Synergistic Benefits of a Nuclear-Renewable Hydrogen Economy

Charles W. 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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SYNERGISTIC BENEFITS OF A NUCLEAR-RENEWABLE HYDROGEN ECONOMY

C. W. Forsberg[1]

Abstract

Nuclear and renewable energy sources have the same characteristics: high capital costs and low operating costs. These energy systems must operate at full capacity to minimize the cost of energy to the consumer; however, their output does not match energy demand by the customer. The mismatch in nuclear renewables energy systems between energy production and consumption can be addressed by using bulk storage of hydrogen in underground facilities and special technologies to convert that hydrogen into electricity or liquid fuels to meet variable energy demand. The critical technology is bulk underground hydrogen storage that is one-to-two orders of magnitude less expensive than other hydrogen storage systems. The low cost allows weekly and seasonal hydrogen storage to match energy production with energy consumption.

1. Introduction

The requirement of any national energy system is to deliver energy to the customer as needed. Energy demands vary with the time of day, the day of the week, and the season (summer, winter, etc.). Fossil fuels can meet these requirements economically because they are inexpensive to store (piles of coal, oil tanks, etc.) and the capital cost of equipment to convert these fuels to heat, electricity, or motive power (transportation) is relatively low. In contrast, nuclear and renewable energy sources have high capital costs and low operating costs. Thus, these energy sources require continuous full load to minimize total production costs. In systems with such characteristics, it is difficult to economically match production with demand.

A synergistic nuclear-renewable hydrogen system is proposed to match energy production by capital-intensive energy sources with demand by using hydrogen stored in bulk underground storage facilities. Underground hydrogen storage as compressed gas (the technology used for natural gas storage) is the only low-cost method for hydrogen storage that is economically viable (1) to store hydrogen for weeks or months and (2) to match production from capital-intensive energy systems with energy demand. However, there are constraints: low-cost storage requires very large capacity facilities, and siting is dependent upon geological conditions. Relative to dispersed methods of hydrogen production, hydrogen available from centralized energy systems (such as nuclear power plants) has large economic advantages for providing the hydrogen for such storage facilities because there is no need to collect and ship hydrogen to these facilities.

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1 Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6166,
Tel: (865) 574-6783, e-mail: forsbergcw@ornl.gov.

The system characteristics for low-cost hydrogen storage, electricity distribution, and hydrogen distribution support (1) nuclear and renewables for electricity production; (2) nuclear hydrogen for centralized large-scale markets for hydrogen, such as filling bulk hydrogen storage facilities; and (3) renewable hydrogen for dispersed hydrogen demands without long-term storage requirements. The following topics are discussed: system characteristics (Sect. 2); bulk hydrogen storage technologies (Sect. 3); and two technologies to use the bulk hydrogen to match variable energy production with variable energy consumption. The Hydrogen Intermediate and Peak Electric System (HIPES) is one option to address the mismatch between electricity production from nuclear and renewables with the electric demand (Sect. 4). Hydrogen-rich biomass liquid-fuels are an alternative to fossil fuels for transport fuel production (Sect. 5).

2. Structural Energy Challenges

Energy systems have three components (Table 1): energy sources, energy storage systems, and energy distribution systems. Energy sources include nuclear, renewables, and fossil. Energy storage systems designed to match production of energy with demand, include water stored behind dams, as well as fossil fuels in the form of coal piles, oil tanks, and natural gas storage facilities. Energy distribution systems include electricity, natural gas pipelines, and liquid fuels. The cost of energy for the user is the sum of production, storage, and distribution costs; thus, the most economic system depends upon all three costs.

Table 1. Components of Energy Systems

Energy Sources	**Energy Storage**[1]	**Energy Distribution**
Nuclear	Water and air	Electricity
Renewables	Hydrogen	Hydrogen
Fossil	Fossil	Fossil

[1]Capability to store energy to meet variable energy demand.

Modern economies are dependent on fossil fuels because of their low costs for production, storage, and distribution. If new energy sources are required─because of the potential for climatic change, the rising costs of fossil energy, or the national security risks of depending upon foreign oil and natural gas─the problem is not just producing energy. There are the equally large challenges of finding ways to store and distribute energy. Hydrogen and the concept of a hydrogen economy are of interest because they represent a method to store and distribute energy.

Nuclear and renewable energy sources have common economic characteristics: high capital costs and low operating costs. Such energy sources can provide low-cost energy services only if they are operated continuously at levels near their maximum capability. If their output is not maximized, such energy sources are expensive. Energy demands vary with the time of day, the day of the week, and the season (summer, winter, etc.). Renewable energy systems provide dispersed, variable sources of energy that do not match consumer demand. Nuclear energy systems provide a centralized steady-state source of energy that also does not match consumer demand. This mismatch between production and demand is not important in energy systems dominated by fossil fuels. Fossil fuels can match production and demand economically because they are inexpensive to store (piles of coal, oil tanks, etc.) and the capital cost of equipment to convert these fuels to heat, electricity, or motive power (transportation) is relatively low. *However, the mismatch between production and use becomes a major energy challenge if a large fraction of the total energy is produced by nonfossil sources.*

An empirical example of the challenge can be seen by assessing current electrical markets [1]. The demand for electricity varies with time of day, week, and year. In unregulated electrical markets, this fluctuation results in high costs for electricity during peak periods of electricity demand. An example of such variations is the price of electricity [$/MW(e)-h] in Alberta, Canada, during 2002 (Fig. 1). In regulated markets, the price of power may be constant. However, the utility must build facilities to meet peak electrical demand. The cost to produce that electricity is significantly higher than the cost of electricity during periods of low demand. The Alberta, Canada, system uses fossil fuels as the primary energy source. However, even here significant variations in costs, with a clear seasonal effect, are noted.

