmountable, especially as one would give a dangerous system to totally untrained people. Furthermore, it is very expensive and impractical to distribute the H_2 to the cars unless we have a national supply grid. There have been filling stations built for H_2 for demonstration and experimental purposes and for small, standardized fleets. Fleets can be strictly scheduled, cars expensively standardized, and attendants highly trained. Such stations do not have the same problems as a large commercial stations serving the public. (See the Appendix for an estimate of the cost of an ordinary filling station for public use.)

To reduce our dependence on imported oil and reduce greenhouse emissions, electric cars are regrettably the only long-term option we have. The hydrogen car is just a prototype, for the foreseeable future. Focusing on research for hybrid and electric cars, and maybe subsidizing production and purchasing, so that we gain the experience to improve both the hybrid and the electric car and give an incentive for developing better and lighter batteries, should be a primary goal.

Electricity has a decisive advantage; it is available almost everywhere in the US and in all other developed countries. The buyers of the first 10 million hydrogen cars would have a hard time finding a service station. The cost of providing a new infrastructure for 200 million hydrogen cars is very optimistically estimated at over a trillion dollars (see Appendix). It probably is much larger, as this assumes that we can place such stations into populated areas. The Appendix shows that direct use of electricity has a five to one price advantage over hydrogen generated from electricity in a filling station. Even with central H_2 generation the advantage is at least triple. Electricity for cars requires a 50% increase in electric generation and grid capacity to replace 6 million barrels of oil per day. However, the buyers of the first 10 million electric cars will have no problems to find an electric outlet in their garage or in any motel. To provide such outlets is cheap. An incremental electricity supply can be provided gradually as needed. Furthermore, for safety reasons it is presently not permitted to put a hydrogen filling station close to a gas station. It would have to have not only a separate large plot, but also highly skilled personnel. This was not included in the Appendix as the cost is in any case prohibitive.

But these are not the only costs. To make it attractive one has to provide a network of filling stations, which is a tremendous expense (see Appendix). These filling stations will lose money until enough customers buy hydrogen cars. This is totally non-attractive for private enterprise. The numbers required for an initial introduction are staggering, as to provide 1000 service stations (100 cars each), which may be a minimum number for California, would require one to two billion dollars, and would have to be done before the cars are built. And how many people will buy a car only useful for California?

There have been suggestions to produce the hydrogen from gasoline in the car itself. As this is not competitive with a hybrid car, it is hard to see any advantage in doing so. There are also proposals to use solid reagents like metal boron hybrids that react with water to form hydrogen. While this provides a pollution-free and safe car, it has distribution problems, and again the real fuel or solar electricity is a fossil fuel to regenerate the hybrid. Solid high temperature reactions are not only costly, but have a low thermal efficiency. Again the overall thermal efficiency cannot compete with a hybrid or electric car.

For the companies, the research effort on hydrogen cars is government-funded and highly profitable. Whether or not it is sincerely motivated, it deflects attention from serious issues such as the declining average fuel economy of current passenger car fleets as the proportion of SUVs and light trucks increases. The time has come to face the reality and focus on real solutions, such as hybrid cars and more efficient and safer small cars. If we are serious about alternative energy, we have to focus on electric cars, which involve penalties in cost and convenience, but are at present the only achievable alternative.

7. Safety issues in a hydrogen economy

Safety was discussed above, but as it is one of the critical issues that put feasibility of the hydrogen into question, it merits further evaluation. Safety is a relative issue. Gasoline is a reasonably safe fuel widely used, but the FAA does not allow its use in large passenger planes, as the risk of a fire in a crash is much larger than with jet fuel. In World War I tanks used gasoline. Today the army uses almost exclusively diesel or jet fuel, as it is less likely to catch fire in battle.

