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Discussion

Fallacies of a Hydrogen Economy: A Critical Analysis of Hydrogen Production and Utilization

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This article presents a critical analysis of all the major pathways to produce hydrogen and to utilize it as an energy carrier to generate heat or electricity. The approach taken is to make a cradle to grave analysis including the production of hydrogen, the conversion of hydrogen to heat or electricity, and finally the utilization of that heat or electricity for a useful purpose. This methodology shows that no currently available hydrogen pathway, irrespective of whether it uses fossil fuels, nuclear fuels, or renewable technology as the primary energy source to generate electricity or heat is as efficient as using the electric power or heat from any of these sources directly. Furthermore, electric vehicles using batteries to store electricity are shown to be more efficient and less polluting than fuel cell powered vehicles using energy stored in hydrogen. [DOI: 10.1115/1.1804193]

1 Introduction

Energy is a mainstay of an industrial society. It is, therefore, not surprising that many prestigious organizations have attempted to analyze the future need for energy and the availability of various energy sources. What is surprising is that despite the repeated efforts of both governmental and private organizations over the past fifty years, no consistent energy policy has emerged from these studies. Until a few years ago, all of the energy studies examined the present and future availability of fossil, nuclear, and renewable energy sources. However, during the past few years a ''new'' paradigm emerged almost abruptly, proposing that hydrogen and the fuel cell are the ultimate means for generating electricity, and the best choice to supply transportation-energy needs. This paradigm shift was given official sanction for the transportation sector when United States President George W. Bush unveiled the administration's hydrogen initiative in his 2003 State of the Union Address with the following statement: ''Tonight I am proposing 1.2 billion in research funding so that America can lead the world in developing clean hydrogen powered automobiles'' [1]. The use of hydrogen to provide electricity and other needs had been endorsed earlier by the U.S. Department of Energy in documents such as, ''National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond'' [2] and ''National Hydrogen Energy Roadmap'' [3].

According to the Committee on Alternatives and Strategies for Future Hydrogen Production and Use, appointed in 2002 by the National Academies National Research Council, ''the vision of a hydrogen economy is based on two expectations: 1) that hydrogen can be produced from domestic energy sources in a manner that is both affordable and environmentally benign; and, 2) that applications using hydrogen . . . can gain market share in competition with the alternatives'' [4]. The purpose of this study is to ascertain whether or not technologies that are currently available or close to commercialization can fulfill these expectations and justify proposing hydrogen as the future fuel for our nation's economy.

Since this is not the first time that engineers have analyzed the future supply of energy, it is useful to examine some of the past efforts, in particular, two significant studies that were conducted independently about 25 years ago. In 1979, the National Academy of Science released the final report of its Committee on Nuclear and Alternative Energy Systems in a book entitled, *Energy in Transition 1985 to 2010* [5]. Participants in this study included some of the most prestigious energy experts in the country under the co-chairmanship of Harvey Brooks and Edward Ginzton. The study concluded that there are several plausible options for an indefinitely sustainable energy supply, but also noted that, ''Energy policy involves very large social and political components . . . of conflicting values and political interests that cannot be resolved except in the political arena.''

A similar study was conducted by Resources for the Future, Inc. and its results were also published in 1979 as *Energy in America's Future* [6]. The study concluded that, ''There are many reasons why US energy policy remains in dispute,'' and identified as a principle reason for this dispute that: ''There is disagreement—and even widespread ignorance—about some fundamental facts.'' Although there are some significant differences between these two important studies, they have one common factor: Neither of them mentions the concept of a hydrogen economy and the word hydrogen does not appear in either of their indexes.

It is not possible to present details about these two historically important studies. However, some of the conclusions and recommendations are as valid now, as they were twenty-five years ago. Some of the recommendations of the Committee on Nuclear and Alternative Energy Systems of the National Academy were:

- ''Conservation deserves the highest immediate priority in energy planning.''
- ''The most important intermediate-term measure is developing synthetic fuels from coal''
- ''Perhaps equally important is the use of coal and nuclear power to produce electricity . . . .''

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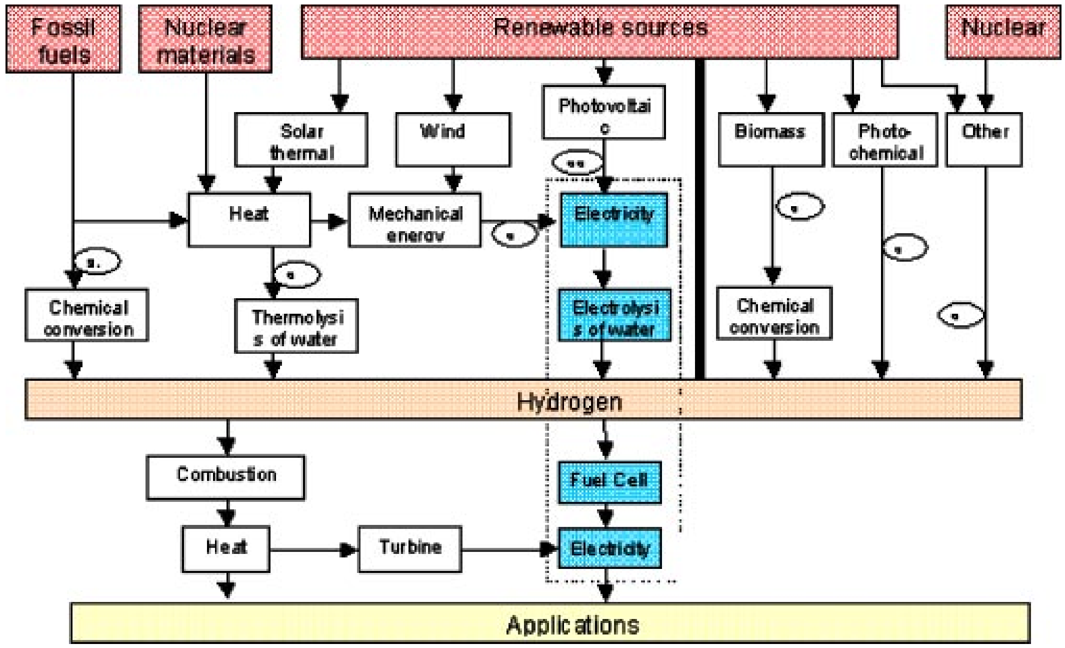