The mismatch between energy production and demand is likely to become worse, even if fossil fuels continue to be used. Work is under way to develop fossil plants that provide for the sequestration of carbon dioxide. This allows the use of fossil fuels with minimal environmental impacts. However, this option results in capital-intensive centralized power plants with some of the characteristics of nuclear energy.

3. Hydrogen Missions

The challenge for capital-intensive, low-operating-cost energy futures (solar, nuclear, and fossil fuel with sequestration of carbon dioxide) is that the energy production systems are not well suited to match the demand by the customer. The potential role of hydrogen is to address this mismatch.

3.1 Traditional Energy Storage

There are daily, weekly, and seasonal energy storage requirements for electricity and heat. A wide variety of methods are available to meet the daily changes in energy demand, with a few options to meet the weekly variation in demand.

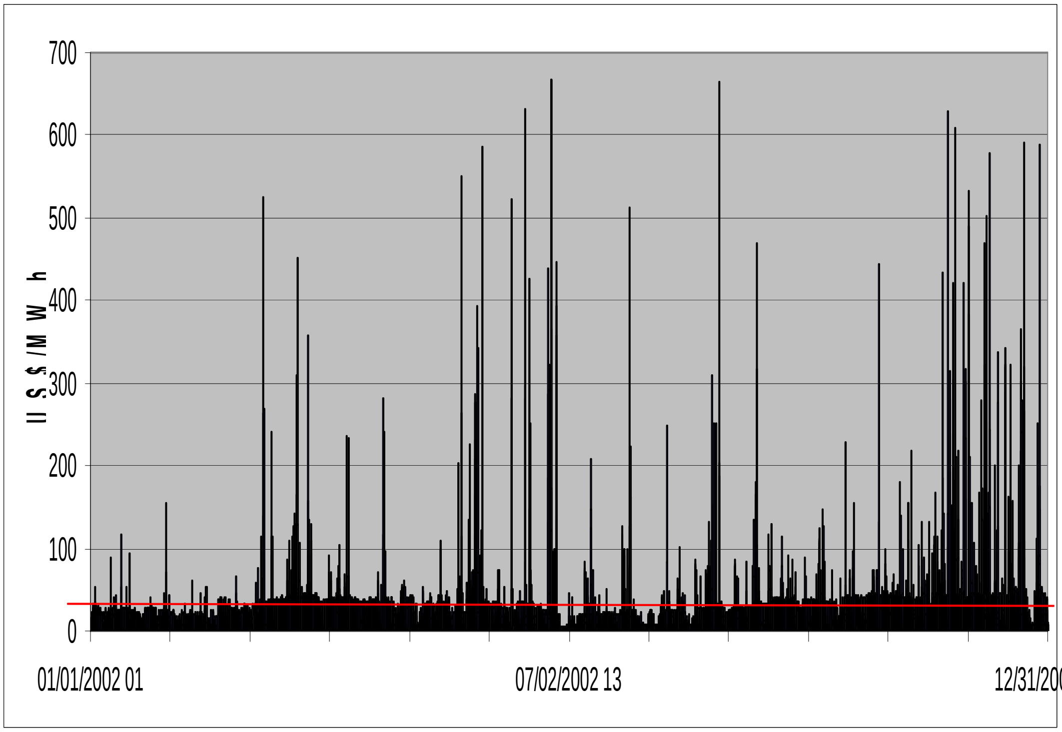

Fig. 1. Price of Electricity [$/MW(e)-h] as a Function of Time in Alberta, Canada.[1]

Heat is stored as sensible heat in a variety of media. On a daily basis, fire brick is heated with lower-cost nighttime electricity to provide heat throughout the day (Europe). Hot water from solar systems or nighttime electricity is stored in tanks to provide hot water and heat for up to several days. Solar troughs and power towers store high-temperature heat as hot salts, with the heat used to make electricity on demand. On a longer time period, geothermal heat is used to meet seasonal heat requirements. In the summer, heat from air-conditioning systems heats the ground and in the winter the heat is recovered. Commercial technologies exist to store low-temperature heat over all time periods of interest and to store high-temperature heat for up to a day.

Electricity produced at times of low demand and cost is also stored and delivered to the electric grid at times of high demand and cost. The traditional technology has been hydro-pumped storage. In a pumped storage facility, water is pumped uphill at night when the cost of electricity is low. At times of high power demand, the water flows downhill through turbines to produce electricity. For example, the Tennessee Valley Authority Raccoon Mountain pumped storage facility has a capability to produce 1530 MW(e) at times of peak demand. Similar systems have been built based on compressed air energy storage with the compressed air stored in deep underground caverns. These technologies can store electricity on a daily basis but are uneconomic for longer-term storage because of the low energy density of the storage media: water stored at higher elevations and compressed air.

In a fossil-fuel-constrained world, the challenge is to store energy for periods of days to months and to replace the use of fossil fuels for this application. In this mission, hydrogen has potentially unique capabilities. Commercial technologies already exist to meet the shorter-term energy storage requirements.

3.2 Hydrogen Storage

Only one non-fossil method exists for weekly or seasonal storage of large quantities of energy (Quads) at low costs—storage of hydrogen as compressed gas in large underground facilities. No other low-cost technologies have been identified. This underground storage is the same technology used for seasonal storage of natural gas [2]. 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 relatively 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 for subsequent use in the winter (Fig. 2).

- *Man-made caverns*. Underground caverns are mined, with access to the surface provided via wells. The most common type of cavern is located in salt domes, where the cavern is made by pumping down fresh water and dissolving out the salt.

