Futures for Hydrogen Produced Using Nuclear Energy

Charles Forsberg
Oak Ridge National Laboratory*
P.O. Box 2008; Oak Ridge, TN 37831-6165
Tel: (865) 574-6783; Fax: (865) 574-0382
e-mail: forsbergcw@ornl.gov

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FUTURES FOR HYDROGEN PRODUCED USING NUCLEAR ENERGY

CHARLES FORSBERG

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

ABSTRACT

What is the future of hydrogen (H_2) produced from nuclear energy? Assuming that economically competitive nuclear H_2 can be produced, production of H_2 may become the primary use of nuclear energy and the basis for both a nuclear-H_2 renewable (solar, wind, etc.) energy economy and a nuclear-H_2 transport system. The technical and economic bases for these conclusions are described. In a nuclear-H_2 renewable energy economy, nuclear energy is used to produce H_2 that is stored and becomes the energy-storage component of the electrical generating system. The stored H_2 replaces piles of coal and tanks of liquid fuel. Capital-intensive renewable energy sources and nuclear reactors produce electricity at their full capacity. The stored H_2 is used in fuel cells to produce the highly variable quantities of electricity needed to fill the gap between the electricity demand by the customer and the electricity generated by the rest of the electrical generating system. Hydrogen is also used to produce the liquid or gaseous transport fuels. This energy-system architecture is a consequence of the fundamental differences between the characteristics of electricity (movement of electrons) and those of H_2 (movement of atoms). Electricity can be generated, transformed, and used economically on either a small or a large scale. However, it is difficult to generate, store, and transform H_2 economically on a small scale. This distinction favors the use of nuclear energy for H_2 production.

KEYWORDS

Hydrogen, Nuclear Energy, Renewables, Transportation, Hybrid Engines

1. INTRODUCTION

A worldwide interest exists in the production of hydrogen (H_2) using nuclear energy. While the implications of using nuclear energy to produce electricity are reasonably well understood, the implications of using nuclear reactors to produce H_2 are less clear. Nuclear H_2 can be used to meet the existing demands for H_2. At present, the large existing markets for H_2 are (1) upgrading heavy crude oils and tar sands to liquid fuels (gasoline, diesel, and jet fuel) and (2) producing ammonia fertilizer. Many smaller markets, such as conversion of iron ore to metallic iron also exist. Beyond these markets, many futures are possible. Two potentially viable futures may radically transform both nuclear energy and the world energy system. Each of these futures is a consequence of the unique characteristics of H_2 versus electricity (Sect. 2). Nuclear energy that produces H_2 may be the enabling technology for the large-scale use of renewables (Sect. 3). Nuclear H_2 may also be a key technology for transportation (Sect. 4).

2. HYDROGEN AND ELECTRICITY

Hydrogen, like electricity, is an energy carrier, a method to move energy from the point of generation to the point of use. Neither H_2 nor electricity occurs naturally in significant quantities. Many energy sources can be used to produce H_2 or electricity using a variety of processes. Hydrogen and electricity are interconvertible, with a potential for relatively small loses to occur in the conversion process. Fuel cells convert H_2 to electricity, while electrolysis converts electricity to H_2.

However, fundamental differences exist between the characteristics of electricity and those of H_2. Electricity involves the movement of electrons back and forth over a short distance in alternating current (AC) systems. Hydrogen, in contrast, involves the movement of mass (diatomic H_2) from point A to point B. It is the fundamentally different characteristics of H_2 that, as described herein, intrinsically favor its production, storage, transport, and use in *large-scale energy production systems*. Because nuclear energy is intrinsically a large-scale energy production system, it may ultimately be more associated with H_2 than with electricity production.

2.1 Energy Storage

The most fundamental difference between electricity and hydrogen as energy carriers is that H_2 can be stored today for use in the future. This characteristic is the basis for a H_2 economy.