Fig. 1 Pathways for hydrogen production and utilization. Number in oval denotes text section where pathway is discussed.

Some caveats were, however, attached to the last recommendation:

- "The safety of nuclear reactors is a controversial topic."
- "The possibility that terrorists . . . might divert nuclear material is a matter of concern."
- "Policies for disposal or radioactive waste have not been developed."

For the direct use of solar energy, the committee noted that, "Heating buildings and domestic water and providing industrial and agricultural process heat and low pressure steam are by far the simplest and most economical applications of solar energy . . . This group of technologies is the most suitable for deployment in the intermediate term . . . ."

The above recommendations could be implemented immediately without the use of hydrogen. The fact that hydrogen is not a primary fuel source and should not be included in an inventory of energy resources was clearly recognized 25 years ago. This makes it all the more difficult to understand why and how a mere 25 years later the idea of a hydrogen economy came to be perceived as a cornerstone of our future national energy policy.

On two points, these previous energy assessments are in agreement: fossil and nuclear energy resources are finite and the cost of energy will continue to increase. Consequently, there is, at least in principle, agreement that energy should be used and distributed with the highest possible efficiency and wasteful energy conversion technologies should be avoided. Furthermore, there is wide agreement that, in order to arrive at technically viable conclusions, the efficiency of energy conversion should be based upon a complete "cradle-to-grave" analysis that includes each step in the energy production and utilization chain, rather than the efficiency of any single step in the overall chain. A similar approach for ground transportation systems that takes into account all the steps necessary to make the hydrogen from a primary energy source, get it into the vehicle fuel tank and then power the wheels is called a "well-to-wheel" analysis.

The concept of a hydrogen economy was proposed back in the 1870s as a fanciful speculation of Jules Verne's in his novel *The Mysterious Island* [7]. Hydrogen production was examined extensively in the 1970s by experts for the Institute of Nuclear Energy in Vienna and the Electric Power Research Institute [8,9]. The basic idea was to generate hydrogen by high temperature nuclear reactions and then use the hydrogen to generate electricity, thereby replacing fossil fuels. The results of this study showed, however, that generating hydrogen with high-temperature thermal methods was inferior in cost and efficiency to generating electricity from nuclear reactors and then producing hydrogen by electrolysis [9]. But the study also showed that using the electricity from the nuclear plants directly was preferable in cost and efficiency to the hydrogen path to generate electricity with a fuel cell. Despite the conclusion reached from this extensive study, the idea of a hydrogen economy has been revived in the past decade, based upon assumptions that need to be examined objectively.

2 Overview of Hydrogen Production and Utilization

Hydrogen is abundant on Earth, but only in chemically bound form. In order to use hydrogen as a fuel, it is necessary that it be available in unbound form. As a consequence of chemical reaction energies involved, a substantial energy input is needed to obtain unbound hydrogen. This energy input exceeds the energy released by the same hydrogen when used as a fuel. For example, to split water into hydrogen and oxygen according to the reaction

$$H_2O \rightarrow H_2 + \tfrac{1}{2}O_2$$

120 MJ/kg-hydrogen are needed (all gases at 25°C); while the reverse reaction of combining hydrogen and oxygen to give water (all gases at 25°C), ideally yields 120 MJ/kg-hydrogen. But, because no real process can be 100% efficient, more than 120 MJ/kg must be added to the first reaction, while less than 120 MJ/kg of useful energy can be recovered from the recombination. To evaluate the losses, it is, therefore, necessary to examine the energetics of hydrogen production processes quantitatively.

Figure 1 shows all the major pathways to produce hydrogen and to utilize it as an energy carrier. The top row shows the primary energy sources: fossil fuels, nuclear materials, and renewable sources. The next three rows show the major processing steps for conversion of the primary energy into hydrogen. Below the hydrogen row are the two methods of using hydrogen in energy

Table 1 Efficiency of delivering fuel, starting with natural gas (NG) in the well [11,12][1]

	Natural gas production efficiency (%)	Conversion to hydrogen efficiency (%)	Storage and distribution efficiency (%)	Additional compression or liquefication efficiency (%)	Overall efficiency (%)
Natural gas (NG) for:					
Heat (low pressure)	95	n/a	97	96	88
Vehicle (high pressure storage as gas)	95	n/a	97	89	82
Hydrogen (H_2) for:					
Heat (low pressure)	95	78.5	97	95	69
Vehicle (high pressure storage as gas)	95	78.5	97	86	62
Vehicle (storage as liquid)	95	78.5	97	79	57

[1]Efficiency numbers differ somewhat between the two articles cited. This is because 42% (representing a grid-wide average) was used for electricity generation efficiency in the 2002 article, while 55% (representing a natural gas combined cycle) was used in the 2003 article. A value of 55% has been used throughout the present article.

applications: one is to combust the hydrogen to produce heat for various applications, and the other is to generate electricity from the hydrogen by means of a fuel cell.