- *Pressure-compensated man-made caverns*. Underground caverns are mined, with access to the surface provided via wells. In addition, a surface lake connected to the bottom of the man-made cavern is created. The water pressure from the surface lake results in a constant pressure in the cavern that is equal to the hydraulic head of the water.

- *Porous rock with caprock*. Porous rock exists with an impermeable caprock above it that forms a natural trap for gases (inverted "U" shape). Wells are drilled into the porous rock, and injected gas pushes out whatever other fluids exist in the rock. Much of the world's natural gas is found in this type of geological trap. Similar structures are found worldwide without natural gas, many of which have been used for natural gas storage. In most cases, these are parts of aquifers and the injection of the gas pushes out the water.

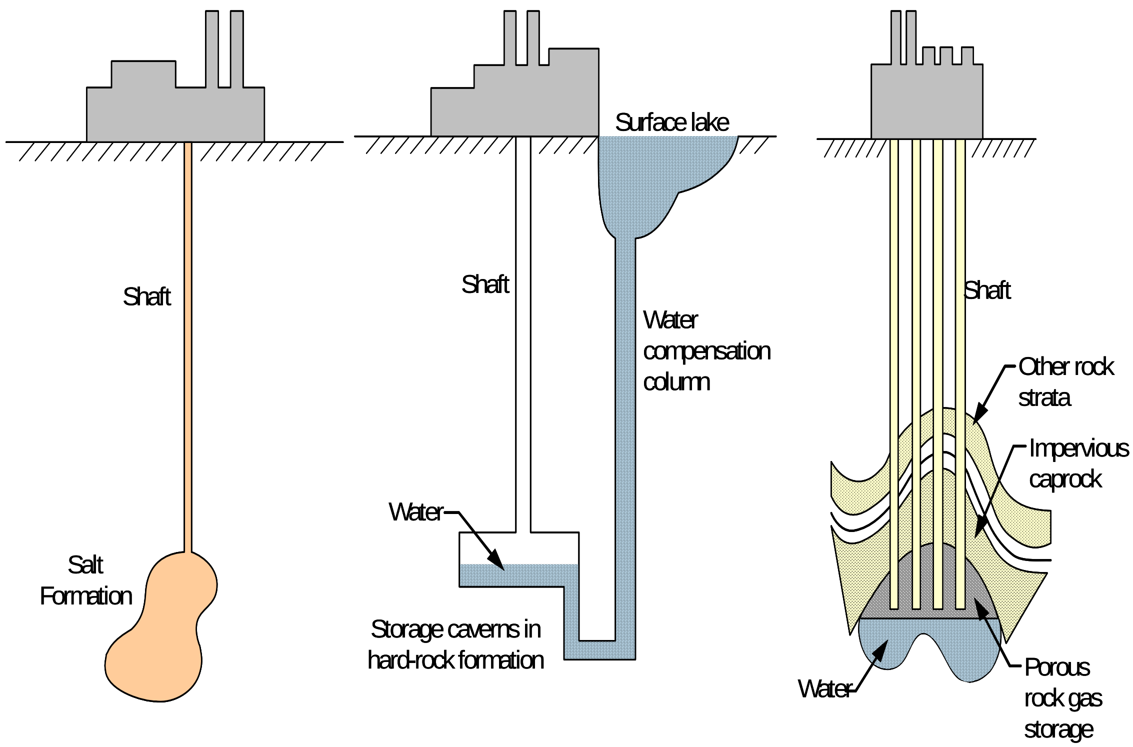

Fig. 2. Technologies for Underground Storage of Compressed Gases.

The total existing natural gas storage capacity in the United States is 8.4×10^{12} ft^3, which is equivalent to about one-third of the natural gas consumed in the United States in 1 year. Table 2 identifies the existing underground natural gas storage facilities by type and capacity. These facilities are large, with average storage capacities between 10 and 20 billion cubic feet. 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 capacity is about one-half, with one-half of the gas used as buffer gas to maintain storage facility pressure and minimize compression back to pipeline pressures.

For several decades, industrial facilities have used salt caverns to store hydrogen thus meeting variable industrial hydrogen demand while allowing shutdowns of hydrogen production plants for maintenance. Hydrogen storage should be viable in other geologies, but this application of the technology has not been demonstrated on a commercial.

Table 2. U.S. Underground Natural Gas Storage Capacity in 2001

Type of Storage Capacity	Number of Facilities	Capacity (10^9 ft^3)
Salt caverns	28	218
Aquifers	39	1195
Depleted fields	351	7002
Total	418	8357

The capital cost of an underground facility to store 1-GW-year of hydrogen (lower heating value) is estimated to be about $200–$400 million ($0.80–1.60/kg storage capacity). The value of the hydrogen stored in such a facility will exceed the capital cost of the facility. The capital cost is sufficiently low as to make viable the seasonal storage of hydrogen. The capital cost estimate (1) assumes that the cost per unit volume stored is the same as that of hydrogen and natural gas and (2) is based on reported capital costs for planned natural gas storage facilities [3].

3.3 Roles of Nuclear and Renewables

Costs for underground hydrogen storage are about two orders of magnitude less than those for other forms of hydrogen storage. Underground storage is the only viable method to store the quantities of energy needed for multiweek or seasonal changes in energy demand if the use of fossil fuels is constrained. The characteristics of the bulk storage system will drive the characteristics of much of the hydrogen economy, including the likely roles of nuclear and renewables for energy production.

