Hydrogen: What Fuel Cell Vehicles and Advanced Nuclear Reactors Have in Common

by

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ABSTRACT

This thesis reports on two technology and policy issues directly related to hydrogen economy. The first issue concentrates on the end-use application of hydrogen as a transportation fuel, and deals with the following question: what is the place of hydrogen fuel cell vehicles among the new, more-efficient advanced vehicle technologies. Our analysis indicates that fuel cell vehicles using hydrogen from fossils fuels offer no significant energy efficiency advantage over hybrid vehicles in urban driving cycle. Therefore, there is a strong justification for federal support for hybrid vehicles that will achieve similar results, quicker. The second issue focuses on another important technology and policy question related to large scale hydrogen production: are there any comparative efficiency, cost and/or political advantages of using an advanced nuclear reactor coupled to a thermochemical conversion plant to produce hydrogen with respect using a conventional nuclear reactor coupled to an electrolysis plant? The results suggest that given the existing technical and cost uncertainties, developing an advanced nuclear reactor technology solely for the use of thermochemical hydrogen production is not good energy (R&D) policy. Electrolysis is a more promising alternative provided a more efficient electrolysis technology can be coupled to an advanced nuclear energy (i.e. electricity) source at a reasonable cost. Therefore, large R&D investment in thermochemical hydrogen production should be balanced with a similar R&D in large scale electrolysis technologies that are relatively easier to deploy and have lower engineering risks.

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Annem Ayşe and Babam Cevat Demirdöven'e

To My Mother Ayşe and My Father Cevat Demirdöven

The better the technology, the less efficient the human use of it.

—AUGUST FRUGÉ

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AE: Alkaline Electrolysis

AFC: Advanced Fuel Cell

ANL: Argonne National Laboratory

CAFE: Corporate Average Fuel Economy

DOE: Department of Energy

DOT: Department of Transportation

FC: Fuel Cell

FUDS: Federal Urban Driving Schedule

GM: General Motors

HHV: High Heating Value

HICE: Hybrid Internal Combustion Engine

HTE: High Temperature Electrolysis

ICE: Internal Combustion Engine

INEEL: Idaho National Engineering and Environmental Laboratory

LWR: Light Water Reactor

NAS: National Academy of Sciences

NERI: Nuclear Energy Research Initiative

NHI: Nuclear Hydrogen Initiative

NREL: National Renewable Energy Laboratory

O&M: Operation and Maintenance

PEM: Proton Exchange Membrane

PNGV: Partnership for a New Generation of Vehicles

SITC: Sulfur-Iodine Thermochemical Cycle

TTW: Tank-To-Wheel

VHTGR: Very High Temperature Gas Reactor

WTT: Well-To-Tank

WTW: Well-To-Wheel

Chapter 1

Hydrogen as a technology and policy issue

This thesis presents two technology and policy issues directly related to hydrogen economy. The first issue, which is developed in Chapter 2, concentrates on the end-use application of hydrogen as a transportation fuel, and deals with the following question: what is the place of hydrogen fuel cell vehicles among the new, more-efficient advanced vehicle technologies? Chapter 2 argues that fuel cell vehicles using hydrogen from fossils fuels offer no significant energy efficiency advantage over hybrid vehicles in urban driving cycle. Therefore, there is a strong justification for federal support for hybrid vehicles that will achieve similar results, quicker.

The second issue, described in Chapter 3, focuses on another important technology and policy question related to large scale hydrogen production: are there any comparative efficiency, cost and/or political advantages of using an advanced nuclear reactor coupled to a thermochemical conversion plant to produce hydrogen with respect using a conventional nuclear reactor coupled to an electrolysis plant? Our results say no. Within our efficiency and capital cost estimates, there is no significant production cost difference between the two options. Therefore, large R&D investment in this field is not balanced with a similar R&D in large scale electrolysis technologies that are relatively easier to deploy and have lower engineering risks. The policy efforts should aim to increase support for other technologically more promising alternatives.

1.1 Objective and motivation

Although the hydrogen economy has recently become popular, it is not a new concept. The technologies and economics of hydrogen production, transmission and end-use applications have been revisited occasionally as technology and public policymakers invested time, attention and money in hydrogen research and development.[1, 2, 3, 4, 5, 6, 7]

Despite increasing public and private support fueled with the Bush Administration's successful promotion, the future of hydrogen economy is not certain. There are a number of technological, economic and institutional barriers that obscure the vision of the hydrogen economy even in the long term. Transition to a hydrogen energy infrastructure requires the creation of a market that is competitive with other fuels and energy sources. Yet there is no consensus on how this could be achieved. Nevertheless, hydrogen remains a promising energy carrier. Along this cautious description of hydrogen's future as a fuel, the three principal purposes of this thesis are

(1) To provide a 'fair and reasonable' technology assessment of two technologies whose engineering and commercial success are closely linked to the future of hydrogen economy.

(2) To establish a sound basis for new technology policies especially regarding R&D strategy for, and investment in, new hydrogen technologies by the government and the industry through a balanced analysis.

(3) To demonstrate how simple technical and economic models can be developed and used to address complicated technology policy questions.

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[1] Dickson, E. M., Ryan, J. W., Smulyan, M. H. "*The Hydrogen Energy Economy : A Realistic Appraisal of Prospects and Impacts*" (New York: Praeger Publishers, 1977)

[2] Winter, J. C., Nitsch, J., eds. "*Hydrogen As An Energy Carrier: Technologies, Systems, Economy*" (Berlin: Springer-Verlag,1988)

[3] The National Academy of Sciences (NAS), "*The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*" (Washington, DC: National Academy Press, 2004).

[4] J. Rifkin, "*The Hydrogen Economy*" (New York: J.P. Tarcher & Putnam, 2002)

[5] V. V. Vaitheeswaran, "*Power to the People*" (New York: Farrar, Straus & Giroux, 2003), chap. 8.

[6] V. Smil, "*Energy at the Crossroads*" (Cambridge: The MIT Press, 2003), chap. 5.

[7] "Special Issue: Toward a Hydrogen Economy" *Science*, **305**(5686), 957-974 (2004)

1.2 Principles of assessment methodology

Objective and credible knowledge appraisal of technology questions that are closely linked to public policy choices are of increasing importance to the decision makers in government and industry. Such appraisal studies are usually done by independent third parties in academia, in non-profit research organizations with close relations with government agencies, in industrial trade organizations, and in non-profit advocacy groups. Therefore the motivation, the interests and the prestige of the third-party assessors play crucial roles in determining the effectiveness of such studies sometimes without due attention to the underlying methods and assumptions.[8, 9]

This thesis covers two important and equally controversial technology and policy questions concerning the future of hydrogen economy in the U.S.

Question 1. What is the place of hydrogen fuel cell vehicles among the new, more-efficient advanced vehicle technologies?

Question 2. Are there any comparative efficiency, cost and/or political advantages of using an advanced nuclear reactor coupled to a thermochemical conversion plant to produce hydrogen with respect using a conventional nuclear reactor coupled to an electrolysis plant?

Our methodology in answering these questions is three-fold:

Step 1. Start with a simple model describing the problem and identifying the major systems components and the links among them.

Step 2. Verify the results of the simple model by comparing the results from more advanced simulation models and other comprehensive studies on the same topic to test the model's robustness to basic assumptions and uncertainties.

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[8] S. Jasanoff, "Contested Boundaries in Policy Relevant Science," *Social Studies of Science*, **17**, 195 (1987)

[9] L. McCray, "Doing Believable Knowledge Assessment for Policy Making: How Six Organizations Go About It" (2003). 17.310 Science, Technology and Public Policy class notes (Prof Kenneth Oye, MIT Department of Political Science, Fall 2004-2005)

Step 3. Compare and contrast current policies and regulations dealing with the problem; evaluate the implications of the assessment results for these policies and regulations; and make recommendations as appropriate.