Fossil fuels, nuclear energy, solar thermal (including OTEC), biomass, wind, and photovoltaics can all be used to generate electricity. All of these, except photovoltaics and wind, generate electricity by first producing heat, which is then converted to mechanical energy, which, in turn, is finally converted to electricity. Photovoltaic cells generate electricity directly from solar radiation, while wind turbines directly generate mechanical energy and then electricity. In principle, some of the heat producing technologies can also make hydrogen by thermolysis of water, i.e., heating of water to a sufficiently high temperature (greater than 3000 K) to break it into hydrogen and oxygen.

Processes to the right of the heavy vertical line in Fig. 1 can produce hydrogen from renewable or nuclear sources without using either electrolysis or thermolysis of water [10]. For example, biomass may be chemically converted to hydrogen by processes similar to those used with fossil fuels, or it may also be converted to hydrogen by biological conversion processes. Photochemical and photoelectrochemical reactions can produce hydrogen directly with solar radiation input. Thermochemical and hybrid thermochemical/electrochemical cycles use nuclear or solar thermal heat and electricity to drive chemical cycles that produce hydrogen from water. However, a detailed evaluation of the potential of the technologies to the right of the heavy line in Fig. 1 is not the objective of this article, because none of them is anywhere close to commercialization, and they should be considered largely as topics for future R&D, not as viable technologies for a national energy policy [4,10].

3 Efficiency of Hydrogen Production and Utilization Pathways

Each of the pathways for production and use of hydrogen will now be considered. Those to the left of the heavy vertical line in Fig. 1 will be quantitatively analyzed, while those to the right, which are in a state of research, will be described and discussed. Lower heating values are used for all substances throughout this paper.[1]2

3.1 Hydrogen Produced From Fossil Fuels via Chemical Reactions. Chemical conversions of fossil fuels to hydrogen, from natural gas and petroleum fractions in particular, are well-established, commercial technologies. The use of coal as a raw material for hydrogen production has been studied extensively, but it is not widely practiced in the U.S.

3.1.1 Hydrogen to Heat via Combustion. Table 1 shows the efficiency of supplying natural gas or hydrogen made from natural gas for combustion applications. For low-pressure uses, such as generating electricity and home heating, the efficiency of delivering hydrogen is only about 69%, whereas it is 88% for of natural gas. With a typical combustion efficiency of 85% [13], the efficiency of utilization of hydrogen is about 59%, compared to 76% for natural gas. Thus the efficiency of combusting hydrogen is about 29% lower than that for supplying the natural gas for the same purpose. This is due to the fact that the energy efficiency of converting natural gas to hydrogen and then storing, transmitting, and distributing it is low. For heat generation hydrogen could be combusted at an efficiency of 85% yielding an overall cradle to grave efficiency of 57% compared to natural gas combustion at 75%. Thus, to use hydrogen in this way would require 32% more natural gas and produce 32% more carbon dioxide pollution than burning the natural gas directly.

To supply compressed hydrogen as a fuel in conventional spark-injection engines, at 62% efficiency, requires about 32% more natural gas as it does to supply the natural gas directly as engine fuel, at 82% efficiency. To supply liquid hydrogen, at 57% efficiency, would require 44% more natural gas, and produce that much more carbon dioxide, as it would to supply the natural gas to spark-injection engines. This is because, even though hydrogen and natural gas burn with essentially the same efficiency in the engine [12], the compression or liquefaction of hydrogen for storage on a vehicle requires substantially more energy. Results for fossil fuels other than natural gas as hydrogen sources are even less favorable to hydrogen, because petroleum and coal are more difficult to convert to hydrogen than is natural gas.

It can be concluded that *to make hydrogen from fossil fuels and then to burn the hydrogen for generating heat or fueling internal combustion engines is less efficient than using the fossil fuel directly*.

3.1.2 Hydrogen to Electricity. Table 2 shows the efficiency of producing electricity from natural gas via hydrogen. If electricity generated with hydrogen made from natural gas is used in a fuel cell to produce electricity, the overall well-to-grid efficiency of 35% is less as the well-to-grid efficiency of 38%, obtained by burning the hydrogen to produce electricity in a gas-turbine combined cycle. Either way, generating power for the grid with hydrogen is less efficient than burning the natural gas directly, for which a well-to-grid power generation efficiency of 48% can be achieved with present technology. Results for other fossil fuels are

[1]Lower heating value (LHV) is the energy released when the water produced by combustion is not condensed. It was chosen because there are no significant applications in which the water is condensed and the corresponding energy is usefully recovered.

Table 2 Efficiency of Delivering Electricity to Grid, Starting with Natural Gas (NG) in the Well [11,12][1]

	Hydrogen or NG Supply Efficiency, %	Conversion to Electricity Efficiency, %	Overall Well to Grid Efficiency, %
Electricity to grid via:			
NG (combined cycle)	88	55	48
H_2 (low pressure gas/combined cycle)	69	55	38
H_2 (low pressure gas/fuel cell)	69	50	35
H_2 (liquid/fuel cell)	57	50	29
Electricity to vehicle motor via:			
H_2 (high pressure gas/fuel cell)	62	50	31
H_2 (liquid/fuel cell)	57	50	29

[1]Efficiency values differ somewhat between the two articles cited. This is because 42% (representing a grid-wide average) was used for electricity generation efficiency in the 2002 article, while 55% (representing a natural gas combined cycle) was used in the 2003 article. A value of 55% has been used throughout the present article.