Hydrogen transport requires the movement of mass rather than electrons. In an electrical grid, electricity can be converted from low voltage (use or generation) to high voltage (transport) or vise versa by the same electrical transformer at high efficiencies. Electrical systems accommodate energy flow in either direction. In contrast, different equipment is required to convert low-pressure hydrogen to high-pressure hydrogen or vise versa. Furthermore, the efficiency of converting low-pressure hydrogen to high-pressure hydrogen is strongly dependent on the scale of equipment, with small gas compressors having low efficiencies. Like those for natural gas, hydrogen distribution systems are directional and favor flow from centralized high-pressure sources to distributed low-pressure users.

The combination of the transportation characteristics of hydrogen and characteristics of bulk hydrogen storage strongly favor nuclear energy for bulk hydrogen production.

- *Transport costs*. The transportation costs of hydrogen and the one-directional characteristics of hydrogen imply high costs for hydrogen delivered to a central facility from decentralized sources [4-6]. In many systems, transport costs approach hydrogen production costs. Decentralized hydrogen production costs must be significantly less than centralized production methods to be economically viable for filling bulk storage facilities. The hydrogen-transportation cost barrier strongly favors using centralized energy sources (such as nuclear energy) for hydrogen production over dispersed renewable energy sources.

- *Siting*. The siting of bulk storage facilities is controlled by geology, like it is for storage of natural gas. The cost of nuclear energy is relatively independent of location, whereas the costs of renewables are highly site dependent. Hydrogen storage sites in most cases will not match renewable energy siting requirements.

- *Heat*. For many options, management of the hydrogen and oxygen will also require heat (see Sect. 4). This secondary requirement favors centrally produced hydrogen systems.

There are several caveats.

- *Short-term storage*. Hydrogen may be used as a storage medium to meet daily or multiday swings in energy demand. Because the quantities of hydrogen storage for such applications are small, these applications may incorporate decentralized hydrogen production to avoid energy transport costs.

- *Production costs*. The other critical parameter in a hydrogen economy is the hydrogen production costs. If any method has drastically lower costs than alternative production methods, it will overcome transport and storage costs to dominate the market.

4. Intermediate and Peak Electricity

For a nuclear-renewables economy, the critical electrical-generating need is a method to produce electricity to meet the differences between (1) the customer demand for electricity and (2) the electricity produced by capital-intensive nuclear and renewable technologies. If low-cost methods to meet peak electrical demand can be devised, renewable energy systems can potentially produce a major fraction of the total energy demand. If methods are not found to match production with demand, the penetration of renewable energy systems (wind and solar) into the electrical market will be limited, because of the need for expensive standby power systems to produce electricity at times of low winds or solar radiation.

Stored hydrogen can provide the energy source to meet intermediate and peak electrical power requirements; however, the capital costs of the hydrogen-to-electricity conversion system must be minimized. If the capital cost of the energy conversion system is high, there is little incentive to use hydrogen as an energy source to meet intermediate and peak electrical loads. Equally important, to meet economic goals, the hydrogen-to-electricity conversion processes must be efficient. There are two classes of hydrogen-fuel options to meet this highly variable electrical generating need.

- *Replacement fuel*. Hydrogen can be used as a replacement for natural gas using traditional heat-to-electricity technologies such as turbines. The current state-of-the-art commercial technology [7] to meet intermediate and peak electric loads is the integrated combined-cycle plant. The natural gas is fed to a Brayton power cycle (jet engine) that produces part of the electrical power. The hot exhaust from the Brayton cycle is then fed to a conventional steam boiler to produce steam, which is sent to a conventional steam turbine. The plant efficiencies are ~55% with overnight capital costs of ~$570/kW(e). These plants could be fueled with hydrogen.

- *Hydrogen Intermediate and Peak Electricity System (HIPES).* Unlike fossil hydrogen production methods, nuclear and most other renewable hydrogen methods convert water to hydrogen and oxygen. HIPES offers the option of storing both the hydrogen and oxygen. This feature creates alternative methods to produce electricity to meet intermediate and peak electricity that may have much lower capital costs and much higher efficiencies in converting hydrogen to electricity than combined cycle plants [8]. The chemical characteristics of hydrogen create unique options.

HIPES consists of three major components (Fig. 3).

- *Hydrogen production*. Hydrogen is produced from water, with the by-product production of oxygen.

- *Hydrogen and oxygen storage*. Underground storage facilities are used for the low-cost storage of hydrogen and oxygen. Because storage costs are low, hydrogen production plants can operate at their most economic production rates. Hydrogen can be stored weekly to seasonally until needed in very large quantities.

- *Hydrogen-to-electricity conversion*. Fuel cells, steam turbines, or other technologies are used to convert the hydrogen to electricity.

The potential economics of HIPES are based on three factors: (1) minimizing the cost of hydrogen production by producing hydrogen at the maximum rate possible from capital-intensive facilities, (2) low-cost hydrogen and oxygen storage, and (3) low-capital-cost, high-efficiency conversion of hydrogen to electricity. Because of the wide variation in peak electricity demand, the hydrogen-to-electricity capacity is many times that of the hydrogen production capacity.