Steps followed in answering Question 1. As described above, the first question is concerned with the additional energy efficiency that hydrogen fuel cell vehicles will achieve compared to currently available gasoline-electric hybrid vehicles.

In Step 1 (Chapter 2, Section 2), we implement a simple model describing the energy flow in a passenger vehicle in urban driving. This model is borrowed from the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy. We then modify this model to calculate the energy requirement for gasoline-electric hybrid and advanced fuel cell vehicles. This involves the introduction of additional efficiency assumptions about engine (fuel cell) performance, idling losses and regenerative brake recovery. At this point, we use the estimates that reflect today's industry practices.

In step 2 (Chapter 2, Section 3), we use an advanced vehicle simulator, developed by the DOE's National Renewable Research Laboratory (NREL) to test the validity the results from Step 1 while keeping the input assumptions consistent with the simple model.

In step 3 (Chapter 2, Section 3), we compare our results with those of other prominent studies by MIT Laboratory for Energy and Environment[41, 42] and Argonne National Laboratories/General Motors.[40] We evaluate the point of disagreements and their potential sources. This evaluation is followed by a discussion of current policies and new remedies we suggest the U.S. Congress and Government consider (Chapter 2, Section 4).

Steps followed in answering Question 2. This question deals with comparative assessment of large-scale central hydrogen production technologies. Its specifically focus on the relative efficiency, cost and/or political advantages of advanced system consisting of a next-generation Very High Temperature Gas Reactor (VHTGR) and thermochemical conversion plant with respect a system that employs a Light Water

reactor (LWR) coupled to a large alkaline electrolysis plant. Analogous to Question #1, the first technology, the more advanced one, is not available today but enjoys strong support from the U.S. government since it requires large R&D and capital spending. The second technology, on the other hand, is currently available and can be deployed at a relatively reasonable capital cost and time frame. Although technical efficiency is still an integral part of our assessment, in Question 2 we concentrate on cost modeling.

In Step 1, (Chapter 3, Section 2 and Section 3), we describe the two central hydrogen production systems, and the efficiency and energy requirement of the systems' components. Next, we construct a simple cost estimation method, and lay out the reasoning behind our capital cost and technical efficiency assumptions. Then we use this cost method to perform sensitivity analysis as a function of capital cost and overall system efficiency to account for the technical and economic uncertainties.

In Step 2 (Chapter 3, Section 5), we undertake an in-depth review of other comprehensive studies that used similar methods to estimate the hydrogen production costs for thermochemical and/or electrolytic options. This step also involves benchmarking of our cost method using the cost and efficiency assumptions of other technology assessments. This in turn allows us to account for the differences among these studies in a self-consistent manner.

In Step 3 (Chapter 3, Section 6), we describe, and to some extent evaluate, the DOE's R&D plans toward a large scale hydrogen production. We point to the weak links in this R&D efforts, and emphasize the role of capital cost and efficiency assumptions in (mis)guiding the future R&D expenditures.

1.3 Findings

Question 1. What is the place of hydrogen fuel cell vehicles among the new, more-efficient advanced vehicle technologies?

Finding 1. We show that a tremendous increase in energy efficiency can be realized today by shifting to hybrid internal combustion engine vehicles - quite likely more than can be realized by a shift from hybrid ICE (HICE) to hybrid fuel cell vehicles. The results from the simple efficiency model are in reasonably good agreement with those of more detailed studies. Except for the Argonne National Laboratory/General Motors study, the relative gain in efficiency in moving from an ordinary ICE to a HICE is more than two fold.

Finding 2. Hybrid vehicles will only be adopted in significant quantities if the cost to the consumer is comparable to the conventional ICE alternative. Hybrid technology is here today, but, of course, hybrid vehicles cost more than equivalent ICE vehicles. Estimates of the cost differential vary, but a range of $1,000 to $2,000 is reasonable. Depending on the miles driven, the cost of ownership of a hybrid vehicle may be lower than a conventional ICE because the discounted value of the fuel saving is greater than the incremental capital cost for the parallel drive train and electric motor.

Finding 3. Thus, hybrid vehicles can contribute to lower emissions and less petroleum use at small or negative social cost.

Finding 4. Hybrid technology is available now, although it represents less than 1% of new car sales. Fuel cell (FC) vehicle technology is not here today and commercialization will require a large investment in research, development, and infrastructure. In the mid-term, hydrogen will come from fossil fuels by reforming natural gas or gasoline.

Question 2. Are there any comparative efficiency, cost and/or political advantages of using an advanced nuclear reactor coupled to a thermochemical conversion plant to produce hydrogen with respect using a conventional nuclear reactor coupled to an electrolysis plant?

Finding 5. There are no significant production cost differences between the thermochemical water splitting plant coupled to a Very High Temperature Gas Reactor (VHTGR) and the alkaline electrolysis plant coupled to a Light Water Reactor (LWR).

Finding 6. With an optimistic production efficiency, technological advances and improved capital costs, the levelized costs of the thermochemical production option become competitive with current average gasoline prices, provided that the transmission and delivery infrastructure is available and its cost is below the price differential.

Finding 7. Our results are relatively cautious with respect to the results of several other studies. The major difference is in the case of thermochemical hydrogen production. We think the capital cost estimates used in several earlier studies for the VHTGR may be overly optimistic.

Finding 8. The two major uncertainties associated with large scale hydrogen production are capital cost and performance of interface systems connecting hydrogen production, storage and delivery.

Finding 9. This study does not advocate or favor either thermochemical or electrolytic hydrogen production. Our focus is to provide a comparative technical assessment. The results suggest that given the existing technical and cost uncertainties, developing the VHTGR technology solely for the use of thermochemical hydrogen production is not good energy (R&D) policy. Electrolysis is a more promising alternative provided a more efficient primary energy (i.e. electricity) source is available at a reasonable cost.

1.4 Policy implications and recommendations

Recommendation 1. If the justification for federal support for R&D on fuel cells is reduction in imported oil and carbon dioxide emissions then there is stronger justification for federal support for hybrid vehicles that will achieve similar results, quicker. Consideration should be given to expanding government support for R&D on advanced hybrid technology and extending tax credits.

1.4.1 Current approach to fuel economy regulation in the U.S.

Corporate Average Fuel Economy (CAFE) Program. Currently the fuel economy of the U.S. vehicle fleet is regulated by the CAFE program, which was created by the Congress as a part of the Energy Policy and Conservation Act in 1975 following the oil-shock of 1973. The CAFE program established sales-weighted fuel economy performance criteria for passenger cars (currently 27.5 mpg) and light-duty vehicles (light trucks) (currently 20.7 mpg). The underlying goal was to decrease oil consumption and dependence on petroleum imports by increasing tank-to-wheel efficiency.

The CAFE program has been controversial. Its effects on the fuel economy of the U.S. vehicle fleet; the vehicle composition of the fleet; the passenger safety; and the U.S. automotive sector, employment and customer satisfaction have been heavily criticized.[10] While proponents of fuel economy standards advocates the reduced expenditures in the form of monetary savings resulting from increased efficiency more than justify such direct regulatory intervention by the government, the critics argue that, although relevant, personal savings on their own are not sufficient justifications of direct policy intervention. The market itself will help consumers determine their preferences for more efficient vehicles depending on oil prices and personal values such as concerns about air pollution and climate change. Therefore, no direct government intervention is necessary.

[10] For a comprehensive evaluation of the CAFE standards, see "*Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*" (Washington, DC: National Academy Press, 2002)

Tax Credits for 'Clean Fuel' Vehicles.[11] Policy intervention through indirect incentives such as tax credits or tax deductions for hybrid vehicles address most of these concerns. Such market-based policies provide incentives for car manufacturers to include hybrid vehicles in their product portfolio in innovative ways such that they can differentiate themselves from their competitors based on their hybrids' acceleration, power management, fuel economy and safety performance.