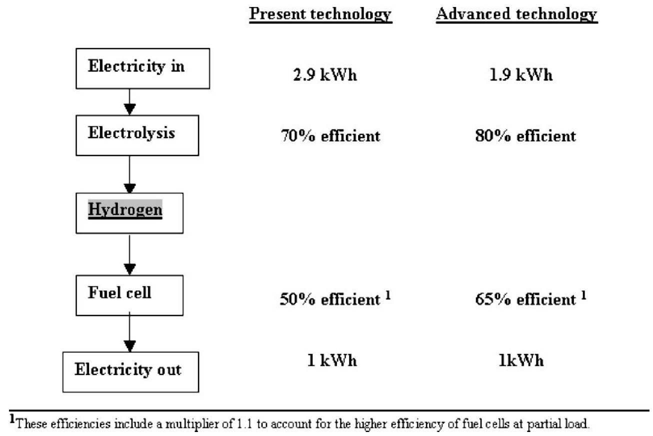

Fig. 2 Efficiency of steps in the pathway of producing electricity with a fuel cell fed by hydrogen produced by electrolysis of water powered by electricity from a primary source [2,16–18]

similar. It can be seen, therefore, that the use of hydrogen generated from fossil fuels to produce electricity uses more fossil fuel and generates more carbon dioxide than generating electricity from fossil fuel directly. It may be concluded that *the use of hydrogen made from fossil fuel to generate electricity for the grid is wasteful and increases carbon dioxide emissions*.

The use of hydrogen fuel cells in vehicles is considered in detail in Sec. 4.

3.2 Hydrogen Produced From Fossil, Nuclear, and Renewable Sources via Thermolysis. Thermolysis is splitting of water into hydrogen and oxygen by heating it. The heat can come from fossil, nuclear, or renewable sources. The production of hydrogen by thermolysis has been explored in detail [14,15]. It was found that, because water is a very stable substance, only at temperatures higher than 3000°C (5400°F) does the equilibrium reaction significantly favor its decomposition into hydrogen and oxygen. Although a catalyst might increase the rate of reaction, it cannot change the reaction equilibrium. Hence, an extremely high temperature is required, because the equilibrium versus temperature relationship is fixed by the chemical reaction. In principle, the reaction can be driven at somewhat lower temperatures by separating the hydrogen and oxygen from the water as they are formed. But unless the hydrogen and oxygen are separated from each other at the reaction temperature, they will react back to water as the mixture is cooled. Separations at such high temperatures are not technically feasible because it is virtually impossible to find suitable materials to be employed in the necessary hardware.

Therefore, it can be concluded that *thermolysis of water is technically not a practical way to produce hydrogen, no matter what source of heat is used*.

3.3 Hydrogen Produced From Fossil, Nuclear, and Renewable Sources via Electrolysis. In Fig. 1, the dashed box isolates that portion of the pathways in which electricity is used to produce hydrogen via electrolysis and the hydrogen subsequently is used to produce electricity via a fuel cell. These steps are common to all energy sources that produce hydrogen by electrolysis, including fossil fuels, nuclear materials, and renewables. These pathways can be evaluated by examining the electrolysis and hydrogen utilization steps.

3.3.1 Hydrogen to Heat via Combustion. Hydrogen produced by electrolysis could be used to produce heat by combustion. However, the efficiency of producing hydrogen from electricity by means of electrolysis is only about 70% [16], and burning the hydrogen at an efficiency of 85% [13] yields heat with an overall efficiency of about 60%, while electricity can be converted to heat at essentially 100% efficiency. Thus it is concluded that *to use hydrogen made by electrolysis to produce heat is inefficient and wasteful*.

3.3.2 Hydrogen to Electricity via Fuel Cell. The use of electricity to generate hydrogen, and the use of this hydrogen to then generate electricity again via a fuel cell is illustrated in Fig. 2. This process is very inefficient because a sequence of steps is involved. Figure 2 shows the estimated present and, highly optimistic, future efficiencies of the electrolysis and fuel cell steps. It would take 2.9 kW h of electricity input to produce 1 kW h of electricity output with present technologies, while even with optimistic advanced efficiencies, 1.9 kW h of input are required to yield 1 kW h of output. The difference between input and output electricity would be wasted. Thus, the output electricity would cost from 1.9 to 2.9 times the cost of the input electricity. Moreover, this cost ratio considers only the cost of the input electricity, and does not include the capital cost and non-electrical operating costs of the electrolysis, fuel cell, and hydrogen storage equipment. Also, it does not include the cost or energy necessary for compression or liquefaction of hydrogen for storage. Since these results do not depend on the source of the original electricity or upon the use of the electricity, the results also apply to using electricity to power a fuel-cell vehicle.

There may be niche applications where weight is a more important factor than cost, such as for space vehicles, or where incremental electricity available from stored hydrogen may be so valuable, such as at times of peak electricity demand, that the extra cost could be acceptable. However, such niche applications do not suggest a major role for hydrogen in a national energy policy.

This analysis shows that any path, no matter what the source of the original electricity, which uses electricity to produce hydrogen and a fuel cell to use this hydrogen to again generate electricity, has low energy efficiency and adverse economic impact. This means that a large portion of the original resource is being wasted, both in an energetic and an economic sense. Furthermore, because of the insufficiency of the process, pollution will increase.