The demand for electricity and other forms of energy varies by a factor of 2 or more each day from the midday peaks to the late-night lows. The large weekly variations are driven by the five-day workweek, while the summer–winter variations are driven by changes in the weather. The historic solution to meet the variable energy demand has been to store energy in the form of fossil fuels: coal in piles, liquid fuels in tanks, and natural gas in underground facilities. Ultimately mankind will exhaust the world's fossil energy sources. Even before that occurs, the use of fossil fuels is likely to be limited because of concerns regarding climatic change. The replacement of fossil fuels with any other energy source requires an ability to store energy.

If we look beyond fossil fuels, the mismatch between energy consumption and energy production becomes more pronounced. Nuclear facilities produce energy at a constant rate, while renewable energy facilities produce energy at a variable rate. Neither type of production matches demand. Because of the day–night and seasonal variations of sunlight, the typical capacity factor of solar devices is 18%. (The capacity factor is the actual energy output in a year divided by the potential energy output if the device were operated at full capacity for the entire period.) The capacity factor for wind is about 35%. For renewable energy sources, the mismatch between generation and demand is so large that it has been estimated that if as little as 15% of the electricity were produced by solar or wind, there would be limited economic incentive to obtain more energy from such sources, even if they are free. This is because backup power production facilities must be built to meet demand when these renewable energy sources are not available.

The use of H_2 as an energy carrier offers the unique advantage that we have the technology to store large quantities of H_2 at low costs as compressed gases in large underground facilities. At present, this is the primary technology used to store natural gas (U.S. Energy Information Agency, 1995). In the natural gas industry, the most rapid consumption of natural gas occurs in winter. However, it is uneconomical to design transcontinental pipelines and natural gas treatment plants to meet peak natural gas demands. Instead, the natural gas is produced and transported at a nearly constant rate throughout the year. A variety of different types of large underground storage systems in different geologies at locations near the customer are used to store the excess natural gas produced during the summer. This practice minimizes the cost of the long-distance natural-gas pipeline system and improves reliability by locating storage facilities near the customer. In the winter, these underground storage facilities provide the natural gas to meet customer demands.

The total existing natural gas storage capacity (Table 1) in the United States is $2.4 \cdot 10^{11}$ m^3 ($8.4 \cdot 10^{12}$ ft^3), which is equivalent to about one-third of the natural gas consumed in the United States each year. Three types of storage systems are used (Forsberg, 2004): (1) depleted oil and gas fields, (2) mined salt caverns, and (3) confined aquifers. These facilities are large (even relative to a large H_2 production facility), with average storage capacities of a half-billion cubic meters. The usable capacity depends upon the required pressure at which the natural gas must be delivered to the pipeline and the rate of delivery. For high-pressure gas delivery, the usable capacity is about 50% with the remainder of the gas used as buffer gas to maintain storage facility pressure.

Table 1. U.S. underground natural gas storage capacity in 2001

Type of storage capacity	Number of facilities	Capacity (10^9 m^3 [10^9 ft^3])
Salt caverns	28	6 [218]
Aquifers	39	34 [1195]
Depleted fields	351	198 [7002]
Total	418	236 [8357]

For the same reasons indicated above (economics and matching demand), H_2 today is stored on a limited scale in underground facilities. Hydrogen is produced in expensive plants that operate at a constant rate. The demand for H_2, however, varies. Thus, underground facilities are used to store H_2 until it is needed. This technology has several implications.

- *Capabilities*. We have an existing technology to store H_2 that is sufficient to meet daily, weekly, and seasonal swings in energy demand.
- *Costs.* Underground storage is the only low-cost technology available for H_2 storage; however, economic facilities are large, with typical storage capacities in excess of 100 million cubic meters. All other large-scale storage options are much more expensive. No low-cost methods to store H_2 on a small or medium scale have yet been identified. Storage of H_2 as a liquid (U. S. National Research Council, 2004) implies using 30 to 40% of the energy to liquefy the H_2. High-pressure tanks and various other storage media have much higher storage costs than underground facilities.
- *Technology constraints*. Underground storage requires high-pressure, high-volume H_2 delivery to large storage facilities.
- *Capacity requirements*. For seasonal storage of H_2, the volumes that must be stored are strongly dependent upon the energy source that produces the H_2. Because most of the H_2 would be produced in the summer while the highest energy demand is in the winter, solar production at locations distant from the equator require very large storage volumes. When wind is the energy source, the volumes to be stored are highly dependent on local seasonal wind conditions. The required storage volumes for nuclear energy will generally be lower than those for most other energy sources. Although nuclear plants produce constant output, maintenance and refueling outages can be timed to reduce seasonal H_2 storage requirements.