There are still objections, though, to how to allocate these credits among different auto manufacturers without leaving some of the second movers such as Daimler-Chrysler and General Motors at disadvantage with respect to the first movers Ford Motor Company (the maker of Escape SUV hybrid), Honda (the maker of Insight and Civic hybrids) and Toyota (the maker of popular Prius hybrid).[12] Currently the two main arguments of the American automotive lobbyists are:[13]

(1) American auto manufacturers would like to see tax benefits proportional to the incremental fuel efficiency achieved by the hybrid version of the same car, not to the absolute fuel economy of the hybrid vehicle. This will enable the Big Three (Daimler-Chrysler, General Motors Company and Ford Motor Company), whose SUVs and trucks are their best selling vehicles, to compete with the smaller, foreign imports of Honda and Toyota on fair grounds.

(2) American automotive lobbyists are also pushing for 80,000-car cap per manufacturer that will limit the number of hybrids a manufacturer can sell in the U.S. in a given year.

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[11] "The clean-fuel vehicle tax deduction was originally scheduled to phase out starting in 2004. Vehicles bought in 2004 were eligible for a maximum deduction of $1,500, and those bought in 2005 were eligible for a $1,000 deduction. However, the *Working Families Tax Relief Act of 2004* has extended the $2,000 deduction through 2005... Consumers purchasing a new clean-fuel vehicle by the end of 2005 may be eligible for a *Clean-Fuel* vehicle tax deduction of up to $2,000. This also applies to gasoline/electric hybrids. The credit will be reduced to $500 in 2006 and will expire in 2007." For more information; see http://www.fueleconomy.gov/feg/tax_afv.shtml#cleanfuel.

[12] Daimler Chrysler and General Motors announced their partnership to develop new hybrid vehicles on December 14th, 2004, that will be on the road by 2007. (D. Hakim, "G.M. and Daimler to Work Jointly on Hybrid Engine", *New York Times*, 14 December 2004)

[13] B. Stempeck, "Automakers divided over tax credits for hybrid cars" Department of Transportation/Environmental protection Agency "It All Adds Up to Cleaner Air" [Information] Exchange (7 July 2004). See http://knowledge.fhwa.dot.gov/cops/italladdsup.nsf/home?openform.

Recommendation 2. The government fuel cell R&D initiative is welcome but it is not clear whether the effort to develop economic fuel cell power plants for passenger cars will be successful. In parallel, we should place priority on deploying hybrid cars beginning with today's automotive platforms and fuels.

1.4.2 Public-private R&D and the FreedomCAR

PNGV (Partnership for a New Generation of Vehicles) Program that was established by the first Clinton Administration in 1993 "evolved" into FreedomCAR (Freedom Corporate Automotive Research) Program under the first Bush Administration in 2002. FreedomCAR is a long-term R&D partnership between the government and the Big Three to develop "affordable full-function cars and trucks that are free from foreign oil and harmful emissions, without sacrificing mobility and vehicle choice" providing

- Freedom from petroleum dependence,
- Freedom from pollutant emissions,
- Freedom to choose [the vehicle one wants],
- Freedom to drive [wherever one wants, when one wants], and
- Freedom to obtain fuel affordably and conveniently.

These are appealing populist causes to advocate; however, the FreedomCAR and the associated Fuel Partnership program "focuses government support on fundamental, high-risk research that applies to multiple passenger-vehicle models and emphasizes the development of fuel cells and hydrogen infrastructure technologies." A successful automotive fuel cell program must develop high durability fuel cell stacks with lifetimes of five to ten thousand hours, well beyond today's experience. It is impossible to estimate today whether the manufacturing cost range that FC stacks must achieve for economical passenger cars can be reached even at the large-scale production runs that might be envisioned.

Recommendation 3. There are no significant production cost differences between the two large scale hydrogen production options: thermochemical water splitting plant coupled to a Very High Temperature Gas Reactor (VHTGR) and the alkaline electrolysis plant coupled to a Light Water Reactor (LWR). Even with optimistic production efficiency, technological advances and improved capital costs, the levelized costs of the thermochemical production option may not become competitive with gasoline.

Therefore, cost and engineering uncertainties associated with the former suggest that large R&D investment in this field is not balanced with a similar R&D in large scale electrolysis technologies that are relatively easier to deploy and have smaller cost and engineering risks. When coupled with more efficient nuclear plants such as VHTGR, electrolysis has a higher potential of overcoming the efficiency and the cost barriers given the existing experience with electrolysis technologies.

Recommendation 4. DOE should seek independent third-party appraisal of the technical and cost studies developed by current stakeholders by an advisory committee of experts or a consortium of non-profit research, university and private industry representatives. DOE should request an adequate emphasis on cost and engineering uncertainties as well as the promise of alternatives.

1.4.3 R&D for nuclear production of hydrogen

The current target of the DOE's Hydrogen Program is to complete R&D by 2015 and to accomplish transition to a hydrogen marketplace by 2025. More specifically for Nuclear Hydrogen Initiative (NHI), there are two important milestones: (1) the decision of which thermochemical cycle would be used in a pilot plant is planned for 2007, and (2) the engineering decision for the demonstration process is scheduled for 2010.

NHI also considers high-temperature electrolysis (also called steam electrolysis) as an option to produce hydrogen. In high-temperature electrolysis, the steam is generated by the thermal energy provided by an advanced nuclear reactor. This high-temperature steam (~950 °C) decreases the electrical energy requirement and therefore increases electrolysis efficiency. According to NHI, the pilot plant decision will be made by the end of 2006 and the decision for the engineering demonstration process will be made by the end of 2010.

Independent technology assessment of the nuclear hydrogen production and the nuclear hydrogen systems interface are the focus of the NHI. As our production cost analysis indicate, capital cost is one of the two major source of uncertainty in any technological assessment. This uncertainty is especially large with hydrogen production technologies that are not here today such as advanced high-temperature nuclear reactor, thermochemical splitting of water and high temperature electrolysis. The second major source of uncertainty is associated with interface of hydrogen production, storage and delivery systems.

The DOE's R&D efforts aim to reduce these uncertainties by going ahead with laboratory scale experiments. Laboratory scale experiments may or may not help resolve these technical and economic uncertainties that may persist at the pilot and demonstration plant level. Even one may chose to be optimistic about the scalability of the capital costs; there is less reason to do so with the scalability of the overall system efficiency. In short, by concentrating to reduce the risk associated with future hydrogen production technologies, DOE seems to underestimate the 'option value' of current technologies for large scale hydrogen production such as a traditional nuclear reactor dedicated to alkaline electrolysis.

As mentioned above, there still is a lack of basic scientific knowledge about the advanced nuclear systems as well as certain aspects of thermochemical water splitting cycles. Therefore, extensive government support for R&D in this field is needed reflecting the societal value of use-inspired basic research. It is reasonable to believe that "[t]he uncertainty as to who will capture the benefit in technology from new scientific

knowledge is lessened when basic research is directly influenced by potential use."[14] However, the DOE's political determination to develop fossil-fuel-free hydrogen production systems might be captured by private stakeholders' favorable technical feasibility and cost assessments. The mismatch between the time needed by comprehensive technical assessment and the interest of the political agenda tend to make public decision makers to go along with available (but possibly not sufficient) information. This reliance (without confidence) generally originates from the lack of alternative information. If a "big hole in the ground" is to be avoided, DOE should seek independent third-party appraisal of the technical and cost studies developed by current stakeholders by an advisory committee of experts or a consortium of non-profit research, university and private industry representatives. DOE should request an adequate emphasis on cost and engineering uncertainties as well as the promise of alternatives. The recent study by the National Academy of Sciences, "*The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*"[83] is a good start but, with regard to advanced nuclear technologies for hydrogen production, it significantly relies on the same report that the DOE supported R&D efforts generated. Therefore, the NAS study falls short of being an appraisal and does not go beyond being a comprehensive review.