It is concluded that *any pathway that includes the conversion of electricity to hydrogen by electrolysis, and then conversion of the hydrogen to electricity via a fuel cell is inefficient and not a desirable basis for an economically and environmentally sound energy policy*.

3.3.3 Hydrogen to Electricity via Combined Cycle Power Plant. The efficiency of converting hydrogen to electricity via a gas turbine combined-cycle is about 55%. Though this is more efficient than present fuel cell systems, it is lower than the optimistic value for fuel cells. It is not expected that the combined-cycle efficiency will increase to the level of the optimistic fuel cell value. Since it has already been demonstrated that even the optimistic fuel cells are an inefficient way of using hydrogen produced by electrolysis, the use of hydrogen in a combined cycle power plant, that is even less efficient, is clearly not desirable. Therefore, it is concluded *that the conversion of electricity to hydrogen and using the hydrogen to generate electricity via a combined cycle power plant is inefficient and is not a desirable process for an energy policy*.

Summary of Secs. 3.1–3.3. Based on the analyses in Secs. 3.1–3.3, we conclude that *all of the hydrogen production pathways to the left of the heavy vertical line in Fig. 1 should be eliminated from a national energy policy that aims to provide energy efficiently and economically.*

3.4 Hydrogen Produced From Renewable or Nuclear Sources that do not Utilize Thermolysis or Electrolysis. According to a recent study by the National Academies of Science [4], the pathways to hydrogen production on the right of the heavy, solid vertical line in Fig. 1 are still research challenges that have not reached a point where they can be considered for a viable national energy policy.

The biomass pathway is actually several pathways by which biomass can be converted into hydrogen. These include: gasification of biomass, anaerobic digestion, and algal photolysis. The gasification pathway is the most developed, but has not yet reached the commercial stage.

The photochemical pathway includes decomposition of water by sunlight (photolysis) using semiconductor ''sensitizer'' particles, and a combination of electrolysis and photolysis (photoelectrochemical or PEC processes) in which semiconductor electrodes utilize an externally applied electrical potential to supplement the solar radiation input to drive the reaction. Since much of the energy is supplied by solar radiation, PEC systems potentially are more efficient with respect to electricity use than electrolysis alone.

None of these renewably based processes has been developed to commercial status as yet, and the presently available information is not sufficient to reach conclusions as to their costs and efficiencies. A review of the DOE Renewable Energy Programs, published in 2000 [10], recognized that these renewable energy pathways are challenges for longer term research, and recommended that the Department of Energy's Office of Power Technology Hydrogen Research Program attempt to develop ''better methods for producing hydrogen directly from sustainable energy sources without using electricity as an intermediate step.'' These other methods, therefore, are not useful at this time in analyzing the viability of a hydrogen economy by the year 2030, the target date in the 2002 DOE strategy. R & D for these hydrogen production processes should be continued and their potential should be evaluated separately as they approach commercialization.

No conclusions can be reached at this time regarding the efficiency of producing hydrogen from renewable sources by routes without thermolysis or electrolysis. But unless commercial and engineering feasibility can be demonstrated, they cannot be considered as candidates for a national hydrogen economy.

The ''Other'' pathway includes thermochemical cycles and hybrid electrochemical/thermochemical cycles, as well as processes that may some day be invented. The thermochemical and hybrid cycles can be driven by nuclear or solar thermal heat. The goal of these thermochemical cycles is to circumvent the need for the extremely high temperatures required to split water directly, by carrying out the splitting in several intermediate steps that ultimately result in the same net reaction.

In 1981 Shinnar et al. [9] studied ten thermochemical and hybrid processes with a nuclear reactor as the heat and electricity source. Those processes, along with some of the key chemicals involved, are: Mark 9 (iron, chlorine); Agnes (iron, magnesium, chlorine); Schulten (methane, methanol, sulfuric acid); Whestinghouse hybrid (sulfuric acid); Cesium (hypothetical); Institute of Gas Technology (copper salts); Argonne National Laboratory (ammonia, potassium, mercury); Hitachi ($NaCO_3$, I); Oak Ridge National Laboratory (Cu, Ba, F); and Los Alamos National Laboratory (cecium, chlorine). They used a screening method that tested how candidate processes compared thermodynamically and economically to electrolysis using electricity generated by the nuclear reactor. Their conclusion was that, ''We can sum up our results by saying that none of the cycles proposed thus far has any chance of being economically attractive compared to electrolysis'' [9]. A similar conclusion was reached in 2003 by Penner [19], although he believes that hydrogen production may someday be of interest if nuclear breeder reactors should become the primary energy supply source. A Zn-ZnO cycle [14] driven by concentrated solar energy recently has been proposed, but has not been fully evaluated.

No thermochemical or hybrid thermochemical process for hydrogen production has as yet been shown to be thermodynamically or economically competitive with electric power generation by the same heat source, followed by electrolytic hydrogen production. It is not possible to rule out future success for such a process, but until fully established it cannot be the basis for an energy policy.

4 Hydrogen for Transportation

There is wide agreement that a paradigm shift in transportation fuel will be necessary in the near future [20]. This shift will be both painful and expensive because petroleum is a unique resource, and the magnitude of the global institutions that have grown from the symbioses between oil and the automobile, as well as the customer satisfaction associated with this technology, make a change very difficult. A generation's worth of effort to develop workable alternative fuels has not been successful. As of the year 2000, alternative fuel use in the U.S. amounted to less then 0.4 billion gallons compared to 166 billion gallons of petroleum fuel consumption [21].

