—CONFERENCE PLENARY PAPER—

Is Hydrogen the Future of Nuclear Energy?

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Is Hydrogen the Future of Nuclear Energy?

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The traditionally held belief is that the future of nuclear energy is for electricity production. However, another possible future exists: nuclear energy used primarily for the production of hydrogen. The hydrogen, in turn, would be used to meet our demands for transport fuels, materials such as steel and fertilizer, and peak-load electricity production. Such a future would follow from several factors: (1) the potential for low-cost daytime electricity from technologies such as solar photovoltaics, (2) concerns about climatic change that limit the use of fossil fuels, (3) the fundamental technological differences between hydrogen and electricity, and (4) the centralized characteristics of nuclear energy and hydrogen production systems that naturally couple these two technologies.

I. INTRODUCTION

The use of nuclear energy is based the assumption that its best use is for the production of electricity. In the long term, this may not be true. Instead, the best use of nuclear energy may be for the generation of hydrogen via electrolysis (low or high-temperature), hybrid cycles, or thermochemical cycles. This paper explores an alternative energy future based primarily upon the single assumption that low-cost renewable methods to produce electricity can be successfully developed. Such a future is based on the three defining characteristics of nuclear hydrogen: a large-scale centralized technology, the coproduction of hydrogen and oxygen, and a fuel that is not dependent on local availability.

II. ELECTRICITY: THE MARKET FOR SOLAR ENERGY?

The preferred technologies for electricity production, which change as new technologies are developed, are dependent upon societal requirements. A major wild card in our energy future is solar electricity production from solar cells, concentrating solar power, and other related technologies. For example, solar cells are currently too expensive for large-scale production of electricity; however, no fundamental reasons have been identified for why they should be intrinsically expensive. The material quantities required per unit of power output are very small. At one time technologies such as aluminum production, Brayton power cycles, and power electronics were expensive; however, new technologies drove down the costs. While only time will ultimately determine if photovoltaics and other solar electric systems will follow the same patterns, the trends are favorable.

Consider what happens if solar cells become inexpensive and can be deployed globally on roofs and similar locations. The power generated would be sufficient to meet our electrical energy demands in a partly decentralized electric generating system. Daytime electricity would become inexpensive. However, such a scenario has implications that extend beyond the daytime electricity market.

- *Lighting*. About 20% of our electricity demand is for lighting. Lighting technology is presently undergoing a technological revolution, with the development of high-efficiency light emitting diodes (LEDs) that drastically reduce power needs. One of the most rapidly growing markets for solar electricity is India. Solar cells are combined with batteries and the new LEDs that require very little electricity to produce light. This technology represents the start of a revolution to provide lights for millions of homes that presently have no lights and may impact the industrial world with replacement of street lights and much of the other lighting needs in the industrial world. In both cases, it is the cost of installed copper cable for grid-generated electricity that makes solar cells competitive for low-power lighting applications.

- *Heating and cooling*. Lower-cost night time electricity is used in Europe to provide heating. Small insulated boxes of inexpensive firebrick store large quantities of heat by raising the firebrick to high temperatures using electric resistance heaters. The heat is then removed via small fans that circulate air surrounding the firebrick and mix it with colder air. Relatively low-cost longer-term heat storage is possible with this technology and inexpensive solar electricity would expand its use. Inexpensive heat is equally good at operating absorption (chemical cycle) air conditioners in which heat ensures cooling.

The limitations of the technology are that solar radiation varies (1) geographically and (2) daily and seasonally, depending upon the weather. However, most of the world's population lives in latitudes with high solar radiation.

III. HYDROGEN: THE OTHER ENERGY MARKET

Today hydrogen is used to convert iron ore and other ores to metal, convert heavy crude oils into liquid fuels, and produce ammonia—our primary fertilizer. It is used on a smaller scale in many other applications. In a greenhouse-constrained world, hydrogen may become directly or indirectly the fuel for our transportation system, the basis of our metallurgical industries, and the preferred method for backup electricity production. Today hydrogen is produced primarily from natural gas and coal.