[14] D. E. Stokes, "*Pasteur's Quadrant – Basic Science and Technological Innovation*" (Washington, DC: Brookings Institution Press, 1997), chap. 4, p. 106.

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Chapter 2

Hybrid cars and fuel cell cars – technical efficiency as a tool for public policy

The transportation sector in the United States is a major contributor to domestic welfare. Transportation as a social activity has important technology and policy implications for the energy use and the environment. Recently, there have been increasing political concerns about energy security, energy efficiency, and adverse health and environmental effects of air pollution from transportation related combustion sources. These concerns have been the primary drivers behind the new vehicle technologies including hybrid vehicles, fuel cell and other advanced power train technologies that use alternative "clean" fuels.

This chapter compares the energy efficiency of three of these technologies, hybrid vehicles, fuel cell vehicles, and conventional internal combustion engines. The results indicate that fuel cell vehicles using hydrogen from fossils fuels offer no significant energy efficiency advantage over gasoline/electric hybrid vehicles in urban driving cycle. We conclude that priority should be placed on hybrid vehicles by industry and government. After a brief introduction, Section 2 introduces our simple energy efficiency model. Section 3 reports the results from an advanced vehicle simulator and compares its results with those of the simple model. Finally Section 4 presents a brief outlook on the future of hybrid vehicle technologies and provides several policy recommendations.

2.1 Introduction

Our interest in moving toward a hydrogen economy is not based on love of the molecule but on the prospect of meeting energy needs at acceptable cost, with greater efficiency, and less environmental damage compared to the use of conventional fuels. One goal is the replacement of today's automobile with a dramatically more energy efficient vehicle. This replacement will reduce combustion related emissions that cause adverse health and environmental effects such as air particulate pollution,[15] acid rain, climate change as well as dependence on imported oil. In 2001, the United States consumed 8.55 million barrels of motor gasoline per day,[16] of which an estimated 63.1% is refined from imported crude oil.[17] This consumption resulted in annual emissions of 303 million metric tones (MMT) of carbon equivalent in 2001, accounting for 19.3% of total U.S. carbon emissions of 1,567 MMT.[18]

To provide a basis for our discussion of the new gasoline-electric hybrid and fuel cell vehicle technologies and their comparative potential to address the transportation related externalities, the following section presents an overview of relavant transportation statistics for highway driving in the U.S. in 2001. These include the characteristics of the U.S. vehicle fleet, the role of transportation sector in the U.S. economy, the transportation's share of the U.S. energy demand and the environmental dimensions of the transportation related activities.

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[15] The adverse health effects of the particulate air pollution are severe. Major causes of concern include increased hospital and emergency room admissions of the people with respiratory (including asthma and chronic bronchitis) and cardiac diseases. Health problems for sensitive people can lead to serious consequences including premature death depending on the exposure levels. For more information see "*Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Air Pollution and Mortality*" (July 2000). Executive Summary and Commentary are available at http://www.healtheffects.org/Pubs/Rean-ExecSumm.pdf.

[16] In 2003, the motor gasoline consumption was 8.88 million barrels per day. Calculated from weekly data of supplied gasoline products published by the U.S. Department of Energy (DOE), Energy Information Agency (EIA); available at http://www.eia.doe.gov/oil_gas/petroleum/info_glance/gasoline.html.

[17] The share of imports increased to 68.1% in 2002. "National transportation statistics 2004", U.S. Department of Transportation, Bureau of Transportation Statistics (Washington, DC, 2004), Table 4-1. Available at http://www.bts.gov/publications/national_transportation_statistics/2003/index.html.

[18] *Ibid.*, calculated using the date from Table 4-49.

2.1.1 Relevant transportation statistics

U.S. Vehicle Fleet. In 2001 there were 235.3 million vehicles in the U.S. (2.2 per household), 22.3% increase from 1991. The passenger vehicles accounted for 58.5% of the entire fleet and light trucks for 35.8%, compared to 66.7% and 27.6% in 1991, respectively.[19] Approximately 8.4 millions of new passenger cars was sold in 2001, of which 24.9% was imported.[20] The average fuel economy of all 2001 model-year vehicles was 24.6 mpg; fuel economy for passenger cars of the same model year was 28.8 mpg and for light trucks, 20.9 mpg.[21]

The average age of all passenger cars in 2001 was 8.3 years and the average age of all trucks was 6.1 years.[22] The average of vehicle-miles traveled in 2001 for the entire fleet was 11,887 miles (5.2% increase from 1991), 10,690 miles for passenger cars (1.0% increase from 1991) and 13,329 miles for light truck (8.9% increase from 1991).[23] These numbers corresponds to 32.5 person-miles per day for the entire fleet, 29.2 person-miles per day for the passenger cars, and 36.5 person-miles per day for light trucks.[24]

Transportation and Economy. Transportation-related final demand[25] accounted for 10.4% of the U.S. Gross Domestic Product (GDP) in 2001[26], of which personal consumption's share was 75.9 % ($794.8 billion; $7,591 per household; 17.6% of average household income), gross private domestic investment's share was 16.3% ($170.8 billion) and government purchases' share was 18.1% ($189.4 billion). 45.5% of

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[19] Footnote 17, calculated using the data from Table 1-11.

[20] 39.9% from Japan, 24.9% from Germany and the remainder from other countries.

[21] U.S. Department of Transporation, National Highway Safety Administration, "Automotive Fuel Economy Program – Annual Update Calendar Year 2002" (DOT HS 809 512, Washington, DC, 2003), Table II-6.; http://www.nhtsa.dot.gov/cars/rules/cafe/FuelEconUpdates/2002/2002AnnualUpdate.pdf.

[22] Footnote 17, Table 1-25.

[23] Footnote 17, calculated using the data from Table 1-31 and Table 1-11.

[24] *Person-miles* is an estimate of the aggregate distances traveled by all persons on a given trip based on the estimated transportation-net-work miles traveled on that trip.

[25] *Transportation-related final demand* is the sum of all consumer, private business and government purchases of transportation-related purchases, and net exports.

[26] Footnote 17, Table 3-2a.

the transportation-related personal demand was for the purchase of motor vehicles and parts, and 20.3% was for gasoline and oil expenses.[26] Also note that the transportation sector employed 6.72% of the civilian workforce.[27]

Transportation and Energy Use. The transportation sector consumed 26.3 QBtu[28] (18.8% increase from 1991) accounting for the 27.3% of the total U.S. energy demand in 2001.[29] 79.6% of the energy consumed by the transportation sector was for highway transportation, of which 35.1% was consumed by passenger cars (and motorcycles) and 25.4% by light trucks.[30] The demand for gasoline for highway transportation in 2001 was 96.7% of the overall gasoline consumption[31], corresponding to 65.8% of the domestic petroleum consumption.[32]

Although the average fuel-economy of all 2001-model year passenger cars was 28.8 mpg, the average fuel economy of the entire passenger car fleet was 22.2 mpg. Similarly, the average fuel economy of the entire light truck fleet was 17.6 mpg although the average fuel-economy of all 2001-model year light trucks was 20.9 mpg. This shows that the replacement of old vehicles in the U.S. has been slowing down, which also apparent from the increasing median age of passenger cars, which was 4.9 years in 1970 and 8.3 years in 2001. The median age of trucks has decreased slowly but steadily from 7.1 years in 1993 to 6.1 years in 2001.[33]

The average fuel wasted due to congestion in 2001 was 76 million gallons; approximately 9-days worth of annual gasoline consumption, a 27% increase from 1996 and 375% increase from 1982. The amount of wasted fuel is very large in big areas, e.g.