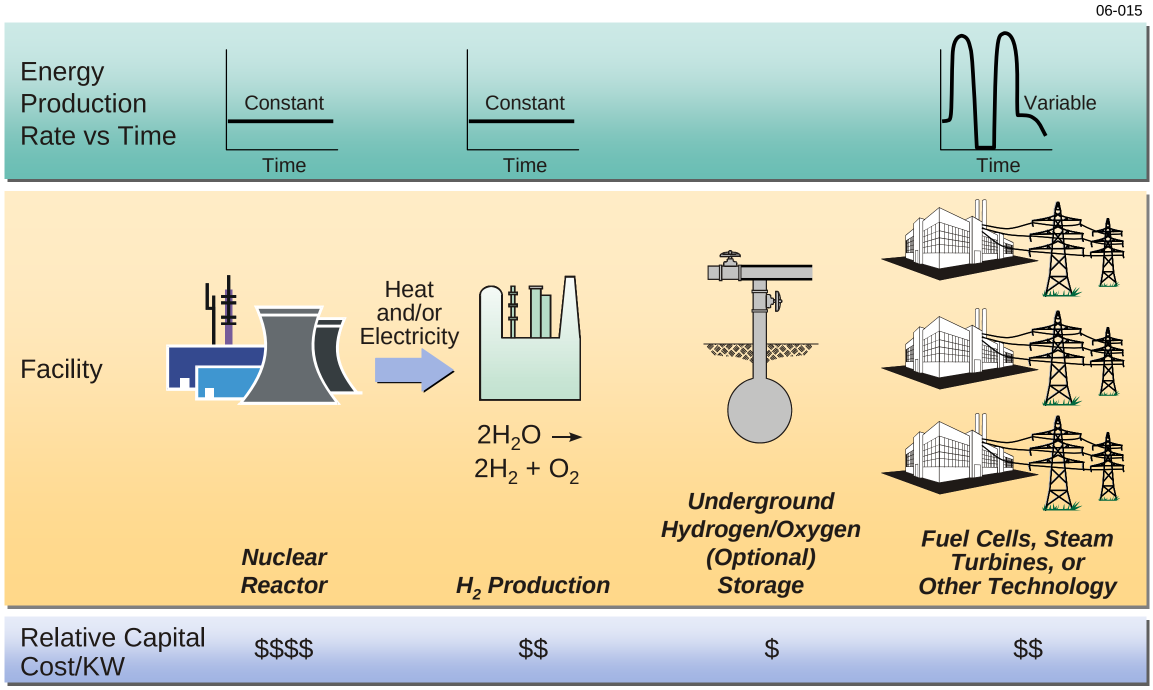

Fig. 3. Hydrogen Intermediate and Peak Electricity System with Hydrogen from a Nuclear Power Plant.

4.1 Peak Electricity Production

Because the design is driven by the electrical need, the hydrogen-to-electricity component is described first. There are several alternative technologies for conversion of hydrogen and oxygen to electricity at potentially higher efficiencies and lower capital costs than those available with traditional combined-cycle plants.

4.1.1 Steam Turbines

The traditional technology to convert heat to electricity is the steam turbine. Heat from burning fossil fuels, nuclear reactors, or solar sources first converts water to steam. To produce electricity, the steam is sent through a turbine that turns a generator. Historically, steam turbine peak temperatures have been limited to ~550°C because of corrosion in the boiler where the water is converted to steam. This restriction has limited the efficiency of converting heat to steam to ~40%. The most expensive component is the boiler, because it requires massive amounts of surface area to transfer heat from its source (burning fossil fuels, nuclear heat, or sunlight).

If a low-cost source of hydrogen and oxygen is available, an alternative to the process exists. Hydrogen, oxygen, and water are fed directly to a burner to produce high-pressure, very high temperature steam. The combustion temperature of a pure hydrogen−oxygen flame is far beyond that for current materials of construction. Thus, water is added to lower the peak temperature. The technology is that of a low-performance rocket engine. The resultant steam is directly fed to a very high temperature turbine that drives an electric generator. Modern gas turbines with actively cooled blades are capable of operating at temperatures approaching 1500°C. The same technology should allow steam turbines with similar peak temperatures. The projected heat-to-electricity efficiency at these temperatures is ~70%.

This type of plant has the potential for significantly lower capital costs than the natural-gas combined-cycle plants [$570/kW(e)] discussed earlier. The high-temperature turbine remains, but the need to compress air as an oxidizer is eliminated. Equally important, the boiler in the combined-cycle plant is eliminated. These changes simultaneously increase efficiency (55 to 70%) and lower capital costs. This is a new option that is very early in its development and significant uncertainties remain.

4.1.2 Fuel Cells

Hydrogen can be converted to electricity using fuel cells. Five classes of fuel cells, each with particular characteristics, presently exist [9]. A preliminary assessment [8] based on near-term technologies indicates that the leading candidates for this application are alkaline and polymer fuel cells. These fuel cells have the best capabilities for rapid transient power operations, operate below 100ºC (avoid potential thermal fatigue of materials in high-temperature fuel cells), have potentially low costs, and have good performance with pure oxygen. Based on the existing knowledge, alkaline fuel cells appear to be superior for this application. However, polymer fuel cells are being developed for transport applications because of their small volume—an important characteristic for vehicles, but not for HIPES. The very large research programs for vehicle fuel cells may lower the costs of polymer fuel cells to make them the preferred option.

Alkaline fuel cells (Fig. 4) are one of the oldest fuel-cell technologies. A large experience base exists, and pure oxygen−hydrogen variants have been used for decades in the space program. The pure−oxygen alkaline fuel cells used in the space shuttle have an efficiency of ~60%. For large-scale industrial systems, the efficiencies may approach 70%, because there are no weight and size limitations. Recent reviews have summarized the status of this technology [9, 10].

Alkaline fuel cells have a five-layer structure: a gas chamber for hydrogen feed, an anode membrane, a liquid potassium hydroxide electrolyte, a cathode membrane, and a gas chamber for the oxygen feed. The overall chemical reactions are as follows:

Anode reaction	$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$
Cathode reaction	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Overall cell reaction	$2H_2 + O_2 \rightarrow 2H_2O$ + electricity + heat

The water is formed in the potassium hydroxide solution between the membranes. The potassium hydroxide solution is circulated to (1) improve transfer of hydroxide ions within the fuel cell and (2) remove any heat and excess water.

