Relative Economic Incentives for Hydrogen from Nuclear, Renewable, and Fossil Energy Sources

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Abstract

The specific hydrogen market determines the value of hydrogen from different sources. Each hydrogen production technology has its own distinct characteristics. For example, steam reforming of natural gas produces only hydrogen. In contrast, nuclear and solar hydrogen production facilities produce hydrogen together with oxygen as a by-product or co-product. For a user who needs both oxygen and hydrogen, the value of hydrogen from nuclear and solar plants is higher than that from a fossil plant because “free” oxygen is produced as a by-product. Six factors that impact the relative economics of fossil, nuclear, and solar hydrogen production to the customer are identified: oxygen by-product, avoidance of carbon dioxide emissions, hydrogen transport costs, storage costs, availability of low-cost heat, and institutional factors. These factors imply that different hydrogen production technologies will be competitive in different markets and that the first markets for nuclear and solar hydrogen will be those markets in which they have a unique competitive advantage. These secondary economic factors are described and quantified in terms of dollars per kilogram of hydrogen.

1. Introduction

Different methods of hydrogen production have different characteristics. Table 1 shows the characteristics of hydrogen produced by nuclear energy, steam reforming of coal, and decentralized solar energy. The economically preferred choice depends upon what the customer requires. There are several important characteristics.

- *Hydrogen*. If this is the only customer requirement, the economic comparison is based on dollars per kilogram of hydrogen.

- *Oxygen*. If the customer needs oxygen, the oxygen is a “free” by-product of nuclear and solar hydrogen production. For such customers, the cost of an oxygen plant must be added to the cost of hydrogen if the hydrogen is produced from fossil fuels.

- *Greenhouse gases*. If restrictions are imposed on release of greenhouse gases to the atmosphere, the customer (or indirectly through the producer) will add to the cost of hydrogen from fossil fuels the costs of disposing of the carbon dioxide or the taxes that will have to be paid.

- *Transportation*. Transportation costs for hydrogen strongly impact the relative costs of hydrogen from different sources. A customer who needs large quantities of hydrogen will add hydrogen transport costs to his centralized facility if the hydrogen is produced by dispersed renewable technologies. However, if the hydrogen is needed for decentralized applications, the cost of hydrogen transport will be added to that for centralized methods of hydrogen production.

- *Storage*. The only proven low-cost method of hydrogen storage is in large underground facilities. If hydrogen storage is required by the customer, the cost of transporting hydrogen to the storage facility will be added. This cost is high for decentralized methods of hydrogen production.

- *Heat.* If the customer needs heat, the cost of providing that heat will be considered. Nuclear systems provide low-cost heat relative to natural gas; thus, large users of hydrogen and heat have incentives to use nuclear-hydrogen production facilities and simultaneously buy low-cost heat.

- *Institutional*. Associated with every hydrogen production technology are specific institutional constraints that have economic implications.

Table 1. Characteristics of different methods of hydrogen production

Production Method	O_2	CO_2 Free	Large-Scale Use	Bulk Storage	Low-Cost Heat	Institutional
Nuclear	X	X	X	X	X	?
Steam Reforming of Coal			X	X		?
Decentralized Solar	X	X				?

Different markets have different requirements. Table 2 lists several major customers and some of their requirements. In this example, the *X*'s in the table indicate where a match exists between nuclear-hydrogen production characteristics and various markets.[1] Such tables provide a perspective on which markets are likely to be preferred for specific hydrogen production technologies. Similar tables can be constructed for any hydrogen production system to identify those markets where a specific hydrogen production technology will have a competitive advantage.

Table 2. Characteristics and value (*X*) of nuclear hydrogen relative to other methods of hydrogen production for specific applications

User	O_2	CO_2 Free	Large-Scale User	Bulk Storage	Low-Cost Heat	Institutional
Small Local User		X				
Pipeline		X	X			
Chemical/Iron Industries		X	X		X	
Refinery	?	X	X	?	X	
Liquid Fuels Production	X	X	X	?	X	
Peak Electric Production	X	X	X	X	X	X

These markets have different characteristics.

- *Pipelines.* In parts of the world there are hydrogen pipelines that deliver hydrogen to multiple customers from multiple producers. In many cases the pipeline owner is the broker and purchaser of the hydrogen. As these systems grow, they will develop the characteristics of the electrical grid. In these systems hydrogen is a commodity market.

- *Chemical/Iron industries*. Several types of chemical plants use massive quantities of hydrogen and could consume all of the hydrogen from a nuclear-hydrogen plant. These include the production of ammonia and the production of iron from iron ore. The characteristic of most of these markets is that there is a single customer with a single need: hydrogen. In such markets, centralized methods of hydrogen production are favored.