2.2 Collection, Transportation, and Distribution

Intrinsic differences (Bossel and Eliasson, 2003; Mazza and Hammerschlag, 2004) exist between the collection, transport, and distribution of H_2 and those of electricity. With the use of transformers and modern electronics, electricity makes possible an efficient two-way distributed system for the collection, transport, and distribution of electricity. This is not the case for H_2.

Hydrogen collection, storage, and distribution, like that for natural gas, is intrinsically a one-way system. In systems that produce natural gas (or, in the future, those that produce H_2 from distributed sources), moving low-pressure gases from distributed production sources to a high-pressure, high-volume pipeline system and then to storage is complex and expensive. Pipelines transmit any impurities fed to the system. Purification systems are required to prevent gas impurities from entering the system and damaging pipelines, compressors, and storage facilities. The efficiency and cost of gas compression and storage are strongly dependent upon scale and the safety requirements are demanding. In addition, H_2 is more expensive to manage than natural gas because the lower molecular weight of H_2 implies larger compressors, a greater potential for leakage, and larger pipeline sizes for moving equivalent amounts of energy.

Recent assessments (Bossel and Eliasson, 2003; Mazza and Hammerschlag, 2004) of H_2 and electrical systems have quantified some of these differences. Based on significant cost and efficiency penalties in the collection, transport, and distribution of H_2 compared with those for electricity, significant incentives exist for small distributed electric sources (solar cells, wind, etc.) to produce electricity rather than H_2. That is, for energy systems with equivalent costs and characteristics for producing H_2 or electricity, the large systems will have a competitive advantage in H_2 production whereas the small systems will have a competitive advantage in electricity production because of the differences in the costs of collecting, storing, transporting, and distributing H_2 versus those for electricity.

2.3 Production

Mankind has learned to build electrical generating systems in which the cost of electricity generation varies by less than a factor of 3 while the scale of the generating system varies in size over 4 to 5 orders of magnitude. The ultimate goal for solar cells with power outputs of kilowatts is to have costs similar to those for 1000-MW plants. Electricity can potentially be economically generated on many scales of production that couple to the distribution of electricity.

In contrast, various studies associated with H_2 production using different techniques show strong economic incentives to produce H_2 on a large scale (Miller and Duffy, 2003; Nuclear Energy Agency, 2003; Goosseng et al., 2003; Bossel and Elrasson, 2003). This is a consequence of scaling equipment that processes fluids (rather than electrons) and has been demonstrated and universally accepted for over a century in the chemical and oil refining industries.

3. THE NUCLEAR-HYDROGEN RENEWABLES ECONOMY

The general characteristics of both nuclear and renewables are similar. Both technologies have high capital costs and low operating costs. The costs of energy from a capital-intensive technology can be low if the facilities are used at full capacity. The cost of energy becomes very high if such technologies are not operated at near full capacity. Hydrogen can replace fossil fuels as a method to store energy; thus, it is a potential replacement as a fuel. However, the question is how to generate and convert that H_2 into electricity to economically meet the variable demands for electricity when (1) the demand for electricity is variable, (2) the production of electricity from nuclear energy plants is nearly constant, and (3) the production of electricity from renewables is variable but does not match the demand for electricity.

Recent systems studies (Mazza and Hammerschlag, 2004) have examined the production of H_2 using renewables and the subsequent conversion of that H_2 into electricity. The general conclusion is that renewables (solar cells, wind, etc.) are better suited for the direct production of electricity than for the production of H_2. The major renewable energy options are intrinsically electrical generating devices. Although work is being done on direct production of H_2 with renewables, this process is much more challenging than the production of electricity and has the major challenge of collecting the H_2 and boosting H_2 pressures to pipeline pressures.