A valiant effort was mounted a few years ago in California to introduce electric vehicles through the so-called ZEV mandate [22]. Its target of promise was a battery-powered electric car with zero tail pipe emissions. However, this effort failed in the marketplace largely because of the long time required to charge batteries, the high initial cost of the vehicles, and their limited mileage range. The ZEV mandate has now been rationalized as paving the way for fuel cell vehicles, which are envisioned as the ultimate goal in the latest revision of the California Air Resources Board (CARB) rule [23]. If the EV technology, which was relying on a largely existing energy transmission infrastructure, failed, a new technology that has no existing infrastructure can only overcome the obstacles inherent in introducing an alternative fuel if it is more efficient, less expensive, and environmentally more benign than the alternatives.

To analyze whether or not hydrogen is a suitable technology for transportation is more complicated than to assess whether hydrogen fuel cells are a suitable technology to generate electricity. An analysis of the hydrogen vehicle concept must take into account all the steps necessary to make the hydrogen from a primary fuel source, get it into the fuel tank, and then power the wheels via a prime mover and the drive trains. A comparison between hydrogen vehicles and other technologies that includes all the steps in the process, as shown in Fig. 3, is called ''Well-to-Wheel Analysis.'' The authors have previously made a Well-to-Wheel Analysis of twelve significant technologies (Fig. 4) that could power U.S. ground transportation [11,12]. This analysis was made with natural gas as the primary energy source, because steam reforming of natural gas is the most widely used and most economical process for the production of hydrogen. The well-to-wheel efficiency, η, for this analysis is defined below [12]:

For each fuel production step,

$$\eta_i = \frac{(\text{Energy in the output fuel})_i}{(\text{Energy in the input fuel} + \text{natural gas energy equivalent of net heat and electricity inputs})_i} \times 100$$

and, for each of the onboard vehicle steps,

$$\eta_j = \frac{(\text{Useful electrical or mechanical energy output from a step})_j}{(\text{Fuel, electrical, or mechanical energy input to that step})_j} \times 100$$

The overall efficiency is given by

$$\eta = \left[\prod_i (\eta_i)\right]\left[\prod_j (\eta_j)\right]$$

The results of this analysis are summarized in Table 3. It shows that the highest Well-to-Wheel efficiency can be obtained with hybrid engines, followed closely by fuel cell hydrogen vehicles using steam reforming of natural gas to produce the hydrogen. So far no hydrogen-fuel-cell-hybrid configuration has been demonstrated, but such a vehicle may well be equivalent in efficiency to other hybrid configurations.

A group of five technologies—including conventional diesel engines with Fischer–Tropsch (FT) fuel or FT/natural gas mixture, conventional spark ignition engines (SI) with natural gas, hybrid SI with hydrogen from natural gas, and an EV with batteries and electricity from a natural gas combined-cycle power plant have efficiencies between 19% and 22%—well below the top four. At the bottom of the well-to-wheel efficiency ranking are fuel cells with methanol (reformed on-board to hydrogen), conventional SI with hydrogen from natural gas, and hydrogen fuel cell vehicles using hydrogen produced by electrolysis of water with the electricity obtained from natural gas in a gas-turbine, combined cycle with 55% efficiency. This electrolysis alternative has the lowest overall efficiency of the twelve options examined, and is less than half as efficient as a fuel cell vehicle with hydrogen derived from natural gas via steam reforming.

A key question for a national energy policy is whether there is a better and cleaner alternative than the hydrogen fuel cell to power transportation vehicles by electricity. In a fuel cell vehicle, hydrogen would have to be stored either as a gas under high pressure, or as a cryogenic liquid at very low temperatures, while in an EV the energy is stored in a bank of batteries. For comparison with the fuel-cell-vehicle efficiencies (shown in Fig. 2) the efficiency of present electric vehicles (EV), similar to the Prius, is shown in Fig. 5. The EV converts electricity via battery storage to electricity with an overall efficiency of about 58%, or 1.7 kW h of electricity input per 1 kW h of output. In contrast, the efficiency of an advanced fuel cell vehicle is only 52%, thus requiring 1.9 kW h of electricity input to per 1 kW h of output. Hence, the most optimistic electricity to electricity via hydrogen system utilizes electricity less efficiently than commercially available electric vehicles. Moreover, with advanced batteries already available (24, 25), the efficiency is 83%, or 1.2 kW h or input per kW h of output. These results are independent of the source of the electricity for the battery.

Many environmentalists and proponents of renewable energy refer to hydrogen generated by steam reforming of natural gas and electrolysis with electricity produced from nuclear or fossil fuels as "Dirty Hydrogen" and only accept hydrogen generated by electrolysis from renewable sources as "Clean Hydrogen" [26]. The use of dirty hydrogen is not the goal of the hydrogen economy because it does not solve the main problem, which is reducing the use of fossil fuels in transportation. Only pathways using nuclear or renewable technologies can meet that goal. But many environmentalists and transportation strategists, such as Lovins [27], have proposed to accept hydrogen produced by steam reforming from fossil fuels or electrolysis of water with fossil or nuclear energy as a necessary transition to a final hydrogen economy, one in which the hydrogen is produced by electrolysis with renewable sources. But, unless the electrolysis-hydrogen/fuel cell technology was superior, there is no justification to construct a complex and expensive hydrogen infrastructure for an interim solution with hydrogen produced from nuclear or fossil sources. Since EVs are already more efficient than "clean hydrogen" fuel cell vehicles (FCVs) are ever expected to be, and since the EV infrastructure is in place (albeit in need of updating) there is no justification for pursuing FCV technology.