Propane is a far safer fuel than hydrogen, but it shares with H_2 the property that a leak can explode. Propane storage tanks use a much lower pressure (300 psi) than the proposed storage tanks for hydrogen cars (6–10,000 psi). However, as said before, there are strict storage laws prohibiting the transportation of even a small propane tank through all of the tunnels in New York. Then why allow hydrogen cars? Hydrogen burns with an invisible and very hot flame. In an industrial plant when an operator approaches a hydrogen tank or unit for checking the valves, he swings a two-by-four or a wooden broom in front of himself to check for a flame (see footnote 6). Is the owner of a hydrogen car going to have to keep a broom in his garage to check the car in the morning before he enters it?

To make things worse, hydrogen, unlike methane or propane, heats up when it expands through a nozzle [5,6,7]. This increases the chance of ignition by any source. There is also the storage problem. In explosives we have learned that it is important to minimize the maximum possible damage by limiting the amount one is allowed to store in a plant and enforcing a distance from populated areas proportional to the maximum amount of explosives. This would make it extremely hazardous to place hydrogen storage tanks, for instance, into gas stations or into populated areas, and would not be permitted with present safety practices.

There is also another big risk. A hydrogen car as presently envisioned is a potential suicide bomb that cannot be detected by any of the standard methods that detect explosives. All one needs is to get a suitable valve and a small detonator. All one has to do is fit a hydrogen storage vessel with a proper release valve and a delayed detonator to release and detonate a large cloud of hydrogen. The same is true for the storage tank of a gas station, which is a potential large bomb (at least equivalent to 10 tons of TNT) ready for any terrorist to explode by opening the feeder line for the cars, and waiting to detonate a small bomb in order to detonate the cloud of hydrogen in the air. Should we put such bombs into densely populated areas, or are we going to have armed guards protecting every gas station? Already the fear of terrorism in chemical plants and refineries has started some work on how to modify them or redesign future ones to be less vulnerable. But at least such plants are rarely in densely populated areas.

As the alternative to a hydrogen economy is an electric economy, which is much safer than natural gas, it raises the question why we should want to introduce the most dangerous fuel known to man to be used by untrained people. Even if we were to do so, we would not tolerate it for long. The public outcry after the first major catastrophe would see to that.

The inherent risks in using H_2 cannot all be avoided by developing safety standards or regulations. What one has to do in any design dealing with dangerous materials, or any fuel, is to limit the potential predictable consequences of the most unlikely accident, as it will ultimately happen. We do not allow a ship with a large load of ammonium nitrate to enter a city harbor even though ammonium nitrate is a widely used fertilizer. Nor do we allow a large LNG storage tank or even a large propane storage tank near a populated area. There have been devastating explosions from hydrogen. A refinery does not build a hydrogen cracker near fuel tanks or within 1000 ft of a populated area. Plants for propane or hydrogen are designed to minimize hold up. With explosives there are strict limits to the size of a storage depot and its distance from populated areas and one also divides the depot into several smaller units separated from each other by safety walls. One tries to minimize any hold up in production.

The nuclear industry neglected that principle and tried to rely solely on safety measures by control, which in the long run caused a strongly justified public objection. However, nuclear energy involves a highly needed energy source, which is not true for hydrogen. Unlike hydrogen, nuclear energy had a choice not for completely safe reactors, but to build reactors for which the maximum possible accident is acceptable. One possibility was to build smaller reactors (100–150 MW) which are small enough to be completely contained by a concrete wall, and no meltdown was feasible. This was possible for the first nuclear power stations built (100 and 150 MW) which still operate today and produce electricity cheaper than present reactors. The Gulf atomic solid feed high temperature reactor was also smaller, and could be designed with self-extinguishing features, as well as with compressors. And by placing them in clusters with safety distances from each other into remote sparsely populated areas, one could prevent catastrophic accidents. But such plants were considered more expensive. The nuclear industry wanted cheaper electricity and opted for larger reactors, which were predicted to cost much less. In reality they were slightly more expensive. But in order to justify such large reactors, the concept of safety by control was introduced. After the Rasmussen report [9] stated that one accident (likely to occur only once every 100 years) could kill one million people, a major part of the scientific community turned against nuclear energy, and no new nuclear reactor has been started in the US since then. But nuclear energy was considered an essential alternative and is currently being reconsidered. For the long run, we should consider if proven thermal solar plants in the southwest are not a better and safer alternative. True, they are more expensive compared to the construction cost of a nuclear plant, but the proven cost of existing thermal solar plant (300 MW in California) [2,10] are cheaper than nuclear power plants if full cycle costs of nuclear power plants (including waste fuel purification and storage, plant decommission, insurance costs borne by society, etc.) are considered. Furthermore, experience shows that large-scale construction in the long run reduces the cost of this type of plant by a factor of two. This would still not be competitive with cheap fossil fuels, but would become affordable. But hydrogen would require a doubled investment in solar energy compared to an all-electric economy.