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[27] Footnote 17, calculated from data in Table 3-20b.

[28] QBtu = Quadrillion (10^{15}) British Thermal Unit

[29] Footnote 17, Table 4-4.

[30] Footnote 17, calculated using the date from Table 4-6.

[31] Footnote 17, calculated using the date from Table 4-7.

[32] Footnote 17, Table 4-1.

[33] Footnote 17, Table 1-25.

996 million gallons in, Los Angeles, CA, and 696 million gallons in New York, NY-Northeastern, NJ.[34]

Transportation and Environment. CO_2 (carbon dioxide) emissions from transportation sources in 2001 were 490.3 MMT (million metric tonnes) (an increase of 17.7% from 1991), 31.8% of total CO_2 emissions in the U.S.[35] The CO_2 emissions from combustion of motor gasoline was 303 MMT, 62.7% of the total emissions from transportation sources and 19.3% of emissions from all sources.

The share of the on-road vehicles in criteria pollutants emissions, which are regulated by the National Ambient Air Quality Standards, are 61.9% for CO (carbon monoxide), 36.9% for NOx (nitrous oxides), 27.1% for VOCs (volatile organic compounds), 0.9% for PM10 (particulate matter with diameter smaller than 10 but larger than 2.5 microns), 2.2% for PM2.5 (particulate matter with diameter smaller than 2.5 microns), 1.6% for SO_2 (sulfur dioxide) and 0.4% for lead in 2001.[36]

In addition to air pollution, transportation related oil spills contribute to water pollution: there were 7,559 incidents in 2001 with total spills of 854,520 gallons of oil. Moreover, the leakage of underground storage tanks amounted to 418,918 gallons of oil release, of which 34.1% was not cleaned up. Highway noise is also an important environmental issue. In 2001, there were 411,000 thousands people living within 65 dB DNL noise-level contours.[37]

All the statistics mentioned in this Section are given in Table 2.1.

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[34] "Wasted" fuel is the difference between the fuel consumed under estimated existing conditions and the fuel consumed if all traffic was moving at free-flow conditions. Calculations are made for peak period speeds and for free-flow speeds on both the freeway and principal arterial systems. Average over 75 areas, including very large urban areas (over 3 million population), large urban areas (over 1 million and less than 3 million population), medium urban areas (over 500,000 and less than 1 million population), small urban areas (less than 500,000 population). For the list; see Footnote 17, Table 1.66.

[35] Other sources include industrial (29.3%), residential (20.2%) and commercial (17.7%) sources.

[36] Footnote 17, calculated using the date from Table 4.40 for CO emissions, Table 4.41 for NOx emissions, Table 4.42 for VOC emissions, Table 4.44 for PM10 emissions, Table 4.45 for PM2.5 emissions, Table 4.46 for SO_2 emissions, and Table 4.47 for lead emissions.

[37] Footnote 17, Table 4.50 for petroleum oil spills, Table 4.51 for underground storage tank leakages and Table 4.53 for noise pollution.

Table 2.1 Relevant transportation statistics for 2001 unless otherwise noted. For source information see the preceding text.

U.S. Vehicle Fleet

		% of total	Average vehicle-miles	Average person-miles	Age, years	Fuel economy, mpg	
						Model 2001	Fleet 2001
Passenger Cars	137,633,467	58.5%	10,690	29.2	8.3	28.8	22.2
Light Trucks[a]	84,187,636	35.8%	13,329	36.5	6.1[b]	20.9	17.6
Total	235,331,381		11,887	32.5		24.6	17.0

Transportation and Economy			**Transportation and Energy Use**		
Transportation-related final demand	$1,049.9B		Transportation-related final demand	26.3 QBtu	
Personal	$794.8B	75.9%[c]	Highway	20.9 QBtu	79.6%[f]
Motor vehicles & Parts	$361.6B	45.5%[d]	Passenger cars	7.3 QBtu	35.1%[g]
Gasoline & Oil	$161.3B	20.3%[d]	Light trucks	5.32 QBtu	25.4%[g]
Per household	$7,591	17.6%[e]	Gasoline consumption	163,478M gallons	
Private investment	$170.8B	16.3%[c]	% of domestic oil consumption	65.8%	
Government purchases	$189.4B	18.1%[c]	Average wasted fuel due to congestion	76M gallons	

Transportation and Environment

Emissions[h]	% of total	Emissions[h]	% of total
CO_2	19.3%	SO_2	1.6%
CO	61.9%	PM10	0.9%
NOx	36.9%	PM2.5	2.2%
VOCs	27.1%	Lead	0.4%

M: million; B: Billion; mpg: miles per gallon; QBtu: Quadrillion British Thermal Unit; [a]other 'passenger cars' with 2-axles and 4-tire including most SUVs, minivans and pick-up trucks; [b] Includes heavy trucks; [c] Percentage of total final demand; [d] Percentage of personal purchases; [e] Percentage of average household income; [f] Percentage of total transportation energy use; [g] Percentage of highway energy use; [h] All Sources

2.1.2 Vehicles technologies considered

Two advanced vehicle technologies that are being considered to replace the current fleet at least partially are hybrid vehicles and fuel cell powered vehicles. Hybrid vehicles add a parallel direct electric drive train with motor and batteries, to the conventional internal combustion engine (ICE) drive train. This hybrid drive train permits significant reduction in idling losses and regeneration of braking losses that leads to greater efficiency and improved fuel economy. Hybrid technology is available now, although it represents less than 1% of new car sales. Fuel cell vehicles also operate by direct current electric drive.[38] They utilize the high efficiency of electrochemical fuel cells to produce power from hydrogen. For the foreseeable future, hydrogen will come from fossil fuels by reforming natural gas or gasoline. Fuel cell (FC) vehicle technology is not here today and commercialization will require a large investment in research, development, and infrastructure. Only gasoline and natural gas are widely available as a transportation fuel today; a hydrogen or methanol fueled transportation system would take decades to deploy, at significant cost.

Here we evaluate the potential of these advanced passenger vehicles to improve energy efficiency. We show that a tremendous increase in energy efficiency can be realized today by shifting to hybrid internal combustion engine vehicles - quite likely more than can be realized by a shift from hybrid ICE (HICE) to hybrid fuel cell vehicles.[39] Section 2 introduces our simple energy efficiency model. Section 3 uses the same assumptions used by the simple models in an advanced vehicle simulator and compares the results. Finally Section 4 presents a brief outlook on the future of hybrid vehicle technologies and provides several policy recommendations.

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[38] For a recent review of the market place for hybrid vehicles, see P. Fairley, "Hybrids' Rising Sun." *Technology Review*, **107** (3), 34 (2004).

[39] The results presented in this chapter previously reported in *Science* Magazine. The reference is: N. Demirdöven, J. Deutch, "Hybrid Cars Now Fuel Cell Cars Later", *Science* **305** (5686), 974 (2004).

2.2 Energy efficiency model

To provide a basis for comparison of these two technologies, we use a simple model for obtaining the energy efficiency of the various power plant/drive train/fuel combinations considered in more detailed studies.[40, 41, 42, 43, 44, 45]

We define the average energy efficiency as the ratio of the energy needed at the wheels, E_{out}, to drive and brake a car of a given weight, M, on a specified test cycle to the total fuel energy needed to drive the vehicle, E_{in}. Regenerative braking, if present, reduced the fuel needed to drive the car. Accessory power is not included in energy output. The "tank-to-wheel" (TTW) efficiency, η_{TTW} is calculated as $\eta_{TTW} = E_{out}/E_{in}$. For the vehicle configurations in Figure 2.2, we keep E_{out} constant and calculate E_{in} by backward induction as

$$E_{in} = \frac{1}{\eta_{fp}\eta_e}\left[\frac{E_{out}}{\eta_{dt}} - B\eta_{rb} + E_{ac} + E_{idle}\right] \qquad (2.2.1)$$

where E_{idle}, and E_{ac} are the energies required in the specified drive cycle for idling and for accessories. B is the energy lost to braking. The various efficiencies of different

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[40] In 2001 General Motors (GM) collaborated with Argonne National Laboratories (ANL) using ANL's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model; General Motors, Argonne National Laboratories, "Well-to-wheel energy use and greenhouse gas emissions of advanced fuel/vehicle system, North American analysis" (2001). Referred to as the ANL/GM study, available at http://greet.anl.gov/publications.html.

