Production of Hydrogen Using Nuclear Energy

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Annotation

One of the leading methods for the future production of hydrogen (H_2) is nuclear energy. The fundamental characteristics of nuclear energy offer several potential advantages for H_2 production: avoidance of the production of greenhouse gases, production of H_2 near the final market, economics-of-scale that match the need for H_2, and availability of large resources of uranium fuel. Several types of reactors are being considered for H_2 production, and several methods exist to produce H_2, including thermochemical cycles (heat plus water yields H_2 and oxygen) and high-temperature electrolysis (heat plus electricity plus water yields H_2 and oxygen). Ultimately H_2, not electricity, may be the primary application of nuclear energy. Hydrogen from nuclear energy may in fact become the enabling technology for a large-scale renewable-nuclear economy.

INTRODUCTION

The annual world consumption of H_2 is ~50 million tons [1], most of which is used for ammonia production (fertilizer) and conversion of heavier crude oils to clean liquid fuels. The rapid growth in demand is a result of decreased availability of light crude oils that do not require extra H_2 for conversion to gasoline, with a corresponding increased use of heavy crude oils that require massive amounts of H_2 for conversion to gasoline. If the cost goals for automotive fuel cells are reached, the transportation sector may ultimately be fueled by H_2. This implies a growth in H_2 consumption of one to two orders of magnitude over a period of several decades. Because of these changes, an examination of the use of nuclear energy to produce H_2 was undertaken. The use of nuclear energy for H_2 production raises three questions:

- Is nuclear energy compatible with H_2 production?
- How should H_2 be produced?
- Is H_2 the future of nuclear energy?

COMPATIBILITY OF NUCLEAR ENERGY WITH HYDROGEN PRODUCTION

Each energy technology [2] has a set of characteristics that determine what applications are potentially viable in terms of both technical feasibility and economics. For example, the characteristics of internal combustion engines (small size, high energy output per unit mass, etc.) make them suitable for automobiles. However, the high cost of liquid fuels makes such engines unsuitable for large-scale production of electricity. The viability of nuclear energy for H_2 production depends upon the match between the intrinsic characteristics of H_2 systems and nuclear energy systems. Four issues are examined: production scale, load factor, H_2 transmission, and pipeline infrastructure.

Experience has demonstrated that nuclear energy production in small units is not economically viable. If nuclear energy is to be used for economic H_2 production, the demand for H_2 must match the scale of H_2 production from a nuclear reactor. Current "world-class" H_2 plants [3] have production capacities of 5.7 million standard cubic meters per day. A new plant has been recently announced with a capacity of 8.5 million standard cubic meters per day (1200 MW of hydrogen energy based on the higher heating value). These plants use steam reforming of natural gas to produce H_2. A 2400-MW(t) reactor would be required to produce 8.5 million standard cubic meters of H_2 per day. Thus in terms of energy flow, the size of today's H_2 production plant is now equivalent to that of a nuclear power plant.

Nuclear power plants are characterized by high capital costs and low operating costs. Good economics are dependent upon maintaining base-load operations with continuous output. The characteristics of the H_2 system decouple production from consumption [4]. Hydrogen is currently transported by pipeline and stored in large underground caverns, similar to natural gas. This is a low-cost storage method that, unlike the production of electricity, allows the power plant to produce H_2 at full capacity without the need for variable production. Thus, for H_2, production characteristics versus time are compatible with nuclear energy.

Nuclear power plant sites are rare and expensive. The need for security, the advantages of using common facilities, and other factors encourage siting multiple reactors at each site. A large electrical transmission line carries about 2 GW. Large H_2 pipelines, similar in size to the proposed

Alaskan natural gas pipeline, would carry more than 20 GW. Transmission of large quantities of energy in the form of H_2 in a few pipelines to urban areas is simpler than construction of large numbers of power lines. Hydrogen production is intrinsically more suitable than electricity for siting large numbers of reactors at a limited number of large sites.