8. Alternative choices to reduce energy imports and global warming

We have to ask what can the hydrogen economy and in the near future hydrogen cars achieve. The main goals are reduction of oil imports, reducing CO_2 emission, and in the long run use of alternative energy. There are, however, other much cheaper ways to achieve the same goals that can be gradually introduced starting immediately. Let us focus on the H_2 car.

I will only consider measures here, which unlike the hydrogen economy reduce both global warming and oil consumption. The US consumes 15 million barrels of crude oil daily, of which nine million barrels are imported, two million from the Middle East. The main products are gasoline (8.8 barrels a day) distillates 3.8 million, and petrochemicals (approximately 1 million barrels a day).[7] Vehicle of change, Hydrogen fuel cell cars could be the catalyst for a cleaner tomorrow, Scientific American, October 2002.[8,9] There are cheaper ways to cut about 4–5 million barrels of oil from imports, simultaneously reducing global emissions. It has been reported in a recent National Research Council study [11] that corporate average fuel economy standards could be cost-effectively increased by as much as 12–27% for automobiles and 25–42% for vehicles built on light-duty truck frames, such as SUVs and vans. It would also require that light-duty trucks and cars would be put into one CAFE category to prevent shift from cars to SUVs and vans. Only conventional technology was used in this study and the cost of the additional tech-

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nology was more than repaid by the future fuel savings. This could reduce gasoline consumption by at least 20–30% or 2 million barrels a day and reduce greenhouse gas emissions proportionately. Even greater fuel savings are possible if additional technology is utilized such as hybrid vehicles, which are much more efficient than hydrogen cars. Although the cost would not be entirely recaptured in the future fuel savings, the costs would be significantly less than using hydrogen cars. Large-scale introduction of hybrid cars and increasing efficiency requirements for SUVs could reduce gasoline consumption by at least 20–30% or 2 million barrels a day in the relatively near future and would reduce greenhouse emissions by the same amount.

Another reduction of both import requirements and CO_2 emissions could be achieved by modifying the refining process. First one could increase the hydrogen content of the products. Gasoline and distillates contain a mixture of paraffins (14.3% hydrogen), naphthenes and aromatics (7.0 to 11.0% hydrogen). Paraffins are environmentally superior to aromatics and naphthenes, as they have significantly lower emissions, and generate less CO_2 per BTU. Present gasoline and distillation contain about 30% aromatics. There are ways to convert aromatics at least partially to paraffins, supplying the increased hydrogen content from hydrogen made from natural gas, coal or residual oil. For diesel oil one can hydrogenate them. This is equivalent to the generation of 0.5 million barrels of high-grade liquid fuels from hydrogen.