III.A. Liquid Fuels

Our transportation system is based on liquid fuels; however, these fossil fuels are increasingly expensive, come from politically unstable regions, and are a major source of greenhouse gases. There are major initiatives to replace oil with biomass-derived liquid fuels such as ethanol. The use of liquid fuels from biomass prevents increases in atmospheric carbon dioxide levels. Plants convert atmospheric air, water, and solar energy to biomass. The burning of biomass-derived liquid fuels returns the carbon to the air as carbon dioxide, a complete cycle that does not impact the carbon dioxide levels of the atmosphere.

It is projected that by 2030 up to 30% of the liquid fuels consumed in the United States could be made from biomass[1–2] with an ultimate production capability twice as large. Long-term studies[3] indicate that biofuels could provide about 30% of the global demand in an environmentally acceptable way without impacting food production. However, the resources of biomass are ultimately limited.

When biomass is converted into liquid fuels, only a fraction of the carbon becomes part of the liquid fuel. Much of the biomass is consumed (oxidized) as an energy source to convert the biomass to a fuel such as ethanol. For example, in the conversion of corn to ethanol (CH_3CH_2OH), about one-third of the original carbon is part of the ethanol product, another third is released as carbon dioxide (the respiration product of the yeast that made the ethanol), and the final fraction contains byproducts of the production process.

$$\text{Biomass} \rightarrow CH_3CH_2OH + CO_2\uparrow + \text{Residues}$$

There are other alternatives. If hydrogen and biomass are fed to the Fisher-Tropsch process, all of the carbon in the biomass can be converted to liquid fuels. Fisher-Tropsch is the classical process to convert fossil fuels such as coal and natural gas to liquid fuels such as diesel fuel. The energy value[4–5] of these liquid fuels is 3 to 4 times greater than that achieved by using biological processes to produce liquid fuels. Hydrogen is the energy source to run the Fisher-Tropsch process and is used to convert biomass (a mixture of compounds containing carbon, hydrogen, and oxygen) to a hydrocarbon fuel. As a secondary benefit, the option[6] produces gasoline, diesel fuel, and jet fuels—all of which are compatible with our current transport system.

$$\text{Biomass} + H_2 \rightarrow (CH_2)_n + H_2O$$

We may someday use hydrogen directly as a fuel; however, today the technology exists to convert biomass efficiently to liquid fuels such as diesel, jet fuel, and gasoline. However, large quantities of hydrogen are required to accomplish this objective.

III.B. Materials Production

The production of most of the materials (iron, cement, etc.) in our society can be summarized by the following equation.

$$\text{Oxidized Raw Material} + \text{Carbon (coal, oil, or natural gas)} \rightarrow \text{Partly Refined Material} + CO_2\uparrow$$

$$\text{Partly Refined Material} + \text{Added Processing} \rightarrow \text{Refined Material}$$

Carbon is the chemical reducing agent that converts the oxides that make up the earth's crust into metals and other useful materials. When coal is the reducing agent (such as when making iron), many of the impurities (such as sulfur) contaminate the end product. Secondary processes are then required for purification. The classic example is the production of steel, in which the blast furnace uses coal in the form of coke to produce pig iron—a form of iron that contains many of the impurities of coal. The pig iron must then be refined in a second process to produce the useful refined product: steel. For a variety of technological reasons, an increased number of these processes have become two-step processes in which hydrogen replaces carbon as the chemical reducing agent. Because the hydrogen can be purified, the contamination of the final product with fossil fuel impurities can be avoided. The classic example is the direct reduction of iron ore to iron—a newer process that now accounts for 4% of the world's iron production and is rapidly growing.

$$\text{Carbon (coal, oil, or natural gas)} + O_2 + H_2O \rightarrow H_2 + CO_2\uparrow$$

$$\text{Oxidized Raw Material} + H_2 \rightarrow \text{Refined Material} + H_2O$$

If restrictions are placed on the burning of carbon or if the cost of hydrogen decreases, the materials our society produces and those of which it is built will be made primarily via the use of hydrogen,[7] the other great chemical reducing agent that converts our natural world of oxides to the materials that man requires.

III.C. Peak Electricity

If solar energy meets a significant fraction of our electrical demand, there will be a massive demand for electricity at night and during cloudy weather. Hydrogen can be used to meet this highly variable electrical demand. Three hydrogen-to-electricity options exist.

- *Combined-cycle plants*. Hydrogen can be used as a replacement for natural gas in traditional heat-to-electricity technologies such as turbines. The current state-of-the-art commercial technology[8] 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).