Studies by the author (Forsberg, 2004) indicate the potential of using nuclear H_2 to economically meet variable electrical demand. This application may be one of the first applications of nuclear H_2, as well as the enabling technology for a nuclear-H_2 renewables economy. These systems are called Peak Electrical Nuclear Systems (PENS). The near-term applications are (1) to replace alternative methods of meeting peak electric power demands, such as gas turbines burning oil and natural gas and (2) to provide spinning reserve. *Spinning reserve* is the electrical production capacity on the electrical grid to provide power in the event of an unexpected shutdown of a power plant or grid failure. The August 14, 2003, blackout of much of the east coast of the United States would not have occurred if sufficient spinning reserve existed and had been properly distributed.

The long-term potential use of PENS is to enable a nuclear-H_2 renewables economy. Work is underway to develop solar devices and other renewable technologies that have low costs per kilowatt. The fundamental problem is energy storage. Were there no energy storage problem, wind or solar would become economic wherever their production cost is the below the price of electricity, not the cost of electricity plus energy storage. Without storage requirements, the potential exists for a significant fraction of electricity and the total energy market to ultimately be provided by renewable energy sources. PENS may provide that storage function. PENS consists of three major components (Fig. 1):

- *Hydrogen production*. A nuclear power plant with an associated thermochemical or high-temperature electrolysis plant is used to produce H_2 at a constant rate.
- *Hydrogen and oxygen storage*. Underground storage facilities are used for the low-cost storage of H_2 and oxygen.
- *Hydrogen-to-electricity conversion*. Large banks of fuel cells are used to convert H_2 to electricity during periods of higher-priced electricity. For every megawatt of steady-state H_2 production from the nuclear reactor, the fuel cells would be capable of producing several megawatts of electricity. At times of low electrical demand and price, the fuel cells would produce no electricity. At times of high electricity demand and price, the electrical output of the fuel cells would be many times that of the reactor.