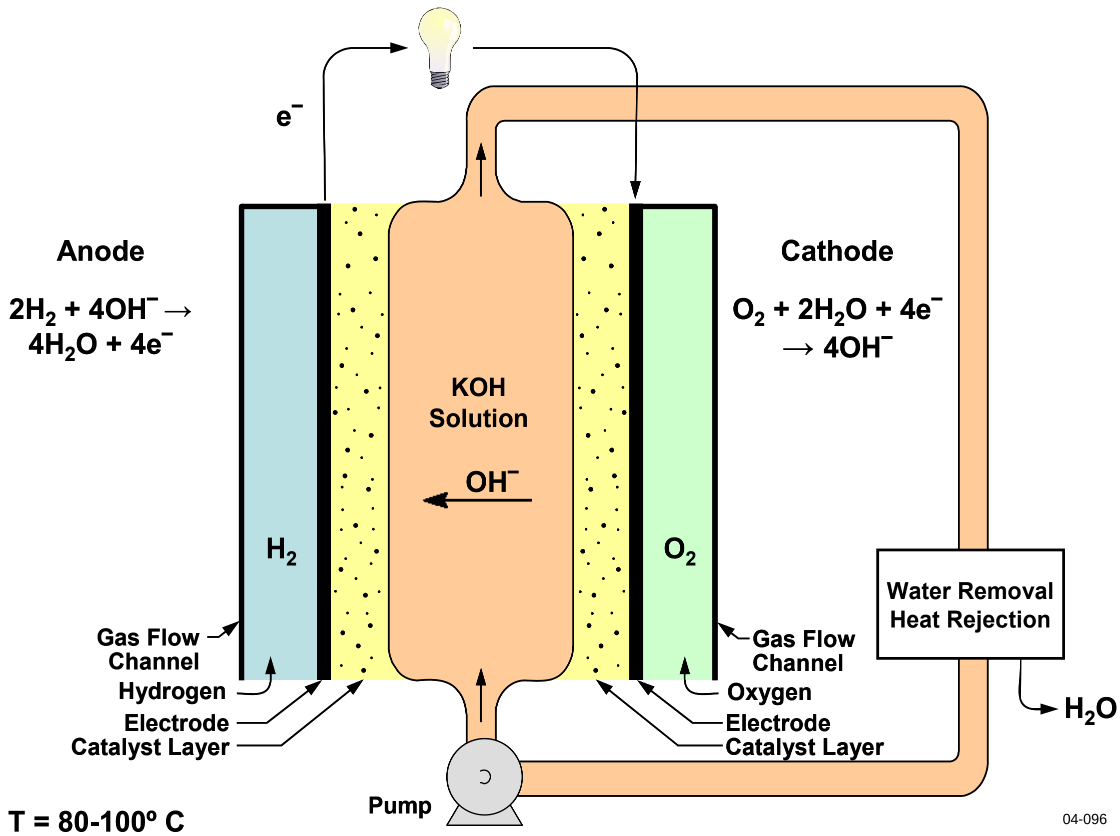

Fig. 4. Alkaline Fuel Cell.

Alkaline fuel cells have several advantages relative to other fuel-cell types: excellent performance using pure oxygen and hydrogen; no expensive materials such as platinum catalysts; scalability to large size; low-pressure, low-temperature operation; potentially low cost; and excellent capabilities for transient power operations [11]. Alkaline fuel cells have limitations for use in vehicles (low power density, the need for cleanup of the potassium hydroxide solution, and electrolytic poisoning of the fuel cell from carbon dioxide in air). However, these limitations do not apply to alkaline fuel cells within HIPES that are fed pure hydrogen and oxygen. For stationary applications, minimum cost per kilowatt electric and maximum efficiency, not size or weight, are the primary requirements. The processing of the hydroxide solution is a low-cost operation on a large scale. If HIPES uses pure oxygen, no carbon dioxide is present in the feed, a major constraint when using alkaline fuel cells with air as the oxidizer. Last, the space program provides a large base of experience in the use of these cells with hydrogen and oxygen.

From an industrial perspective, a large-scale alkaline-fuel-cell facility has striking similarities to chlorine production facilities. Chlorine is used for water treatment, is produced on a massive scale, and is one of the largest sectors of the chemical industry. In a chlorine production facility, electricity is used in electrolytic cells to convert a sodium chloride brine solution to chlorine and sodium hydroxide. The facility includes large electrolytic cells, gas-handling systems for toxic gases, alkaline solution (sodium hydroxide) processing systems with heat removal, and electrical power conversion systems. A large alkaline-fuel-cell facility has many similarities to the chlorine facility [electrolytic cells; hazardous gas (oxygen rather than chlorine); alkaline solution processing systems with heat removal; etc.]. These similarities and the extensive knowledge concerning performance with oxygen may enable early development of conceptual designs and relatively reliable cost estimates for a HIPES facility based on alkaline fuel cells.

Traditional fuel-cell applications produce kilowatts to a few megawatts of energy. The application herein is for hundreds or thousands of megawatts of power when oxygen feed is used. No studies of the costs of large-scale fuel-cell facilities have been undertaken. However, three economic factors have been identified that will alter the fuel-cell economics relative to other applications.