- *Fuel cells*. In the longer term, fuel cells that directly convert hydrogen to electricity have the potential for higher efficiency and potentially lower costs.

- *Hydrogen Intermediate and Peak Electricity System (HIPES).* Unlike fossil hydrogen production methods, nonfossil hydrogen production methods convert water to hydrogen and oxygen. The hydrogen and oxygen may be used to produce intermediate and peak electricity at potentially much lower capital costs and significantly higher efficiencies[9–10] than burning hydrogen in combined-cycle plants. This new technology option is being explored but has not yet been demonstrated.

HIPES consists of three major components (Fig. 1).

- *Hydrogen production*. Hydrogen is produced from water, with the by-product production of oxygen. The hydrogen and oxygen can be produced by (1) dedicated nuclear plants or (2) use of electricity at times of low electrical demand.

- *Hydrogen and oxygen storage*. Underground storage facilities are used for the low-cost storage of hydrogen and oxygen on a daily, weekly, or seasonal basis.

- *Hydrogen-to-electricity conversion*. Fuel cells, steam turbines, or other technologies are used to convert the hydrogen and oxygen to electricity. The use of the oxygen with the hydrogen distinguishes this technology from other methods used to produce peak electric power.

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

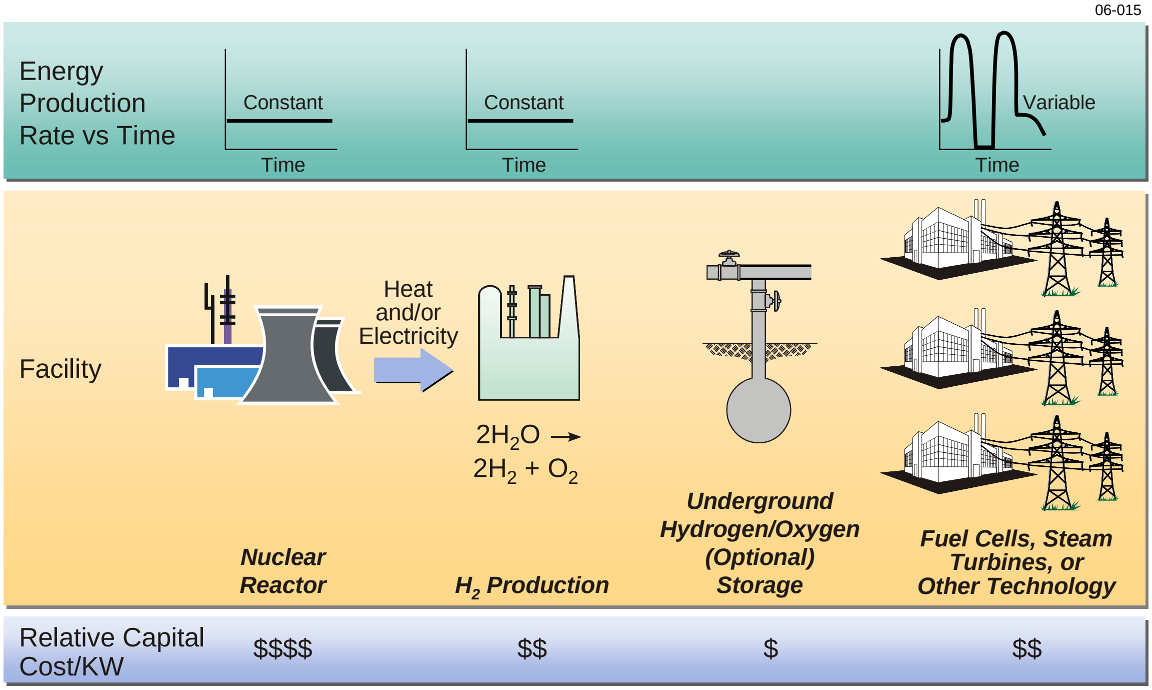

Fig. 1. Hydrogen Intermediate and Peak Electrical System.

Because the system design is driven by the peak electrical need, the hydrogen-to-electricity component is described first. Two technologies (fuel cells and steam turbines) have been identified for conversion of hydrogen and oxygen to electricity at higher efficiencies and lower capital costs than those available with traditional combined-cycle plants.