There is another aspect of refinery, which allows conversion of hydrogen to high-grade liquid products. Present crudes contain about 30% low boiling fractions (vacuum resid), which in most cases is either used as heavy fuel oil or sent to a coker. Coking produces, in addition to coke, about 50% low quality liquid products. We have the technology today to hydrocrack these 4.5 million barrels of resid per day, and upgrade them to high-grade liquid products. Again by a simple mass balance this would be equal to creating about 2.5 million barrels a day of high-grade liquid gasoline and diesel using hydrogen instead of coke. But this is achieved by reacting with hydrogen, which stays in the product. The amount of hydrogen that can be added during the whole refinery process is equivalent to 600,000 barrels of oil. The total potential savings in oil imports are about 5 million barrels a day, of which 2 million are due to lower gasoline consumption, and 2 million due to larger yields of gasoline and diesel from the barrel, and one million barrels due to utilizing hydrogen generated from other fossil fuels into the gasoline. Unlike H_2 generated in gas stations, this hydrogen is generated in central facilities where the CO_2 can be sequestered. Even if only 60% of this potential is realized, it is equal to exchanging 35% of all present cars to hydrogen cars. It is feasible to achieve this in 20 years. There is no way to do that with hydrogen cars. We could look at this method as an improved form of a hydrogen economy.

There is available proven technology for hydrogen production from resid, natural gas, and coal, as well as for hydrocracking of resid. We also have the technology to increase alkylate production (the environmentally best gasoline) from various oil fractions, as well as to make high quality paraffinic diesel. Aggressive research is needed to find better and cheaper catalytic pathways to do so. We also

Table 6
Amount of CO_2 available for underground disposal

Source of the CO_2	Million tons/year of natural gas
Purification of natural gas	33
Ammonia production	15
Hydrogen production	45
Other petrochemicals	5
Total	98

need good studies as to the cost and potential of all these options, and all of these options are by a magnitude cheaper than hydrogen. We need no study to prove that, just experience, technical common sense and thermodynamics. Still all these measures will require large investments, and will not happen by themselves.

Ultimately the only real way to reduce global warming, to reduce pollution and achieve energy independence is by developing alternative sources for electricity, especially solar energy. This would also require introducing electric cars, and was discussed in Section 7. All these options require starting their implementation long before they are needed. We have the technology to do them all now, and no research will really lead to any significant change, unless it is followed by implementation. Large-scale implementation itself will reduce costs significantly. It is time that those concerned about achieving these goals learn from our experience with clean coal. In the 1970s, there was a large drive to reduce emissions from coal power plants. The technology to do so was available in the form of scrubbers. It would have cost 20 to 30 billion dollars. Power companies strongly objected, as they had no assurance that they would be allowed to profitably recover the cost, and no research could change that simple fact. The US spent the same 20 billion dollars in research with no real result [12]. If instead it had found a way to implement scrubbers, competition would have reduced the cost and improved the technology. All of us would breathe healthier air and enjoy cleaner skies today. The same applies to all measures to reduce global warming or achieve energy independence. We will never sequester CO_2 unless it becomes profitable for those doing so. The US already captures 100 million tons of CO_2 a year (Table 6), and releases the CO_2 again, but it would be unfair to demand that those who do so pay for the cost of sequestering CO_2 when nobody else is required to do so.

The same applies to all the measures introduced here. As long as gasoline is cheap there is little incentive to pay more for a hybrid car to save gasoline. All the measures cited here are not competitive with cheap oil or gas and when the price finally increases enough it might be too late to do anything except at enormous cost and with massive disruption. As we have the technology to start all these measures, there is no technical barrier to doing so. If the US is ready to find ways to remove political barriers and create conditions that make realistic solutions profitable, private enterprise and competition will do the rest.