[41] M.A. Weiss, J.B. Heywood, E.M. Drake, A. Schafer, F. AuYeung, "On the road in 2020: A life cycle analysis ggof new automobile technologies" (MIT Energy Laboratory Report No. MIT EL 00-003, 2000). We thank Malcolm Weiss for helpful discussions about this work.

[42] M.A. Weiss, J.B. Heywood, A. Schafer, V.K. Natarajan, "Comparative assessment of fuel cell cars" (MIT Laboratory for Energy and Environment Report No. 2003-001 RP, 2003).

[43] P. Ahlvi, A. Brandberg, Ecotraffic R&D, "Well to wheel efficiency for alternative fuels from natural gas to biomass," Vagverket (Swedish National Road Administration), 2001-85 (2001). See Appendix 1.8.

[44] F. An, D. Santini, "Assessing Tank-to-Wheel efficiencies of advanced technology vehicles," Society of Automotive Engineers Paper No. 2003-01-0412 (2003).

[45] B. Hohlein, G. Isenber, R. Edinger, T. Grube, *Handbook of Fuel Cells*, Ed. W. Vielstich, A. Gasteiger, A. Lamm, Volume 3 (John Wiley & Sons, 2003), §21, p. 245.

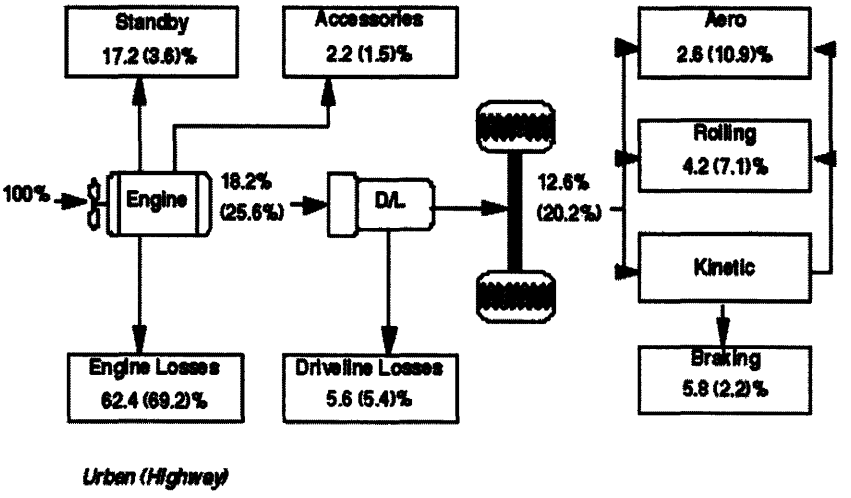
stages are η_{fp}, η_e, η_{dt}, and η_{rb}, for fuel processing, engine or fuel cell, drive train, and regenerative braking (including recharging of the battery) respectively. We focus on efficiency rather than the more common fuel economy because the efficiency is less sensitive to vehicle weight than fuel economy.

In general, the energy efficiency of ICEs with a hybrid drive train, and from FC powered vehicles vary depending on the vehicle configuration and the type of engine, drive train, and fuel (natural gas, gasoline, or diesel).

For each configuration, we determine "well-to-wheel" (WTW) energy efficiency for a vehicle of a given weight operating on a specified drive cycle. The overall WTW efficiency is divided into a "well-to-tank" (WTT) and "tank-to-wheel" (TTW) efficiency so that WTW = WTT x TTW. (See Table 2.2 and Table 2.3)

We begin with the U.S. Department of Energy (DOE) specification of average passenger energy use in a Federal urban drive cycle, the so-called "FUDS" cycle.[46] For example, for today's ICE vehicle that uses a spark ignition engine fueled by gasoline, the TTW efficiency for propulsion and braking is 12.6% (See Figure 2.1).

Figure 2.1 U.S. Department of Energy (DOE) specification of average passenger energy use in a Federal urban (highway) drive cycle.46



[46] Available at the DOE web site: http://www.fueleconomy.gov/feg/atv.shtml.

The TTW efficiency of other configurations is estimated by making changes in the base line ICE parameters and calculating energy requirements beginning with energy output. A hypothetical hybrid ICE, based on current hybrid technology, that completely eliminates idling losses and captures a portion (50%) of braking losses for productive use will have a TTW efficiency of 26.6% (Figure 2.2B). Both the ICE and HICE use gasoline fuel directly, so no fuel processing is needed. We wish to keep the presentation of our model simple. The assumption of complete regenerative braking and reduction in idling losses is not realistic. However improvement in ICE engine efficiency is also possible.[42] The current performance of hybrid ICE passenger vehicles such as the Toyota PRIUS is impressive. Toyota reports TTW efficiency of the PRIUS as 32% compared to 16% for a conventional ICE.[47]

A likely hydrogen-based car might be a proton exchange membrane (PEM) fuel cell powered vehicle with a hybrid power train. This advanced fuel cell (AFC) vehicle has an on-board fuel processor that reforms gasoline to hydrogen fuel suitable for feed for the PEM fuel cell. We assume a reformer efficiency of 80%, and 50% efficiency for the fuel cell stack operating over the urban drive cycle. We include a power train with the same characteristics as the HICE vehicle. The TTW efficiency of this configuration is 28.3% (Figure 2.2C).

It is apparent that any alternative vehicle configuration of fuel/power plant/drive train can be considered in a similar fashion. For example, if hydrogen were available without energy cost, the overall efficiency would improve to 39.0% - over three times the conventional ICE.[48] A diesel internal combustion engine with a hybrid power train could achieve an efficiency of 31.9%, provided that this higher compression direct injection engine has an efficiency of 45.0% compared to 37.6% for the gasoline ICE.