- *Refineries*. Refineries use massive quantities of hydrogen to remove sulfur from crude oil and convert heavy oils to liquid fuels such as gasoline, diesel, and jet fuel. The facilities also use massive quantities of heat and thus are simultaneously potential markets for high-temperature heat. Refineries use over 7% of the total energy demand of the United States and thus are a mega-market by themselves.

- *Liquid fuels production*. Plants using coal or biomass to produce liquid fuels require both hydrogen and oxygen.

- *Peak electric production*. This market requires hydrogen, oxygen, and heat. It is part of the same industry that produces base-load electricity from existing nuclear power plants; thus, it is a market where nuclear energy is accepted.

The following sections examine each of the characteristics that impact the relative value of hydrogen in specific markets.

2. Oxygen as a By-Product

Oxygen is a by-product of hydrogen production methods in which water is the feed input. This is the case for most nuclear and solar methods of hydrogen production. If there is a demand for oxygen, it becomes a second product for a hydrogen production plant. The cost of oxygen is a strong function of the price of electricity, because typical large cryogenic separation plants that separate oxygen from air consume ~230 kWh/ton O_2. At $0.04/kWh, the energy costs total $9.20/ton of oxygen.[2] For the analysis herein, it is assumed that oxygen costs $20/ton. On a mass basis, 8 times as much oxygen is produced as hydrogen. Consequently (assuming there is a demand), the value of the oxygen per kilogram of hydrogen produced is

$$(\$20/\text{ton } O_2)\ (\text{ton}/2000\text{ lb})\ (2.2\text{ lb/kg})\ (8\text{ kg } O_2/\text{kg } H_2) = \$0.176/\text{kg } H_2.$$

3. Avoidance of Carbon Dioxide Releases

Hydrogen today is produced primarily by steam reforming of fossil fuels, especially natural gas. The overall chemical reaction is

$$2H_2O + C \rightarrow 2H_2 + CO_2.$$

Concerns about global climate change may lead to taxes on the release of carbon dioxide to the atmosphere or to requirements for geological sequestration of carbon dioxide. A wide range of estimates have been proposed for possible future taxes on carbon dioxide releases to the atmosphere and the cost of carbon dioxide sequestration. Low-end estimates indicate taxes or sequestration costs of ~$25/ton of carbon dioxide.[3]

The implications of adding a carbon dioxide tax or disposal cost of $25/ton to the cost of hydrogen were calculated by assuming that carbon is used for hydrogen production and that the efficiency of converting carbon and water to hydrogen and carbon dioxide is about 60%. Typical coal-to-hydrogen plants have efficiencies near 60%.

Input assumptions:

- Free energy of formation of water: 54.63 kcal/gmol
- Free energy of formation of carbon dioxide: 94.26 kcal/gmol
- Energy efficiency in conversion of carbon to hydrogen: 60%

Energy release in the production of 1 ton of CO_2 from burning carbon is

$$(2000 \text{ lb } CO_2)\ (1000 \text{ g}/2.2 \text{ lb})\ (12 \text{ g C}/44 \text{ g } CO_2)\ (1 \text{ gmol C}/12 \text{ g C})\ (94.26 \text{ kcal/gmol C}) = 1.948 \times 10^6 \text{ kcal}$$

Energy in the form of hydrogen with 60% conversion efficiency from the production of one ton of CO_2 is

$$(1.948 \times 10^6 \text{ kcal})\ (0.6) = 1.169 \times 10^6 \text{ kcal}$$

Hydrogen produced from using carbon and releasing one ton of CO_2 to the atmosphere

$$(1.169 \times 10^6 \text{ kcal})\ (\text{gmol } H_2/54.63 \text{ kcal})\ (2 \text{ g } H_2/1 \text{ gmol})\ (\text{kg}/ 1000\text{g}) = 42.8 \text{ kg of } H_2$$

If there is a $25/ton disposal cost for carbon dioxide, the cost impact on hydrogen if the hydrogen is produced from carbon is

$$(\$25.00/\text{ton } CO_2)\ (1 \text{ ton } CO_2/42.8 \text{ kg } H_2) = \$0.58/\text{kg } H_2$$

Constraints on greenhouse gases can significantly alter the economics of hydrogen production from fossil fuels versus hydrogen production via other methods.

4. Hydrogen Transport

Hydrogen transportation by pipeline is expensive. Over any distance such transport can add $1.00/kg or more. If there are centralized users of hydrogen, strong incentives exist to use centralized production of hydrogen to meet those needs to avoid the transport costs. The exact benefit or cost is dependent upon the specific case.