9. Summary

In the preceding, I tried to present a technical and economic analysis of the proposed hydrogen economy by comparing it to an available alternative, which is an electric economy. The disadvantage of hydrogen is inherent in its nature and evident from its properties, the basic laws of physics, as well as our cumulative experience. No research can reverse this obvious fact. The advantages for electricity are:

1. Ease of switching: Electricity from alternative sources, especially solar energy, can be slowly phased in, as we have an electric infrastructure in the whole USA. This allows a gradual transition. We have no infrastructure for hydrogen, which makes the switch practically impossible.
2. Better thermal efficiency: For almost all applications, use of electricity is far more efficient than hydrogen. Generation of H_2 involves a large energy loss. The most important alternative energy sources, solar and nuclear, generate electricity as the primary product. To generate hydrogen from electricity, it will be necessary to generate twice the amount of electricity and cost at least twice as much as using the electricity directly. This alone clearly shows that a hydrogen economy makes no sense.
3. Better safety: Electricity is inherently safer and can be immediately shut off. Hydrogen is inherently the most dangerous fuel known to man, and one just has to read safety instructions for pressurized H_2 to realize how unrealistic would be the widespread use of H_2, by totally untrained people.
4. Less environmental impact: As both hydrogen and electricity are not an energy resource, but only energy carriers, the impact on pollution and especially global warming depends for both on the fuel or energy source and the thermal efficiency. The thermal efficiency is lower for almost all uses of hydrogen; therefore it will cause more global warming.
5. Available technology: It should be realized that we have the technology for an affordable, all-electric economy based on thermal solar plants with built in storage or less desirable nuclear energy. It is true that no solar energy can compete with cheap fossil fuels or with natural gas at today's prices. Thus we have to make sacrifices if we really want to preserve our environment. But an alternative, renewable and non-polluting energy source is required for either option. Both the electric and the hydrogen economy also require providing an increased distribution capability, an increased grid for electricity and pipelines and home distribution for hydrogen. We have no experience with what large-scale hydrogen distribution would involve. We have many decades of experience with electricity.

The decisive advantage for electricity is that we can start at once. What we should also do is to encourage research on improving the known methods to reduce energy consumption and global warming. But research will not help unless it is tied to actual implementation. As those measures are not attractive with present prices, we have to find a way to subsidize them to stimulate real competition. Tax breaks, indirect subsidies, or a carbon tax, or taxes on gasoline to promote more efficient use could achieve this. We presently subsidize the small users of electricity indirectly without any direct taxes. Experience shows that direct subsidies cause objection when they become big (see Ref. [2] and the current discussion on increasing the subsidy to alcohol for cars). We will never have better electric cars or batteries unless we create a market for 100,000 cars a year by indirect subsidies or high gasoline prices. Nor will we ever have solar energy unless we create a market for few large solar power plants with free competition, letting the engineering companies and the market choose the technology.

Market forces work even if the conditions for the market are structured by public policies (such as by import duties). One has only to be careful to do this for technologies which are desirable and for which we have a real need, eliminating support for technologies that have no realistic justification, but only a strong lobbying power and superficial public appeal. Fuel cells receive public subsidy for an expensive, energy-inefficient technology in an almost certainly futile attempt to find a utopian way to reduce dependency on fossil fuels.

Appendix. Estimating the cost of a hydrogen filling station for cars

To introduce H_2 cars, one has to ultimately provide filling stations all over the country. Otherwise one can introduce them only to very small, local fleets, as has been done in limited cases, and which would have no large-scale impact.

So let us consider, hypothetically, that a typical gas station will initially provide H_2 for a fleet of 500 cars. As proposed, fuel tanks for H_2 cars have a 5 ft^3 volume of hydrogen compressed to 6000 psi, which is equivalent to 5 gallons of gasoline. The station on average has to supply the equivalent of 500 gallons of gasoline a day, which requires 1 million standard ft^3 of hydrogen/day. But this is only the average capacity. There are strong seasonal swings (nationwide) by almost a factor of 1.5 and also swings on different days of the week and for holidays, such as Thanksgiving, Fourth of July, etc. For gasoline, which is storable, this is no problem. A hydrogen filling station has to be able to provide this without long-term storage, doubling the required total capacity. Furthermore, if we do not want to store a full day's production, we have to produce this amount in 14 h, which increases the capacity required by another factor of 1.5, as most stations are closed overnight.