Based upon the foregoing considerations, we conclude that *there are alternative electric transportation technologies already available that are more efficient than the most highly optimistic projections for hydrogen fuel cell vehicles. Hence, pursuing FCV technology, which requires construction of an entirely new and costly infrastructure for hydrogen, is not justified*.

5 Other Issues for the Hydrogen Economy

5.1 Hydrogen Storage and Transport. One advantage claimed for hydrogen is that its energy is storable, as indeed it is. This is of particular importance in connection with using solar energy and wind, because of the variable nature of these sources. The issue, though, is not whether hydrogen energy can be stored, but whether it can be stored more efficiently and less expensively than other sources of energy, especially electricity. A robust electrical grid that is able to follow demand effectively can be used to achieve a function similar to short-term storage. Namely, it can deliver excess electricity to where it is needed, with transmission efficiencies in the low 90% range. Electric energy can also be stored long-term by hydraulic pumping and recovered as electricity with turbines, at an efficiency of approximately 78%. On a small scale electricity can be stored in batteries, particularly for applications such as road and rail transportation, with efficiencies approaching 85% [24,25]. Heat for solar thermal power plants can be stored in the working fluid at efficiencies approaching 100% [28]. This option is relatively inexpensive and can be timed for storing energy to meet high demand periods, such as air conditioning peaks. In contrast, liquefication of hydrogen requires 32 MJ/kg, resulting in an efficiency of 79% [29,30]. In addition, there would also be a continuous loss of hydrogen from the storage vessel due to heat leak from the surroundings. Storage as a gas requires compressing the hydrogen to about 55 MPa (8000 psi) with a fuel energy input of 19 MJ/kg, at an efficiency of 86% (with electricity produced at 55% efficiency) [12]. Other hydrogen storage options, such as metal hydrides and carbon nanotubes, are under investigation.

Transport of hydrogen presents equally daunting obstacles. Some argue that gaseous hydrogen could be distributed in pipelines currently used for natural gas [27]. The obvious fallacy of this proposal is that all these pipelines are already fully loaded to transport natural gas. Moreover, there are also questions regarding whether or not fittings, gaskets, and other materials in the natural gas pipelines could withstand hydrogen diffusion. Hence, a new pipeline system would be needed for hydrogen. Transporting liquid hydrogen would incur large amounts of heat losses and require insulating the pipelines to hold a cryogenic temperature. Furthermore, a nationwide cryogenically insulated piping system would have to be constructed at enormous financial costs. In comparison with all these obstacles to transporting hydrogen, an electric grid

Table 3 Well-to-wheel efficiency of twelve transportation technologies, each starting with natural gas. For comparison, the Chevrolet Silverado has a well-to-wheel efficiency of 13% with gasoline [11].

Vehicle drive technology	Fuel	Well-to-wheel efficiency[1] (%)
Hybrid SI	Natural gas	32
Hybrid diesel	Natural gas +FT[2]	32
Hybrid diesel	FT[2]	30
Fuel cell+electric motor	Hydrogen[3]	27
Hybrid SI	Hydrogen[3]	22
Conventional diesel	Natural gas +FT[2]	22
Battery+electric motor	Electricity from natural gas combined cycle	21
Conventional SI	Natural gas	19
Conventional diesel	FT[2]	19
Fuel cell+electric motor	Methanol[4]	16
Conventional SI	Hydrogen[3]	14
Fuel cell+electric motor	Hydrogen[5]	13

[1]Well-to-wheel efficiency for using natural gas along the sequence of steps shown in Fig. 3.
[2]Diesel fuel made by Fischer–Tropsch synthesis from natural gas.
[3]Hydrogen made by steam reforming of natural gas.
[4]Methanol made from natural gas, and converted to hydrogen by on-board reactor.
[5]Hydrogen made by electrolysis with electricity from natural gas combined cycle power plant with 55% efficiency.

serving the country is available and operating. It could easily be expanded and made sufficiently reliable to meet future demand.

5.2 Safety and Environmental Impact. There is considerable disagreement over the safety of using hydrogen. On the one hand, hydrogen has been called ''safer than gasoline and other hydrocarbon fuels'' [31], while on the other hand it has been referred to as ''most dangerous'' [9]. Current regulations regarding storage and transportation of hydrogen [32] support the latter view. Certainly hydrogen poses some unique challenges, such as its tendency to permeate readily through many materials. These issues would have to be resolved before hydrogen could be safely used.

A highly touted aspect of hydrogen is that it is clean burning, or ''zero polluting.'' While it is true that there would be negligible emissions of nearly all pollutants at the point of use of the hydrogen (except for NO_x, which likely be higher if the hydrogen is burned, because of the high temperature of hydrogen combustion),

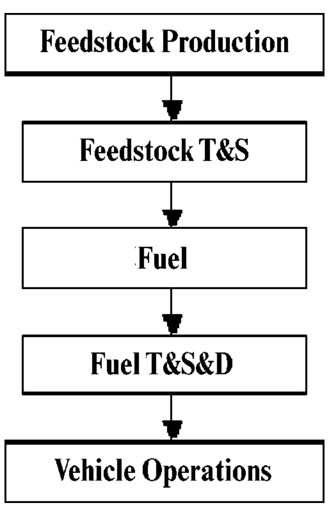

Fig. 3 Steps in a well-to-wheel analysis for a ground transportation vehicle [12]