The traditional technology to convert heat to electricity is the steam turbine. Heat from burning fossil fuels, nuclear reactors, or solar sources 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 the process 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 hydrogen and oxygen are available, an alternative steam cycle (Fig. 2) exists.[10–11] Hydrogen, oxygen, and water are fed directly to a burner to produce high-pressure, very high temperature steam. Because the combustion temperature of a pure hydrogen–oxygen flame is far beyond that acceptable for current materials of construction, water is added to lower the peak temperatures. The technology is that of a low-performance rocket engine. The resultant steam is fed directly to a very high temperature turbine that drives an electric generator. Through the use of advancing gas turbine technology with actively cooled blades, it is expected that peak steam temperatures at the inlet of the first turbines will approach 1500°C. The projected heat-to-electricity efficiency for advanced turbines approaches ~70%.

The technology is based on ongoing development of an advanced natural-gas electric plant that uses oxygen rather than air.[12] Figure 3 shows the test burner that replaces a steam boiler. Combustors with outputs of ~20 MW(t) are being tested. With a natural gas and oxygen feed, a mixture of steam and carbon dioxide is created. In the condenser, the steam is condensed and the carbon dioxide is available for (1) injection into oil fields to increase the recovery of oil and/or (2) for sequestration. The higher heat-to-electricity efficiency and the production of a clean carbon dioxide gas stream for long-term sequestration of the carbon dioxide greenhouse gases create strong incentives to develop the technology for burning of fossil fuels.

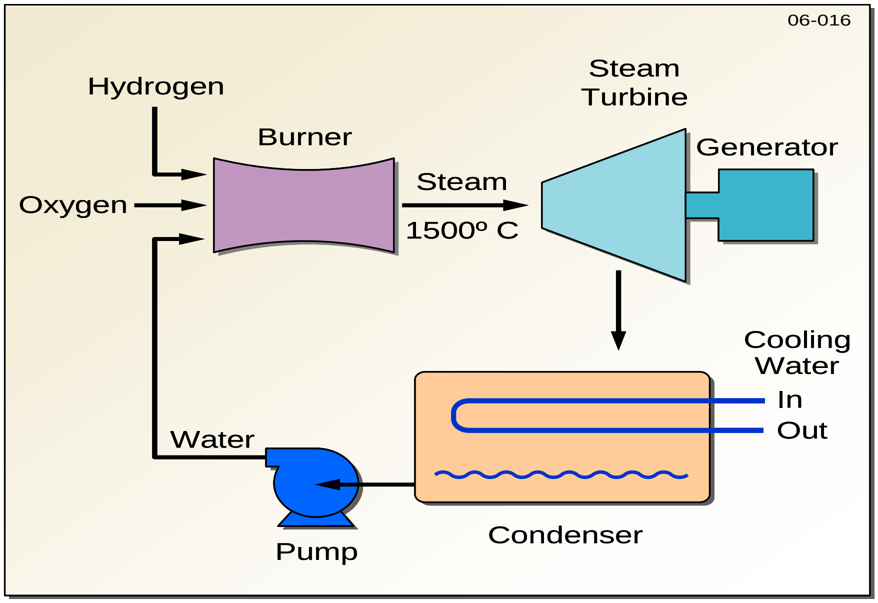

Fig. 2. Oxygen-hydrogen-water steam cycle.

Fig. 3. Fuel-oxygen combustor (Courtesy of Clean Energy Systems).

HIPES has potentially lower capital costs than the hydrogen-fueled combined-cycle plants [$570/kW(e)], as previously discussed earlier.[13] The high-temperature turbine remains, but the need to compress air as an oxidizer is eliminated. The massive gas flow of nitrogen (80% of air) through the system is eliminated. Equally important, the expensive high-surface-area boiler in the combined-cycle plant is eliminated and replaced by a small burner. These changes simultaneously increase efficiency (55 to 70%) and the lower capital costs. This is a new option in a very early stage of development, and significant uncertainties remain.

III.D. Distributed Power Production

Hydrogen enables the use of a wide variety of distributed power systems (such as fuel cells) for electricity and heat production. Existing systems use fossil fuels; however, if restrictions are imposed on the atmospheric concentration of carbon dioxide to reduce long-term greenhouse impacts, such options are no longer viable.