The economic viability of any energy system depends upon the delivered cost of energy, which includes the costs of production, storage, and transportation. If one H_2 system has significantly higher costs for transport or storage than another system, such factors can determine the preferred method of H_2 production. The average long-term transport costs of H_2 produced using nuclear energy will be lower than those for H_2 produced from natural gas and many other energy sources. Nuclear power stations are typically located a hundred kilometers from large urban areas, which defines the necessary distance for H_2 transport. Natural gas deposits are typically several thousand kilometers from large markets. While most other energy sources require the long-distance transport of H_2, the lower transport costs of H_2 from nuclear energy provide an economic advantage.

HYDROGEN PRODUCTION

Hydrogen Production Methods

Several methods have been proposed to produce H_2 from nuclear power. Electrolysis of water [4] is an established technology that is used to produce H_2 in small quantities at dispersed sites. It is not currently competitive for the large-scale production of H_2, except where low-cost electricity is available. Although the conversion of electricity to H_2 by electrolysis is an efficient process (80% efficiency), the efficiency of converting heat (nuclear, fossil, geothermal, etc.) to electricity is typically between 30 and 50%. Consequently, the total conversion efficiency of this two-step process from heat to electricity to H_2 is low, between 24 and 40%. In many industrialized countries, the peak electrical demand is twice the minimum demand. If the off-peak electricity is produced by a source of energy with low fuel costs (such as nuclear), electrolysis may be viable for H_2 production. Otherwise, the H_2 production costs will be high.

Electrolysis [5] can be performed at high temperatures (700 to 900°C) to replace some of the electrical input with thermal energy. Because heat is less costly than electricity, the H_2 costs via this production method could ultimately be lower than those for traditional electrolysis. Equally important, the high temperature results in better chemical kinetics within the electrolyzer that reduces (1) equipment size and (2) inefficiencies. However, this high-temperature technology is in an early state of development. Hot electrolysis requires collocation of H_2 production with the nuclear reactor to provide the heat.

Hydrogen can be produced by direct thermochemical processes [6, 7] in which the net reaction is heat plus water yields H_2 and oxygen. These are the leading long-term options for production of H_2 using nuclear energy. For low production costs, however, high temperatures (>750°C) are required to ensure rapid chemical kinetics (i.e., small plant size with low capital costs) and high efficiency in converting heat to H_2.

Many types of thermochemical processes for H_2 production exist. The sulfuric acid processes (hybrid-sulfur, iodine-sulfur, etc.) are currently the leading candidates. In the sulfuric acid processes, the high-temperature endothermic (heat-absorbing) reaction is the thermal decomposition of sulfuric acid to produce oxygen:

$$H_2SO_4 \; 6 \; H_2O + SO_2 + ½O_2 \; (850EC) \; . \qquad (1)$$

After oxygen separation, additional chemical reactions are required to produce H_2. The leading candidate for thermochemical H_2 generation is the iodine-sulfur process, which has two additional chemical reactions:

$$I_2 + SO_2 + 2H_2O \; 6 \; 2HI + H_2SO_4 \; (120EC) \; , \qquad (2)$$

and the H_2-producing step,

$$2HI \; 6 \; H_2 + I_2 \; (450EC) \; . \qquad (3)$$

In addition to the pure thermochemical cycles there are hybrid cycles that include one or more thermochemical steps and a low-power (low-voltage) electrolysis step. The leading candidate is the hybrid-sulfur process [7], which has the same high temperature step (Equation 1) and a different low-temperature step.

$$SO_2 \text{ (aq)} + 2H_2O \; 6 \; H_2SO_4 \text{ (aq)} + H_2 \text{ (g)} \;\; \text{(Electrolysis: 80EC)} \; , \qquad (4)$$

Of the advanced methods for H_2 generation using nuclear power, thermochemical cycles (pure and hybrid) have received the most attention because cost estimates [7] indicate that thermochemical H_2 production costs are ~70% those from room-temperature electrolysis. These estimates assume the use of near-term current technology; however, there is the potential for major improvements in thermochemical cycles. In contrast, only limited potential exists for improving the efficiency of water electrolysis. The estimated lower costs of thermochemical H_2 production reflect the additional expense in electrolysis of converting thermal energy to electricity and then to chemical energy (H_2) rather than converting thermal energy directly to chemical energy (H_2). Overall thermochemical cycle efficiencies (H_2 energy/heat input) have been projected to be >50% with combined-cycle (H_2 and electricity) plants with higher efficiencies. Significant technical development will be required to develop this technology.