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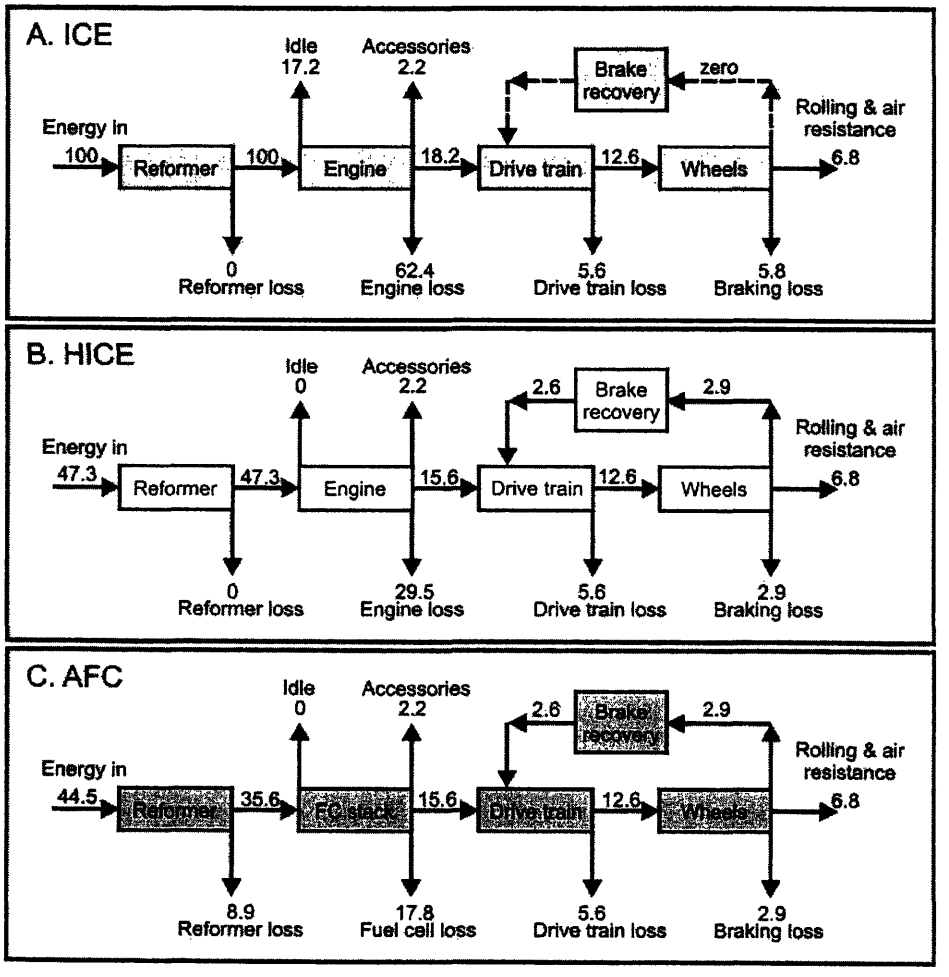
[47] See: www.toyota.co.jp/en/tech/environment/fchv/fchv12.html. PRIUS regenerative braking reportedly recaptures 30%; see http://www.ott.doe.gov/hev/regenerative.html.

[48] For this case there is no processor loss and the fuel cell stack efficiency improves to 55% because the fuel cell functions better on pure hydrogen than reformate.

Figure 2.2 Energy flow for various vehicle configurations. A) ICE, the conventional internal combustion, spark ignition engine; B) HICE, a hybrid vehicle that includes an electric motor and parallel drive train which eliminates idling loss and captures some energy of braking; C) AFC a fuel cell vehicle with parallel drive train. The configuration assumes on-board gasoline reforming to fuel suitable for PEM fuel cell operation.



Our results shown in Table 2.2 are in reasonably good agreement with those of more detailed studies but do not require elaborate simulation models. Table I shows that except for the Argonne National Laboratory/General Motors (ANL/GM) study,[40] the relative gain in efficiency in moving from an ordinary ICE to a HICE is more than two fold. The reason for this difference is not clear, because the TTW analysis in that study was based on a GM proprietary simulation model.

Table 2.2 System component efficiencies for the three vehicle configurations in the simple model illustrated in Figure 2.2 and described by Equation 2.2.1.

	ICE	HICE	
Energy in, E_{in}	100	47.3	
Energy out, E_{out}	12.6	12.6	
Energy lost for idling, E_{idle}	17.2	0	
Energy for accessories, E_{ac}	2.2	2.2	
Recovered braking energy, B	0	5.8	
Average efficiencies, %			
Fuel processing, η_{fp}	100	100	
Engine, η_e	37.6	37.6	
Drive train, η_{dt}	69.2	69.2	
Regenerative braking, η_{rb}	0	44.8	

Table 2.3 Comparison of well-to-wheel (WTW) energy efficiencies of advanced vehicle systems employing gasoline fuel.[49]

MODEL	ICE	HICE	
Simple model	11.3	23.9	
MIT-LFEE 2000[50]	11.7	23.8	
ANL/GM[51]	15.2	18.6	
NREL ADVISOR[52]	11.3	24.5	

[49] Color coding follows that in Figure 2.2. 90% WTT efficiency in all cases; thus WTW = 0.90 TTW

[50] Data for ICE and HICE from Weiss *et al.* (2000) (Footnote 41), Table 5.3. Data for AFC from Weiss *et al.* (2003) (Footnote 42). This reference does not give energy efficiency directly. We derive a range for energy efficiency by comparing data in Tables 8 and 9 for MJ/km for vehicle and fuel cycle for the 2020 ICE hybrid to that of the gasoline FC hybrid given in Footnote 41, Table 5.3.

[51] Data from ANL/GM study (Footnote 40), Table 2.1.

[52] Data from NREL's ADVISOR simulation; for details, see Table 2.4.

2.3 Validation of energy efficiency model

To test the validity of these comparisons and our simple model we have used an advanced vehicle simulator called ADVISOR, developed by the National Renewable Research Laboratory (NREL) of the Department of Energy (DOE).[53] ADVISOR provides estimates of energy efficiencies for different vehicle configurations. ADVISOR shows the broad range of vehicle performance that is possible with reasonable choice of system parameters such as maximum engine power, maximum motor power, transmission type, and brake energy regeneration. The parameters we selected for the simulation of the ICE, HICE, and AFC are given in Table 2; for comparison, TTW's based on this simulation for the Toyota PRIUS is 28.8% and the Honda INSIGHT is 26.2%. Except for the ANL/GM results, all studies point to large potential gains from hybrid vehicles in urban drive cycle compared to cars with conventional ICEs.[54]

Our analysis shows that hybrids offer the potential for tremendous improvement in energy use and significant reduction in carbon emissions compared to current ICE technology. But, hybrid vehicles will only be adopted in significant quantities if the cost to the consumer is comparable to the conventional ICE alternative. Hybrid technology is here today, but, of course, hybrid vehicles cost more than equivalent ICE vehicles because of the parallel drive train. Estimates of the cost differential vary, but a range of $1,000 to $2,000 is not unreasonable.[55] Depending on the miles driven, the cost of ownership of a hybrid vehicle may be lower than a conventional ICE because the

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[53] The NREL ADVISOR simulator is described on the web at http://www.ctts.nrel.gov/analysis. Use of the model is described in several publications listed at the NREL website: http://www.ctts.nrel.gov/analysis/reading_room.html. See, for example, T. Markel, A. Brooker, T. Hendricks, K. Kelly, B. Kramer, M. O'Keefe, S. Sprik, K. Wipke, J. of Power Sources **110**, 225 (2002); and M.R. Cuddy, K.G. Wipke, Society of Automotive Engineers Paper No. 970289 (1997).

[54] General Motors quotes 15 to 20% fuel economy improvements in 2007 for hybrid TAHOE and YUKON SUVs. Not surprisingly, Toyota seems more optimistic about hybrids than General Motors.

[55] "A J.D. Power and Associates survey shows that 43 percent of car buyers would consider a hybrid if the price differential between hybrid and conventional models were $1,500; however, only 20 percent would consider the switch with a price differential of $4,000. Source: http://www.todaysengineer.org/Apr04/hybrid.asp.

discounted value of the fuel saving is greater than the incremental capital cost for the parallel drive train and electric motor.

Thus, hybrid vehicles can contribute to lower emissions and less petroleum use at small or negative social cost.[56] Today only Toyota and Honda offer hybrids in the United States, Daimler-Chrysler, Ford, and General Motors are planning to introduce hybrids in the period 2004-2006. At present there is a federal tax credit of $1,500 for purchase of a hybrid vehicle, but it is scheduled to phase out in 2006.[57]

[56] In Europe, where fuel prices are much higher than in the United States, the advantage of hybrids over conventional ICE's is significantly greater.