A number of commercial hydrogen pipelines that service a number of chemical users are currently in operation in the United States. Their lengths range from less than a mile to several hundred miles. Refineries are the largest users of imported hydrogen, at about 50 million standard cubic feet per day (MMSCFD), while chemical plants typically use less than 10 MMSCFD (with the exception of those producing ammonia and methanol).

The cost[4] of hydrogen transport by pipelines of different sizes carrying different quantities of gas is shown in Table 3. The investment and operating cost of pipeline compressors is also shown. Hydrogen has the lowest possible molecular weight, so reciprocating compressors are needed regardless of the size of the pipeline.

Table 3. Cost of hydrogen transport by Pipeline[4]

H_2 Gas Capacity, MMSCFD	Line Size, In	Pipeline Investment, $M/100 miles	Compression Investment, $M/100 miles	Compression Power Cost, $/day	Pipeline cost/100 miles, $/MMBtu HHV
740	20	149,000	33,000	20,300	0.50
600	18	138,000	30,000	18,400	0.57
490	16	127,000	29,800	18,300	0.65
370	14	116,000	25,200	15,500	0.77
270	12	105,000	21,400	13,200	0.94
240	10	94,000	41,500	25,600	1.28
110	8	83,000	12,000	7,000	1.65
70	6	72,000	13,600	8,300	2.43
32	4	62,000	12,500	7,200	4.62

Specific constraints are associated with fossil and solar hydrogen production. Because of hydrogen transport costs, constraints on greenhouse gas releases may significantly alter the economics of hydrogen production from fossil fuels versus hydrogen production via other methods. Multiple projects are under way to develop methods to produce hydrogen from fossil fuels with underground sequestration of the carbon dioxide. However, only parts of the United States have geologies suitable for such sequestration. Hydrogen made from fossil fuels with carbon dioxide sequestration may have the lowest production costs in cases where fossil fuels and sequestration sites are located next to one another. Hydrogen made from fossil fuels with carbon sequestration will have higher delivered costs elsewhere because of the cost of transporting the hydrogen by pipeline.

Hydrogen from renewable energy sources faces similar geographical constraints. Unlike nuclear energy, the cost and availability of renewable energy sources are strongly dependent on location. Solar-based systems are most economic in the sunny southwest United States. Wind resources are most abundant on the upper Great Plains (North Dakota, Montana, South Dakota, Minnesota, etc.) and in coastal areas. There is a second factor: solar hydrogen systems are being developed for local hydrogen production and use. These small scale systems for small users are designed to avoid transport costs.

5. Hydrogen Storage

Only one technology[5] currently exists for low-cost storage of hydrogen—storage underground in caverns or geological reservoirs. This is the same technology used to store natural gas. In the United States, natural gas is moved by pipeline throughout the year to northern markets from production in the south-central United States. The natural gas is stored in ~400 large facilities, with a total capacity to store a third of a year's production of natural gas. Underground storage is a low-cost technology with market prices for storage typically 10% of the value of the natural gas.

Commercial hydrogen storage facilities using this technology have been built in the United States and Europe. For hydrogen, the capital costs for such facilities are estimated to be $0.80–$1.60/kg, which is lower than the production costs for hydrogen. The hydrogen storage technology has been used commercially in several geologies but not yet demonstrated in all the geologies that have been used for natural gas.

Storage economics demand large facilities. Two factors drive the facility size. First are siting and site development costs (including understanding the local geology) that are almost independent of facility capacity. Second, gas storage requires compression of the gases, typically to pressures of ~1000 psi for storage. Gas equipment efficiencies and costs are strong functions of the size of the equipment. The practical implications is that if bulk hydrogen storage is required by the customer, strong incentives exist for large-scale centralized hydrogen production to avoid hydrogen collection costs from decentralized hydrogen production units.

6. Low-Cost Heat

Many industrial applications of hydrogen also require heat. The cost of nuclear heat from nuclear plants is far less than heat from natural gas (typically $6–11/MMBTU) and, in much of the United States, less than heat from coal. If hydrogen is being produced and the hydrogen consumer is across the fence, heat can be sold. How the heat is delivered depends upon the required temperature. For temperatures below 600°C, the heat will most likely be delivered as steam because this is the standard proven industrial technology to transfer heat to industrial facilities. At higher temperatures, helium or liquid salts may be used to transfer heat.

The price of nuclear plant heat can be estimated from the price of electricity. A nuclear power plant produces steam that can be sold or used to produce electricity. The utility will demand at least the same revenue from the sale of steam as from the sale of electricity. A rough estimate of the price of steam can be calculated from the wholesale price of electricity. The price depends upon the temperature and pressure of the steam because more electricity can be made from high-temperature, high-pressure steam than from low-temperature, low-pressure steam.