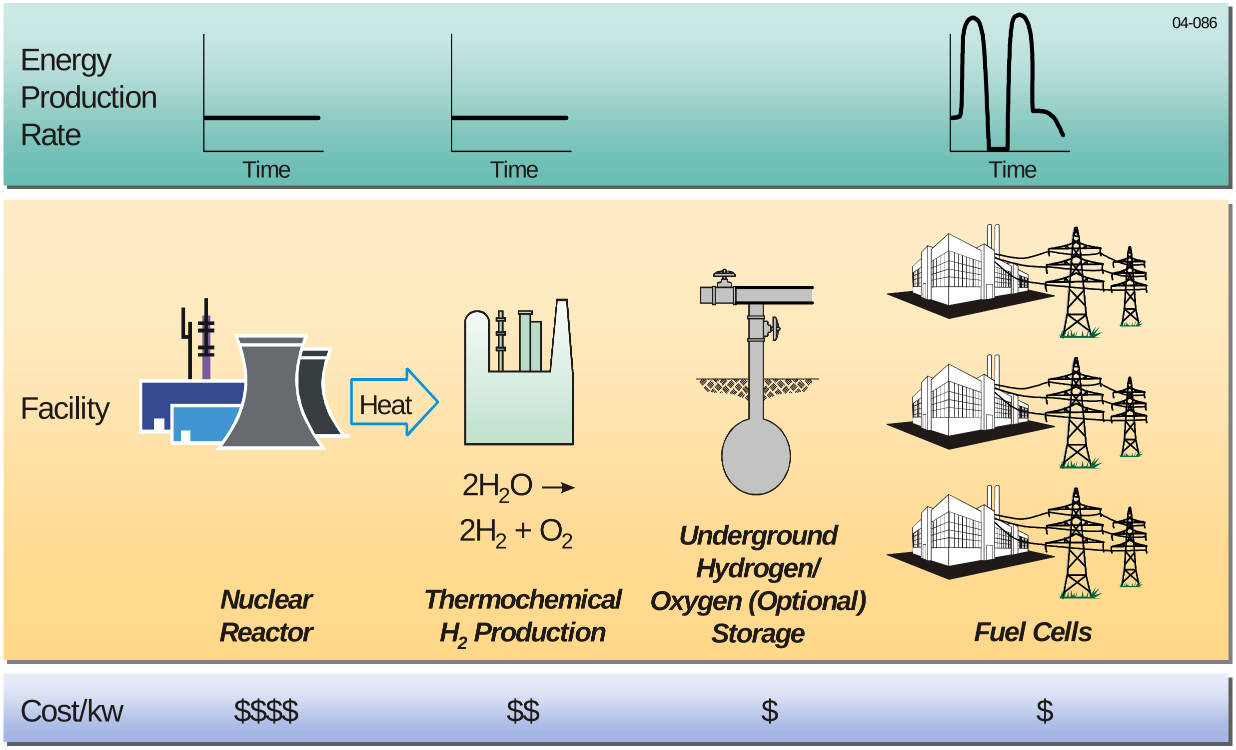

Fig. 1. Peak electricity nuclear system, including relative costs for production.

Today, in the United States, the demand for peak and intermediate electrical load is met primarily by gas turbines that burn natural gas. The cost of electricity depends upon the capital cost of the power plant and the cost of the fuel. Gas turbines are used because of their low capital cost. The capital costs of gas turbines are about $500/kW(e), and efficiencies are near 50%. The penalty in using gas turbines is that they burn more expensive fuel: natural gas or oil. Because gas turbine peaking units are engaged only part of the time, a more expensive fuel can be justified if the capital cost is lower.

Hydrogen is a premium fuel compared with natural gas. Thus, H_2 must offer a benefit if it is to be used to meet intermediate and peak electrical loads. The economic viability of PENS is dependent upon three conditions:

- *Nuclear-H_2 costs.* Nuclear-H_2 production under steady-state conditions must be relatively competitive.
- *Low-cost large-scale H_2 storage.* Based on the experience of the natural gas industry in storing natural gas and more limited experience in storing H_2 underground, large scale storage of H_2 is inexpensive.

- *Low-cost H_2—oxygen fuel cells compared with the costs for gas turbines per kilowatt (the competition to meet peak and intermediate electrical loads).* The potential low cost for the fuel cells is based on several PENS characteristics: (1) economies of scale associated with the large fuel-cell facilities; (2) fewer fuel-cell design constraints than those that exist in other fuel-cell applications, for example, weight and size constraints in vehicle applications; (3) a feed of pure H_2 to boost fuel-cell performance; and (4) the use of oxygen from the thermochemical H_2 production systems, rather than air, to reduce capital costs per kW(e) and increase the efficiency of the fuel cell. The long-term goal of the U.S. government (U. S. National Research Council, 2004) is to develop fuel cells with costs of <$50/kW(e) when fed H_2 and air for automotive applications. While it is unknown whether these goals can be met, the capital costs of fuel cells for PENS will be substantially less than those for vehicle applications because (1) the scale of operations is about 10,000 times larger and (2) the use of oxygen (versus air) boosts fuel-cell power output by several times while increasing efficiency. The increase output of the fuel cell with oxygen is equivalent to a major reduction in the capital costs of fuel cells. The projected fuel cell efficiency is about 70% with pure oxygen. Based on the specific requirements for this application, the leading candidates for this application are alkaline and polymer electrolyte fuel cells.

In this context, it is noted that gas turbines are heat engines. Converting gas turbines to H_2 does not significantly improve their performance. Moreover, the use of oxygen does not significantly improve their efficiency or lower their costs. Gas turbine efficiency depends upon peak operating temperatures. While the use of oxygen (rather than air) would increase peak operating temperatures, “real world” peak turbine temperatures are limited by the availability of high-temperature materials. Air-fired combustors are capable of higher temperatures than turbine blades can currently accept. In contrast, fuel-cell output is dramatically increased by using oxygen rather than air. This occurs because fuel-cell output is limited by oxygen mass transfer within the fuel cell and pure oxygen greatly increases mass transfer relative to that produced by air.