- *Oxygen feed*. Pure oxygen feed (rather than air) will increase cell output by several hundred percent [9] relative to air with major reductions in capital costs. Simultaneously, there is a significant improvement in efficiency. The size of the fuel-cell system is controlled by the oxygen electrode. Pure oxygen increases the gas phase oxygen concentration at this electrode a factor of 5 over that achieved via the use of air. This is a major advantage when using alkaline fuel cells, but the technique may not be applicable to all fuel cells. High power densities imply significant cooling loads. While such cooling loads are easy to manage with a fuel cell that has a flowing electrolyte, they are difficult to manage with fuel cells, such as proton exchange membrane (PEM) cells, with solid electrolytes.

- *Manufacturing economics*. A large fuel-cell complex allows efficiencies in the manufacture of specific components such as the fuel-cell stacks.

- *Economics of scale*. Large economics of scale are associated with buildings, electrical conversion equipment, and gas-handling systems (compressors, pipes, valves, etc.). In this specific case, some understanding of the potential economics of scale is obtained by examining large chlorine production facilities. The scaling factor [12] for chlorine plants has been estimated at 0.54; that is, increasing the size of the facility by a factor of 4 results in the capital cost of the larger facility being only 53% of that of the smaller facility per unit of capacity. Very large economics of scale exist in such a process.

4.2 Hydrogen and Oxygen Storage

While HIPES does not require oxygen storage, the preliminary assessment indicates strong economic incentives to store oxygen as well as hydrogen for steam turbines or fuel cells. Underground storage would also be used for the oxygen. Storage in geologies where there are no burnable materials (salt, granite, etc.) is a near-term option, while storage with materials that can react with oxygen is a longer-term option. Experience in the underground behavior of oxygen in geologies with burnable materials already exists, and experiments are being conducted using "oxygen fire flood" for the recovery of oil from depleted oil fields. In these experiments, oxygen is injected down a series of wells and the residual oil is ignited. The burning of the residual oil in the rock creates heat, pressure, and carbon dioxide. This combination is used to push the remaining oil from the porous rock to other wells some distance away to increase the ultimate recovery of oil. The approach would be expected to open up the reservoir for possible future use for storage of oxygen and hydrogen. This is an area of current research and clearly a longer-term underground storage option.

About 20% of air is oxygen; however, pure oxygen is hazardous and dangerous. Pure oxygen can cause spontaneous combustion of clothing and many other objects. If high-pressure oxygen is stored and released, it cools as it is depressurized. Consequently, if a large-scale accidental release of oxygen occurs, the oxygen can form a cold high-density ground-level plume that floats off-site. Consequently, if oxygen is to be stored in large quantities, safety is a major design requirement.

One method to avoid this safety hazard has been identified. If the oxygen is heated 20 to 40°C above ambient temperatures before storage, should a release occur, the oxygen will have a lower density than that of air. This allows any oxygen plume to rise and be diluted by air. Nuclear reactors produce large quantities of low-cost heat, which would be suitable for heating the oxygen for safe storage. Other methods to ensure safety may exist as well, and significant work will be required in this area.

In contrast hydrogen, which becomes warmer and lighter when depressurized, is a light gas that rises and rapidly disperses. There are significant operational safety challenges with hydrogen; however, a century of experience indicates that there is not an off-site risk to the public for reasonable-sized sites.

4.3 Hydrogen and Oxygen Production

HIPES places major constraints on the hydrogen and oxygen production technology. While hydrogen can be shipped by pipeline, pipeline shipment of oxygen is significantly more expensive and challenging because of associated safety concerns. Similarly, the storage of oxygen may require a significant heat input. These factors imply co-siting of hydrogen-oxygen production systems, storage systems, and electrical production systems and favor nuclear hydrogen production [13, 14] or centralized solar production technologies such as solar power towers [15].

4.4 HIPES Implications

If an economic method is developed to match nuclear and renewable electricity production with consumer electricity demand, a major economic constraint for large-scale use of nuclear and renewable electricity is removed. These are capital-intensive low-operating-cost technologies that can produce economic electricity if operated at full capacity but produce expensive electricity if operated at partial load or if backup power is required when they are not operating.

This is particularly important for renewable energy sources such as wind. Peak wind conditions do not always match peak electric demand. Furthermore, as observed in Europe, there have been short periods of low wind conditions over large areas. To assure reliable electricity either (1) the fraction of electricity from renewables must be limited to a small fraction of the total electric demand so the rest of the system can provide electricity when needed or (2) there must be backup electric power. For electric renewables to provide a major fraction of the total electricity demand, systems such as HIPES are required to match electricity production with demand. The primary economic requirement for HIPES is for low-capital-cost efficient methods to convert hydrogen to electricity because some of that equipment will only be used for limited periods of time each year.

5. Liquid Fuels and Biomass

The second energy system need is energy for transportation. The transportation system is dependent upon liquid fossil fuels (gasoline, diesel, and jet fuel) because of the high energy density that makes these fuels easy to store and transport. There are alternative hydrogen-transport futures [16]: the use of hydrogen to maximize liquid-fuel production per unit of feedstock (crude oil, tar sands, coal, or biomass), the production of liquid fuels from hydrogen and carbon dioxide extracted from the air, and the direct use of hydrogen.

The near-term transport fuel option without greenhouse impacts is the use of biomass to make liquid fuels [17]. Retaining the use of liquid fuels avoids the storage and transport challenges of alternative transport fuels. For example, biomass is used today to produce liquid fuels such as alcohol by fermentation. In this process, there are no greenhouse gas impacts if all the energy in the production process is from biomass, because the carbon dioxide used to make the biomass comes from the atmosphere.