IV. CHARACTERISTICS OF HYDROGEN AND ELECTRICITY

Hydrogen is fundamentally different from electricity as an energy carrier. Electricity is the movement of electrons. On either a small or large scale, electricity can be transported efficiently at relatively low costs via transformers, power electronics, and transmission lines. The electrical distribution system is a two-way system in which electricity can move both directions through transformers. Electricity is produced by different primary energy sources (fossil fuels, hydro, nuclear, renewables) at different scales and roughly equivalent costs. It is consumed in devices with energy demands that vary from milliwatts to megawatts. In contrast, hydrogen as an energy source requires the transport and use of atoms. That difference has major implications.

- *Production economics*. The cost of hydrogen production and gas compression is strongly dependent on the scale of operations. The massive economics of scale reflect fundamental technological factors. Whereas small efficient transformers exist to increase the voltage (pressure) of electricity, no one has successfully built small and efficient hydrogen compressors. In most hydrogen production processes, the economics favor high pressure, a characteristic that favors large equipment. The safety and instrumentation requirements are nearly scale independent. In the context of solar hydrogen production systems similar to photovoltaic cells, there are fundamental challenges. With photovoltaics, it is easy to insulate electrical systems and easy to detect leaks (short circuits). In contrast, hydrogen tends to diffuse through everything. Economically detecting and fixing hydrogen leaks is difficult. In hydrogen systems, the leakage losses, as a fraction of the production, are strongly dependent upon the external surface area to internal volume of the equipment.

- *Markets*. Unless it is directly used as a fuel, the largest markets for hydrogen are large industrial facilities that have large demands for hydrogen provided on a continuous basis.

- *Storage*. Unlike electricity, hydrogen can be stored inexpensively for days, weeks, or months in large underground facilities—much as those in which natural gas is stored today. Approximately 400 underground storage facilities store a third of a year's production of natural gas in the fall before the winter heating season. This is the enabling technology to match hydrogen production to demand. However, the required technology has massive economics of scale. Hydrogen storage on a small scale is 1 to 2 orders of magnitude more expensive than on a large scale. A limited number of such hydrogen storage facilities now exist in Europe and the United States. Equally important, measurements of the helium in different geologies from radioactive decay and the long-term existence of natural gas deposits provide evidence that many geologies have the low permeability required for hydrogen storage.

- *Transportation*. Although it is expensive to move hydrogen from distributed production sources to centralized low-cost storage facilities to meet the requirements for variable demand, it is relatively easy and economic to move hydrogen (like natural gas) from centralized facilities to distributed users down the pressure gradient. Economics and safety limit the distances oxygen can be transported.

- *Safety*. Although hydrogen can be used safely, the process is technologically much more demanding.

At the most fundamental level, hydrogen is a large-scale technology. Unlike electricity, it is not as user-friendly or economic on a small scale.

V. NUCLEAR ENERGY

Nuclear energy is a large-scale centralized source of energy that requires high levels of technological competence. Large economic incentives (the need for security, training, maintenance, etc.) favor siting multiple reactors in large nuclear parks. Many of the institutional challenges would be reduced if nuclear energy could be confined to such sites.

Nuclear energy is not intrinsically coupled to electricity production. However, with our current technologies, nuclear energy is an economic method to produce electricity relative to its competitors. Still, a natural technological alliance does not exist. Technological changes, such as the development of low-cost photovoltaic cells, may alter the relative economics.

In contrast, for fundamental technological reasons, the characteristics of nuclear energy and hydrogen systems match. The economics of both systems strongly favor large-scale centralized facilities. Large-scale hydrogen production, storage, and use require high levels of competence. Using nuclear energy to produce hydrogen is a natural partnership, regardless of whether the hydrogen is made by low-temperature electrolysis, high-temperature electrolysis, or thermochemical systems.

VI. CONCLUSIONS

Hydrogen production may be the future of nuclear energy. In such a future, we may see that solar energy systems meet a large fraction of our electricity demand.

The intrinsic characteristics of electricity enable this option. Nuclear energy would be used primarily for hydrogen production, which, in turn, is used to meet our demands for transport fuels, materials, and electricity production when the sun does not shine. The characteristics of nuclear energy that make it difficult to use (i.e., requirements for centralized facilities, implementation on a large scale, and high competent operators) are the characteristics that favor its coupling with the hydrogen economy.

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