PENS has an additional application. The major technical and economic challenge in providing spinning reserve is that the additional electrical production must come on-line very rapidly in the case of failure of another electrical generating plant or failure of part of the electrical grid. This is currently accomplished by having power plants at part load with their turbines spinning. Although this approach allows the rapid increase in power generation when required, it has associated high costs. Fuel cells have a unique capability: in a fraction of a second, they can go from no power output to high power output. Because of this capability, one of the major existing markets for fuel cells is for computer data centers, where there is a very high cost associated with temporary power outages—even those that last a fraction of a second. *The development of PENS creates a new set of options with new and unique capabilities to provide spinning reserve, improve grid reliability, and improve electric power quality.*

The peak electricity market, if it is technically and economically viable, has several unique characteristics that make it attractive as an early market for nuclear H_2. In the United States, the total market is approximately equivalent in size to the existing nuclear electric enterprise. The entire market is within the utility industry, which has experience in operating nuclear power reactors. The market is internal and does not require development of an external market for H_2 or a significant H_2 infrastructure beyond the utility site.

4. NUCLEAR HYDROGEN TRANSPORT FUTURES

Hydrogen has been described as the fuel of the future for transportation. Although this is an accurate statement, it is true in a much broader context than using H_2 gas to power automobiles. It is this broad application of H_2, and perhaps electricity, that must be considered: first, in the context of fuels for transportation and, second, in the context of engines that convert the fuel to movement. Transportation represents the second major market for nuclear H_2.

4.1 Hydrogen in Transportation

Conventional world oil production is expected to peak within a decade [Giles, 2004; Forsberg et al, 2004]. In the next several decades, shortfalls in production of liquid fuels (gasoline, diesel, and jet fuel) from conventional oil production are expected to be offset by increased production of fuels from heavy oils and tar sands [Williams, 2003]. These hydrocarbon resources have H_2-to-carbon ratios as low as one, while the H_2-to-carbon ratio in liquid fuels is about two. Therefore, the ratio must be increased to produce liquid fuels from heavy oils and tar sands. This can be accomplished by (1) by thermal cracking (i.e., extracting “excess” carbon which is ultimately released as carbon dioxide) or (2) by hydrocracking (i.e., adding of massive quantities of H_2). Today, H_2 is made by steam reforming of fossil fuels, a process that results in the release of large quantities of carbon dioxide. If these hydrocarbon resources are to be used to produce liquid fuels while simultaneously minimizing greenhouse emissions, it is necessary to employ hydrocracking, with the use of nonfossil methods for the production of H_2.

In many parts of the world, ethanol and several other liquid fuels are made from biomass. One of the major energy inputs into biomass is fertilizer, primarily nitrogen in the form of ammonia. The production of ammonia fertilizer requires massive quantities of H_2 and currently represents one-half of the market for H_2. If biomass is to be a major source of liquid fuels, additional quantities of H_2 are required for fertilizer production.

In the long term, H_2 is being considered as a transport fuel. However, it is unclear whether methods for on-board vehicle storage of H_2 will be successfully developed. If these methods are not successfully developed, the potential liquid fuels include methanol (H_2 plus carbon dioxide from the air), ammonia (H_2 plus nitrogen from the air), and other hydrogen carriers (Deluga et al., 2004; Kato et al., 2003) that avoid release of greenhouse gases. Except for the electric car, all of the transport futures are strongly dependent on H_2 as the basis for transport fuel production, with increased H_2 production over time. *For most of these futures, the H_2 demand is at large centralized facilities.*

Centralized nuclear H_2 has a competitive advantage for H_2 production in such markets because, unlike H_2 from distributed sources, there is no collection cost for the H_2.

4.2 Engines for Transportation

Transportation is a story of fuels and engines. For a century, the internal combustion engine (gasoline and diesel) has ruled. However, a revolution has started: the hybrid automobile, which uses a combination of electric batteries and an internal combustion engine. As a key enabling technology for both the electric car and the H_2-fueled car, the hybrid car represents the enabling technology for a H_2 transport system.