As peak hours have high traffic, this station has to be able to serve about 20 cars in a rush hour compared to an average of seven (100 divided by 14 h) or 14 on a peak day. We can provide this either by short-term storage or higher production capacity, and it is actually cheaper to increase capacity to a certain level than storage, which is also preferable as storage involves tremendous risk. Storage for 1 day requires storing 120 MMBTU H_2 equivalent to 10 tons of TNT. A storage tank for 20 cars would give the equivalent of 10 tons of TNT, already very high for a residential area, and under standard safety regulations for H_2 could not be built in any populated area. One can definitely not put such a station into an existing gas station. We need a small buffer storage for filling the cars even if we had a very large H_2 plant to make it.

In the following, I will give one approximate cost estimate for a station, using these assumptions, neglecting plot and other station cost, and estimate the cost of one gallon produced.

First, let us consider the size of the electrolysis plant needed. To fill 20 cars in 1 h, we need to produce the 100-gallon equivalent, based on the total average production of 21 gallons/h (500 divided by 24). The capacity is 4.8 times higher, but it is still cheaper and safer compared to a large storage tank. The reason for this is that if the car fuel tank is at 6000 psi, one cannot depressurize the storage tank below 6500 psi to avoid recompression and at best we could use a storage tank of 8000 psi. Thus, our available capacity is only 1500 psi out of 8000, which is about 20%. We thus need a storage tank of 400 ft^3 (1 ft^3 at 6000 psi of H_2 is equivalent to a gallon of gasoline). This is equivalent to about 40 tons of TNT, because the hold-up in the tank is four times the storage capacity. This amount of explosive force is prohibitive for any populated area.

We will estimate both production and storage cost based on one-gallon average per day, which is equal to 400 hydrogen cubic feet average using the factor of 4.8 to compensate for all the problems mentioned above. For a methane reforming plant, the investment cost is optimistically in a small plant \$2.00/SCF/day or \$4000. For a small electrolysis plant this is probably less expensive, optimistically \$2000. Let's look at the storage. Storage for a gallon per day would involve 4 ft^3/gallon and as we double that for high demand days it requires 8 ft^3 per gallon at a cost of 8000 to 16,000 dollars.

Capital and operating cost are in dollars (Table A1), based on one averaged gallon per day, assuming that the station serves 100 cars at 5 equivalent gallons each. One hour requires storing +100 gallons serving at rush hour 20 cars per hour

Table A1
Capital and operating cost for filling station (all data are in \$/gallon)

Capital cost	Electrolysis	Steam reforming
Hydrogen production	2000	4000
Storage 1 h[a]	8000	8000
Station compressors, etc.	1000	1000
Total	11,000	13,000
Price per gallon		
Capital related cost, 20% of investment (interest, capital recovery, taxes, maintenance, insurance)	5.1	7.2
Feed electricity at 10 cents/kWh	6.0	0.6[b]
Natural gas at \$5 a MMBTU	0.0	0.8
Total	11.1	8.6
Total (after a +25% markup for station)	13.9	10.8

[a] At 8000 psi. 4 cubic feet (in 400 ft^3 vessel). Includes valving.

[b] For compressors.

instead of 4.16 cars, which is the average load assumed in many other studies. As there is no large storage, the filling station has to take care of seasonal changes, weekends, holydays and rush hours, as well as the fact that the station is closed overnight.

While we need 60 kWh of electricity to produce one-gallon equivalent of hydrogen (theoretically 36 kWh) at 8000 psi, a gallon of gasoline (at 45% efficiency for the fuel cell) is equal to 16.2 kWh. Assuming an efficiency of the battery of 80% we need 20 kWh costing $2 per gallon equivalent instead of $16 (a factor of eight). If we use more optimistic assumption for the fuel cell in the electrolysis, hydrogen will still be five times more expensive to deliver to the cars compared to electricity. Personally, I think that even the factor eight is very optimistic. Furthermore, the station violates all safety regulations for hydrogen and no sensible zoning board would permit it, if made aware of the facts.

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