Requirements

The system and process requirements for H_2 production define the requirements for the nuclear reactor. Reactor power levels should be several thousand megawatts to match the economics-of-scale of existing H_2 production plants. All the low-cost methods for H_2 production require high temperatures (750 to 900°C). Furthermore, the nuclear and chemical facilities should be isolated from each other so that upsets in one facility do not impact the other.

Nuclear Reactor Options for Hydrogen Production

Five reactors meet the minimum requirement for production of H_2

- *Very-High-Temperature Reactor (VHTR).* The VHTR [8] is a higher-temperature version of the high-temperature gas-cooled reactor (HTGR). The solid fuel consists of microspheres of uranium oxide or carbide with multiple refractory coatings that retain fission products. The microspheres are embedded in a graphite matrix fuel element. High-pressure helium, the reactor coolant, is used to transfer heat from the reactor core to the H_2 production facility. The energy output is limited to ~600 MW(t)—the largest size compatible with its passive safety systems. Japan recently started operation of a small VHTR [30 MW(t)] to develop the technology for efficient production of H_2 and electricity.

- *Advanced High-Temperature Reactor (AHTR).* The AHTR [9] uses the same fuel as the VHTR but a different coolant. The AHTR coolant is clean molten salt with a boiling point of 1400EC. The liquid coolant improves heat transfer and thus reduces the temperature drops between the hottest fuel in the reactor and the chemical plant, thus lowering the required peak temperatures compared with those of the VHTR. The low-pressure coolant improves the efficiency of passive decay heat cooling systems and may thus allow construction of reactors as large as 2400 MW(t) with passive safety systems. This is a new reactor concept that is a joint effort of Oak Ridge National Laboratory, Sandia National Laboratories, and the University of California at Berkeley—all located in the United States of America. Because it is a relatively new concept, work is at an earlier stage of development.

- *Molten Salt Reactor (MSR).* The MSR [8] uses a liquid molten-fluoride salt as fuel and coolant with the uranium or plutonium fuel dissolved in the molten salt. Two test reactors were built.

- *Lead-Cooled Fast Reactor (LFR).* The LFR [8] uses a solid metal or nitride fuel with metal cladding and molten lead (or a lead alloy) as the reactor coolant to transfer heat from the reactor core to the H_2 production facility. The technology was originally developed by Russia.

- *Gas-Cooled Fast Reactor (GFR).* The GFR [8] uses an advanced fuel (several options being investigated) and high-pressure helium as the coolant. It couples the helium coolant technology of the HTGR and the VHTR with the fast-neutron reactor technology originally developed for sodium-cooled fast reactors and LFRs.

The leading contenders [10] for H_2 production in the next several decades are the VHTR and the AHTR. Both reactors use the same proven nuclear fuel. The VHTR technology is further developed, with a small operating reactor in Japan, while the AHTR is in an earlier stage of development. The larger size of the AHTR may ultimately result in capital costs that are significantly lower per megawatt (thermal) than those of the VHTR.

The development times needed to build the LFR and GFR are much longer, and more resources are required. Both of these reactors require the development of (1) new high-temperature fuels and (2) closed fuel cycles in which the nuclear fuel is processed for recovery of fissile materials. Although there has been significant development of the LFR and GFR for electricity production, H_2 production requires significantly higher temperatures and thus new fuels and materials are required for these reactors.

NUCLEAR–RENEWABLES HYDROGEN FUTURES

The characteristics of nuclear energy match those required for large-scale H_2 production. However, the more distant and speculative question remains: What is the impact if the challenges of producing H_2 from nuclear power are overcome? The preliminary evidence suggests a world in which renewable (solar and wind) and nuclear energy sources are coupled—a future based on the intrinsic characteristics of nuclear energy, renewable energy, and H_2.

The Great Energy Mismatch: Generation Versus Use

The demand for electricity and other forms of energy varies by a factor of two 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 demand has been to store energy in the form of fossil fuels: coal in piles, liquid fuels in tanks, and natural gas in underground caverns.