A hybrid car contains an engine, batteries, and an electric motor-generator. In a hybrid car, the electric battery and motor provide the power to rapidly accelerate the car and provide power at low speeds. The battery is charged by recuperative braking (i.e., recovering the energy of forward motion when the car brakes) and by the internal combustion engine. The internal combustion engine operates at a constant speed and load under conditions to maximize the energy output per liter of fuel. When the batteries are fully charged and the power demand is low, the engine is shut down until needed. When the batteries are low or are rapidly being drained, the engine is turned on to recharge the batteries and provide motive power. The efficiency of internal combustion engines is a very strong function of engine speed and load. By operating the engine under efficient "base load" conditions and using the battery as an energy storage device to meet peak energy demands, the total fuel consumption per kilometer traveled is greatly reduced. With its energy storage capability, the hybrid is to transportation what PENS may become for the electrical grid.

However, the hybrid engine is potentially much more revolutionary in its impacts. The internal combustion engine became the engine of the choice in transportation because it could economically deliver power rapidly over a wide range of conditions, including very high power levels for short periods of time. The hybrid engine eliminates this variable-power requirement. It allows for engines that are optimized for efficiency (not variable power levels) and can easily burn many types of fuel, including H_2. It enables many other types of engines to become viable for transportation, including fuel cells. The design goal becomes an engine that can deliver 50 kW continuously and efficiently, not 5 to 300 kW with wide variations in power output over very short time periods. Because the hybrid requires a much smaller engine, it also is the economically enabling technology that allows somewhat higher costs per kW—if the engine efficiency is significantly higher. This change in requirements is the enabling technology for fuel cells and other engine technologies in vehicles.

A second potentially revolutionary implication is also associated with this technology. Advanced hybrid vehicles may allow the battery to be recharged by connection to the electrical grid when the car is parked. For shorter trips, the hybrid car batteries provide the energy. For longer trips, after the battery is exhausted, the engine provides the energy. It has been estimated that if the battery can provide power for 20 miles, the fuel consumption in cars could be reduced in half compared to conventional vehicles. These advanced hybrids are called plug-in hybrid electric vehicles (PHEVs). This type of hybrid addresses the two major barriers that presently exist for using electricity in cars.

- *Vehicle range*. Because of battery limitations, electric vehicles have restricted range. For most trips, this range is sufficient. However, customers do not want to buy two vehicles: an electric vehicle for short trips and a gasoline vehicle for long trips. The hybrid engine enables a single vehicle to be used for both applications.
- *Battery recharging*. In a gasoline refueling station, the rate of energy transport in the form of gasoline from the pump to the automobile tank is ~10 MW, an extraordinary transfer rate that enables an automobile to be refueled in minutes. For several reasons, it is not practical to recharge electrical vehicles at similar rates. The required electrical connections would be massive as would the instantaneous power surge at the recharging station. In addition, battery recharging is not 100% efficient. If the recharge process were 90% efficient, the batteries would have to reject 100 kW of heat for every megawatt of energy input, which represents a major heat rejection challenge for an automobile. At the same time, recharging batteries overnight or while a person is at work is relatively easy. The recharge rate is measured in kilowatts, not in megawatts. A PHEV allows slow battery recharging while providing the gasoline engine for propulsion if there is insufficient time to recharge batteries.

Today's hybrid cars are leading to the development of PHEVs (Graham, 2001). The first-generation PHEVs are now beginning road tests. Consequently, the hybrid engine is potentially the enabling technology to couple transportation to a nuclear-H_2 renewables electrical system via the hybrid battery and nuclear H_2 via engines designed for H_2 fuels.

5. CONCLUSION

Because we have imperfect information on what is technologically and economically possible, the future is unknowable. However, fundamental physical constraints suggest that H_2, not electricity, may ultimately be the primary output of nuclear power plants. The characteristics of electricity allow it to be produced economically at many different scales; thus, many technologies can be used to produce electricity. In contrast, the characteristics of H_2 production and storage favor large facilities that match the characteristics of nuclear energy. Nuclear H_2 may be the enabling technology for a nuclear-H_2 renewable energy future because it provides a method to store energy and thus match variable energy production with variable energy demand. Similarly, because almost all transport futures require H_2, nuclear H_2 may be the future of transportation.

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