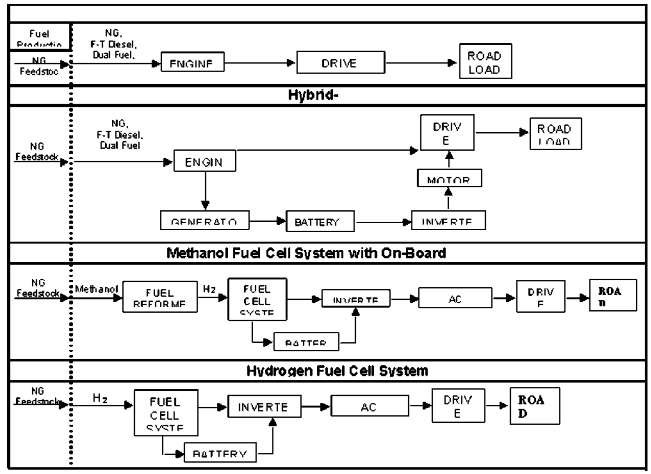

Fig. 4 Schematic diagram of the steps in a well-to-wheel analysis for four basic ground transportation systems [12]. Other configurations examined are variations on these basic concepts.

this is not true when the entire production pathway is examined. If hydrogen were to be made from fossil fuels, then carbon dioxide emissions would be larger compared to those generated from the use of the fossil fuels directly. Nuclear fuels create radioactive by-products that must be stored. Renewable energy technologies produce much less pollution than fossil or nuclear fuels, but if they were used to make hydrogen, more pollution would result than if they were used directly to generate heat and electricity.

5.3 Cost. The cost of production of gaseous hydrogen made from natural gas is around \$ 1/kg, with the natural gas priced at \$ 0.18/m^3 (\$ 5.0 per 1000 cubic feet at standard conditions), about 45% of the cost is due to the natural gas [16]. Hydrogen produced by electrolysis costs about three times this much, around \$ 3/kg, with electricity at \$ 0.05/kW h, and about 85% of the price is due to the electricity [16]. The cost for making hydrogen by other pathways is more difficult to estimate, but values ranging from \$ 2.5/kg to \$ 8/kg have been projected for several of the processes in Sec. 3.4 [33]. These stated costs generally do not include producers' profit, transmission, storage, and compression. The energy available from 1 kg of hydrogen is approximately equal to that in 1 gallon (3.78×10^{-3} m^3) of gasoline if the water produced by combustion were uncondensed in both cases. These matters are important when comparing the cost of hydrogen with the price of

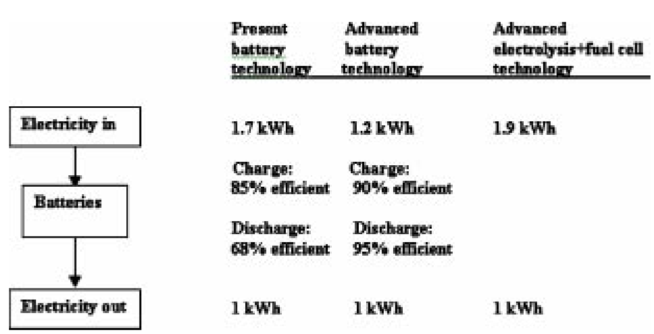

Fig. 5 Comparison of the efficiency of obtaining electric power from batteries charged from a primary source with the efficiency of a fuel cell/electrolysis system [24,25]

gasoline at the pump or the cost of electricity from the grid, which include these additional factors. Presently, hydrogen delivered to the user via truck is priced around $ 6/kg to $ 8/kg, some 3 to 6 times greater than the cost of production [34]. Hydrogen delivered by pipeline is less expensive, and hydrogen produced at the dispenser might also be less expensive. Excise taxes and dealer markup have to be added to arrive at the price to the consumer.

6 Discussion and Conclusions

There have been numerous books and articles presenting the technical steps necessary for the establishment of a hydrogen based economy. This article does not question the technical feasibility of a hydrogen based economy utilizing renewable energy sources as proposed by McAlister [35] and Rifkin [36] among others but a technically feasible option is not necessarily the most efficient, the most economical, or the most environmentally benign choice to meet the need for heat and electricity as is shown in the cradle to grave analysis above. Furthermore, as stated by the former Acting Assistant Secretary of Energy, Dr. Joseph Romm [37] in his testimony to the House Science Committee, ''Probably the biggest analytical mistake made in most hydrogen studies-including the recent National Academy Report is failing to consider whether the fuels that might be used to make hydrogen [such as natural gas or renewables] could be better used simply to make electricity.''

Based upon the cradle to grave analysis presented in this paper, the following conclusions can be drawn:

1. Any currently available hydrogen production pathway, irrespective of whether it uses fossil fuels, nuclear fuels, or renewable technologies as the primary energy source to generate electricity or heat is inefficient compared to using the electric power or heat from any of these sources directly. Hence, these hydrogen processes will not lead to an energy policy that reduces pollution and produces energy efficiently and economically.
2. Electricity produced by fuel cells using hydrogen obtained by electrolysis of water is a highly inefficient process that wastes electricity.
3. Electric vehicles using batteries to store electricity are more efficient and less polluting than fuel cell-powered vehicles using energy stored in hydrogen produced by electrolysis of water.
4. There is no reason to build a hydrogen infrastructure, because the overall concept of a hydrogen economy with any currently available technology is flawed.
5. Unless future R & D provides convincing evidence that hydrogen can be produced in an economical and environmentally benign manner and can compete successfully in market applications, strategies other than the hydrogen economy should be pursued to provide this country with an affordable and safe energy supply for the future.

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