However, there is insufficient biomass to meet the world's demand for liquid fuels. Current estimates [18] indicate that with plausible technology developments, biofuels could only supply about 30% of the global liquid fuels demand. A major part of the problem is that only a fraction of the carbon in the biomass and a fraction of the energy in the biomass become liquid fuel. For example, the conversion of corn to ethanol results in roughly one-third of the carbon from the original corn in the ethanol, one-third in the by-product animal feed, and one-third in the form of carbon dioxide released to the atmosphere from respiration of the yeast.

The biomass limitation can be greatly reduced if reliable hydrogen is available from bulk storage facilities when needed. The alternative liquid-biomass future is to consider biomass primarily as a source of carbon to make liquid fuels and only secondarily as an energy source [16].

Liquid fuels can be made from hydrogen and any carbon source (including biomass) by a modified Fisher-Tropsch synthesis process [19]. Fisher-Tropsch is the primary process used worldwide to convert coal, natural gas, wastes, and other materials to liquid fuels. In traditional systems, the Fisher-Tropsch process uses a fraction of the feedstock for the production of hydrogen. However, if an external source of hydrogen is available, the hydrogen can be used (1) as a feedstock to make the liquid fuels and (2) as an internal energy source to drive the process of producing the fuel. Relative to traditional ethanol production processes, this technique triples the liquid-fuel production per unit biomass by traditional processes because all of the carbon is in the final fuel.

The production of a liquid hydrocarbon fuel, rather than a partly oxidized fuel such as alcohol, further increases the fuel value. Biomass contains significant quantities of oxygen and can be thought of as a partially oxidized hydrocarbon. It is a complex mixture containing cellulose, lignins, and hemicellulose. In assessing fuel efficiencies, cellulose ($C_6H_{10}O_5$), the primary component, can be used to represent biomass as an energy source. The Fisher-Tropsch process produces hydrocarbon mixtures. Hexane (C_6H_{14}) can be used to represent hydrocarbons as an energy source. The energy value of hexane per mole is 50% greater than that of cellulose; thus, the production of a hydrocarbon fuel maximizes the energy value in the liquid fuel of each carbon atom collected by the biomass. Fisher-Tropsch is a commercial process; however, there are the longer term options of developing processes to directly hydrogenate biomass to liquid fuels. These processes have potentially lower costs and lower hydrogen demands.

The production of liquid fuels with hydrogen and biomass will produce several times more liquid fuel, measured in its energy value, than biomass-to-liquid-fuel systems where the biomass also provides all the energy for the conversion processes. The use of biomass as primarily a non greenhouse carbon source (not an energy source) for liquid-fuel production implies outside sources of hydrogen. However, biomass-to-liquid-fuel production systems such as the Fischer-Tropsch process [19] have relatively high capital costs. Hydrogen must be provided when needed for processing. Centralized monthly and seasonal storage is the enabling technology to provide the hydrogen when required for such processing.

6. Conclusions

The analysis, subject to much uncertainty, leads to the following conclusions

- *Fossil-fuel characteristics*. The relatively low costs of delivered energy today are a consequence of the characteristics of fossil fuels. Variable energy demand can be matched with energy production because (1) the costs of fossil-fuel storage are low and (2) the capital costs of the equipment to convert fossil fuels to heat, transportation, or electricity are relatively low.

- *High nuclear and renewable capital costs*. Nuclear and renewable energy sources have similar characteristics: they are capital intensive technologies with low operating costs. Such technologies can provide low-cost energy only if they operate at near their maximum outputs. The costs of energy from these sources are high if such facilities are operated at partial load. If nuclear and renewables are to become our primary energy sources, new technologies are needed to match energy production from these sources with energy demand.

- *Hydrogen storage*. Hydrogen as an energy storage medium can be used to match future energy demand with energy production. However, there is only one low-cost method for large-scale hydrogen storage on a weekly to seasonal basis: underground storage as compressed gas. This is the same technology used to store natural gas on a seasonal basis. Low-cost storage is possible only in very large centralized facilities with the locations of the facilities controlled by geology.

- *Hydrogen production roles*. Centralized hydrogen production, such as that possible via nuclear energy, is likely to be significantly more economic for filling bulk hydrogen storage facilities than dispersed renewable hydrogen sources. Hydrogen transport is a major cost barrier for using dispersed hydrogen sources to fill bulk storage facilities. Furthermore, geology determines where storage facilities can be sited. While nuclear energy systems can be sited almost anywhere, the siting of renewable energy systems depends upon the energy source.

- *Hydrogen intermediate and peak electricity system*. Bulk storage of hydrogen with storage of oxygen creates potentially low-cost systems to produce electricity to match peak demand with current production from other energy sources. If economic peak and intermediate electric production can be achieved via HIPES, it becomes the enabling technology for large-scale use of renewables for electric production, because HIPES eliminates the need for the existing fossil-energy backup energy supply systems to renewable energy sources.

- *Liquid-fuels production*. Bulk hydrogen storage is a necessary system component to maximize economic production of liquid fuels from biomass.

- *System uncertainties*. Relatively little work has been performed in the area of hydrogen systems, and hydrogen technologies are rapidly evolving. Consequently, significant uncertainties and significant research and development challenges remain.

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Biography

Dr. Charles Forsberg received his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. After working for Bechtel Corporation, he joined the staff of Oak Ridge National Laboratory, where he is presently a senior scientist. Dr. Forsberg is a fellow of the American Nuclear Society and was awarded the 2005 Robert E. Wilson Award by the American Institute of Chemical Engineers (AIChE) Nuclear Energy Division in recognition of his outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production. He served as the 2005 AIChE chair for hydrogen programs, has been awarded 10 patents, and has published over 200 papers. Dr. Forsberg has written extensively on hydrogen futures.