An example can clarify this. Because the technology is well defined, the sale of steam from a light-water reactor will be used. Once the parameters of a high-temperature reactor are defined, similar calculations can be done. Consider the sale of 150-psi steam (~180°C) used for general heating and many industrial processes—including drying of many products and production of fuel ethanol. The price of electricity varies across the country; thus, this example uses the recent average market price for wholesale electricity in Minnesota, which is $53.89/MWh(e).

The efficiency of nuclear power plants is ~33%; that is, if one less BTU of electricity is produced, 3 BTU of steam becomes available. Although nuclear reactors produce high-temperature steam, in this example the heat is delivered as 150-psi steam. In converting high-temperature steam to electricity, 40% of the electricity is obtained by the time the steam pressure is 150 psi, with the remaining 60% of the electricity produced in the low-pressure turbines. Using this information, a rough estimate can be made of the corresponding price of steam from a nuclear plant, given the price of electricity:

$$\$53.89/\text{MWh(electricity)} \cdot 0.33 \cdot 0.6 = \$10.67/\text{MWh(steam)} = \$3.13/\text{MMBtu}.$$

This cost represents less than half the price of natural gas in the United States. Therefore, if a customer needs both hydrogen and heat, there is an incentive to obtain the hydrogen from a nuclear plant if, at the same time, the customer can obtain lower-cost heat to meet his energy needs.

7. Institutional

All industries have institutional structures that include regulation, organizational structures, international trade agreements, and accepted business practices for that industry. These structures have major impacts on the choice of hydrogen production technology. Two examples provide a perspective on the extremes of these institutional structures.

- *Peak electric power production.*[6] Assuming that the technology and economics are favorable, the institutional structure for using nuclear hydrogen for peak electrical power is highly favorable. Nuclear power plants are built to produce base-load electricity. The production of peak electricity is an extension of that business by organizations that understand nuclear energy, operate nuclear power plants, and sell electricity. In such cases, the producer of hydrogen is the user of hydrogen; thus, the market is not an issue. Furthermore, the market for peak power is local. What happens in the rest of the world has only limited impacts on local peak power demand.

- *Ammonia production.* The primary cost of ammonia production is the cost of hydrogen; thus, economics are dependent upon hydrogen production costs. However, ammonia is transported by ship around the world and, in the United States, by pipeline from Louisiana as far north as Minnesota. The price of ammonia is set on a global basis. New ammonia plants are built where there is low-cost natural gas that has no local market. Over a period of a decade, the lowest cost natural gas in the world can strongly impact the cost of ammonia everywhere in the world. Governments can push ammonia production and drive down world prices to encourage local development. This is an institutional structure that potentially makes it risky to invest in capital-intensive technologies such as nuclear hydrogen for ammonia production.

8. Conclusions

User requirements ultimately determine the preferred method of hydrogen production. Because user requirements vary widely, it is likely that different hydrogen production techniques will be economic for different users. This also implies that for any new hydrogen production technology, there are specific markets in which that technology is most likely to become competitive relative to other production techniques.

9. References

1. Forsberg, C.W., *Competitive-Advantage Markets for Hydrogen from Nuclear Energy: Peak Electric Power, Liquid Fuels from Coal and Biomass, and Refineries*, Oak Ridge National Laboratory (in press).

2. Alstrom Power Inc., *Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers: Phase I – A Preliminary Systems Evaluation: Final Report,* National Energy Technology Laboratory, May 15, 2003.

3. Massachusetts Institute of Technology, *The Future of Coal: Options for a Carbon-Constrained World*, Cambridge, Massachusetts, 2007.

4. Summers, W.A., "Interim Project Report, Task A.1, Nuclear Hydrogen Plant Definition," NERI Project 02-0160, *Centralized Hydrogen Production from Nuclear Power: Infrastructure Analysis and Test-Case Design Study*, WSRC-TR-2003-00484, Savannah River Technology Center, October 30, 2003.

5. Forsberg, C.W., "Is Hydrogen the Future of Nuclear Energy?" *International Topical Meeting on the Safety and Technology of Nuclear Hydrogen Production, Control, and Management*, American Nuclear Society, Boston, Massachusetts, June 24–28, 2007.

6. Forsberg, C.W., "Economics of Meeting Peak Electricity Demand Using Nuclear Hydrogen and Oxygen," *International Topical Meeting on the Safety and Technology of Nuclear Hydrogen Production, Control, and Management*, American Nuclear Society, Boston, Massachusetts, June 24–28, 2007.