If we look beyond fossil fuels, the mismatch between energy demand 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 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 energy output in a year divided by the energy output if the device operated at full capacity for the total year.) The capacity factor for wind is about 35%. For renewable energy sources, the mismatch between generation and demand is so large for renewable energy sources that it has been estimated that if as little as 15% of the electricity were produced by solar or wind, there would be no economic incentive for more energy from such sources, even if they are free. This is because backup power production facilities must be built to meet demand when solar energy is not available.

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. However, the cost of energy becomes prohibitive if such technologies are not operated at near full capacity, because of a fundamental difference between devices that create high-quality energy (electricity and H_2) and devices that convert and use high-quality energy. Methods to produce electricity have capital costs of hundreds to thousands of dollars per kilowatt. Devices that convert high-quality energy into services (motors, heaters, etc.) have costs of a few tens of dollars per kilowatt. Although society can afford cars, heaters, and motors that operate only a few hundred hours per year, society cannot afford energy production devices that operate a limited number of hours per year.

Complementary Characteristics of Nuclear Energy and Renewables

The mismatch between energy generation and use in a post-fossil-fuel world can be bridged using H_2 to store energy. The development of fuel cells potentially offers an efficient way to convert H_2 to electricity to meet variable electricity demand. However, H_2 storage imposes its own requirements. The only demonstrated low-cost method of H_2 storage is in large underground caverns. For a variety of reasons, it is unlikely that any other storage technology will approach the low cost of this bulk storage method. Other methods of storage are expensive. Storage of H_2 as a liquid implies using a quarter of the energy to liquefy the H_2. High-pressure tanks and various other storage media have storage costs an order-of-magnitude greater than underground caverns.

Based on economic considerations, the requirements of H_2 storage favor the use of nuclear energy for H_2 production with renewable energy for heat and electricity—assuming that the technology is successfully developed.

- *Storage volumes.* The quantities of H_2 to be stored are strongly dependent upon the source of the H_2. Nuclear power plants operate on a continuous basis. They must be shut down for maintenance and refueling but the time for these operations can be selected to match the times of year with lower energy demand. This capability to vary production with demand significantly reduces the H_2 storage requirements. Renewable (solar and wind) energy production changes with the seasons. Unless seasonal energy demand matches seasonal energy production, much larger storage facilities for H_2 are required or much larger energy production systems must be built. Seasonal changes in energy demand provide an economic incentive for H_2 from nuclear energy.

- *Technology*. If underground storage of H_2 on a massive scale is required, H_2 production must match the requirements of large-scale H_2 storage: high-pressure high-volume H_2 delivery to large storage facilities. Large-scale nuclear H_2 production matches storage requirements. In systems that produce H_2 from distributed sources, moving gases from distributed production sources to a high-pressure, high-volume pipeline system and storage is more difficult. Pipelines transmit H_2 and any impurities fed to the system. Complex

> 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 strongly depend upon scale. While small systems can be developed to produce H_2 at high pressure, the safety requirements will impose a heavy burden on such facilities. High-pressure H_2 can be handled economically on a large scale, but is expensive to handle on a small scale. This combination of factors implies that a decentralized, small-scale method to produce H_2 must have much lower production costs to be competitive with large-scale methods of H_2 production.

Conversely, the availability of economic H_2 and the associated storage systems would eliminate the energy storage challenge for renewables, *which represents the greatest long-term economic barrier to their use*. Wind or solar cells would become economic wherever their production cost is the cost of electricity, not the cost of electricity and energy storage. Without storage requirements, the potential exists for a significant fraction of electricity and the total energy market to be economically provided by renewable energy sources. Hydrogen from nuclear energy (with associated large-scale underground storage facilities) becomes the enabling technology for the expansion of both nuclear and renewable sources of energy with the nuclear power plant maintenance and refueling times chosen to minimize storage requirements.

CONCLUSIONS

Production of H_2 on the scale required for a H_2 economy is a massive challenge. The intrinsic characteristics of nuclear energy are well matched to this mission. Hydrogen may ultimately be the primary product of nuclear energy. Hydrogen from nuclear energy coupled with underground storage of H_2 may become the enabling technology for large scale use of renewable energy sources by providing the storable form of energy required to match variable energy demands to the variable energy production of renewables. The challenge is to develop the required technologies.

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