[57] "The clean-fuel vehicle tax deduction was originally scheduled to phase out starting in 2004. Vehicles bought in 2004 were eligible for a maximum deduction of $1,500, and those bought in 2005 were eligible for a $1,000 deduction. However, the *Working Families Tax Relief Act of 2004* has extended the $2,000 deduction through 2005... Consumers purchasing a new clean-fuel vehicle by the end of 2005 may be eligible for a *Clean-Fuel* vehicle tax deduction of up to $2,000. This also applies to gasoline/electric hybrids. The credit will be reduced to $500 in 2006 and will expire in 2007." For more information; see http://www.fueleconomy.gov/feg/tax_afv.shtml#cleanfuel.

Table 2.4 Input and output vehicle parameters obtained from NREL's ADVISOR simulations.

Vehicle[58]	ICE	HICE	AFC	PRIUS	INSIGHT
Max power (kW)	102	83	70	74	60
Power: weight ratio (W/kg)	68	55	47	54	60
Frontal area (m^2)	2	2	2	1.75	1.9
Rolling resistance coefficient	0.009	0.009	0.009	0.009	0.0054
Engine/Motor/Fuel cell stack					
Max engine power (kW)	102	43		43	50
Max engine efficiency (%)	38	38		39	40
Max motor power (kW)		40	40	31	10
Max motor efficiency (%)		92	92	91	96
Max fuel cell power (kW)			30		
Max fuel cell stack efficiency (%)			56		
Acceleration					
Time for 0-60 mph (s)	18	10	13	15	12
Fuel use[59]					
Fuel energy use (kJ/km)	3,282	1,536	1,553	1,317 (1,274)	1189 (982)
Fuel economy (mpg)	21	44	43	53	69
Average efficiencies (%)					
Engine efficiency	21	30		28	25
Motor efficiency		79	84	81	90
Reformer efficiency			80		
Fuel cell stack efficiency			51		
Round-trip battery efficiency		100	84	81	82
Transmission efficiency	75	75	93	100	92
Regenerative braking efficiency		35	39	41	38
TTW efficiency59	12.6	27.2	26.6	28.8	26.2

[58] We assumed 1,500 kg for the total vehicle weight including two passengers and fuel on board. The actual weights of the Toyota PRIUS and Honda INSIGHT with two passengers and fuel on board are 1,368 kg and 1,000 kg respectively. Auxiliary power is 700 W except for Honda Insight for which it is 200 W. The simulations are over a "FUDS" urban driving cycle. FUDS is also known as UDDS (urban dynamometer driving schedule), LA4, FTP 72, EPA II and as "the city test."

[59] Fuel use and TTW calculations follow the definition of efficiency given in Eq. 2.2.1, which is different than the "overall system efficiency" defined in the NREL's ADVISOR. Of course, the underlying performance is the same.

2.4 Outlook and policy implications

Fuel cell technology is not here today. Both the Bush administration's *FreedomCAR* (Freedom Cooperative Automotive Research) program[60] and the earlier Clinton administration *Partnership for a New Generation of Vehicles* (PNGV) launched major DOE R&D initiatives for fuel cell powered vehicles. The current *FreedomCAR* program "focuses government support on fundamental, high-risk research that applies to multiple passenger-vehicle models and emphasizes the development of fuel cells and hydrogen infrastructure technologies."[61] A successful automotive fuel cell program must develop high durability fuel cell stacks with lifetimes of five to ten thousand hours, well beyond today's experience. It is impossible to estimate today whether the manufacturing cost range that FC stacks must achieve for economical passenger cars can be reached even at the large-scale production runs that might be envisioned.

The government fuel cell R&D initiative is welcome but it is not clear whether the effort to develop economic fuel cell power plants for passenger cars will be successful. In parallel, we should place priority on deploying hybrid cars beginning with today's automotive platforms and fuels. If the justification for federal support for R&D on fuel cells is reduction in imported oil and carbon dioxide emissions then there is stronger justification for federal support for hybrid vehicles that will achieve similar results, quicker. Consideration should be given to expanding government support for R&D on advanced hybrid technology and extending tax credits.

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[60] "The goal of FreedomCAR is fundamental and dramatic: the development of emission- and petroleum-free cars and light trucks. FreedomCAR focuses on the high-risk research needed to develop the technologies necessary to provide a full range of affordable cars and light trucks that are free of foreign oil and harmful emissions, without sacrificing freedom of mobility and freedom of vehicle choice." This quote is taken from the website of Oak Ridge National Laboratory; see http://www.ornl.gov/sci/eere/transportation/freedomcar.htm. For additional information, see the website of DOE Office of Energy Efficiency and Renewable Energy, Office of FreedomCAR and Vehicle Technologies at http://www.eere.energy.gov/vehiclesandfuels/. For the viewpoints of the FreedomCAR's private partners (i.e., Daimler Chrysler, General Motor and Ford Motor Company), see the United States Council for Automotive Research website at http://www.uscar.org/freedomcar/.

[61] This quote is taken from http://www.eere.energy.gov/vehiclesandfuels/.

Chapter 3

Thermochemical and electrolytic hydrogen production – costs, technologies & policies

Although the hydrogen economy has recently become popular, it is not a new concept. The ideas of large scale hydrogen production using thermochemical splitting and electrolysis of water have been revisited occasionally as technology and public policymakers invested time, attention and money in hydrogen research and development.

This chapter presents a technical and cost analysis for central hydrogen production for two production pathways that use nuclear power as the primary source of energy: (1) thermochemical splitting of water in a conversion plant coupled to a Very High Temperature Gas Reactor, and (2) conventional alkaline electrolysis of water in an electrolysis plant coupled to a Light Water Reactor. Our results show that within our efficiency and capital cost estimates, there is no significant production cost difference between the two options.

This chapter is organized as follows: Section 1 provides an executive summary. Section 2 reports on details of the thermochemical hydrogen production option. This is followed by the discussion of electrolytic hydrogen production in Section 3. Section 4 compares the hydrogen production costs. Section 5 compares our results with the results of similar studies. Finally Section 6 summarizes current R&D efforts in the U.S. and provides an outlook for large scale hydrogen production technologies and policies.

3.1 Introduction

The purpose of this study is to provide a 'fair and reasonable' appraisal for two nuclear energy based central hydrogen production options. These two options are:

(1) Nuclear heat assisted hydrogen production in a central facility consisted of a Very High Temperature Nuclear Reactor (VHTGR) and thermochemical hydrogen conversion plant, which couples the high heat from the VHTGR to a Sulfur-Iodine thermochemical cycle (SITC) – VHTGR-SITC.

(2) Central hydrogen production in a large alkaline electrolysis (AE) plant coupled to a conventional Light Water Reactor (LWR) – LWR-AE.

The reason we chose these two options for our evaluation because they have the potential of meeting the three long-term goals of the DOE's Hydrogen Program, which are (a) to produce hydrogen from domestic sources, (b) to avoid the production of greenhouse gases, and (c) to make hydrogen cost-competitive with gasoline.

A realistic and independent systems appraisal requires feasible efficiency and cost estimates. For current technologies, we use component efficiency and cost values that reflect today's practices. For proposed technologies, we refer to the forecasted efficiencies and costs reported in the literature. For both options, we performed sensitivity analysis as a function of the capital costs of major system components such as VHTGR, LWR and electrolyzers and their operating efficiencies to account for the technological and economic uncertainties.

We base our comparison of the thermochemical and electrolytic hydrogen production options on the estimated overall hydrogen production efficiency and the levelized production costs of hydrogen. We start our analysis by assuming a baseline hydrogen production capacity (720 MW-H_2, or 160,081 tonnes/y of H_2).[62] To provide a sense of scale to the reader, this annual production would approximately replace, in energy

[62] (a) kW-H_2 = kWth/η where η is the thermal to hydrogen production efficiency and kW-H_2 is kilowatt of hydrogen output capacity.
(b) The production of 1 kg of H_2 requires 39.4 kW-H_2-hr based on High Heating Value (HHV).
(c) 160,081 tonnes/y = 181.8 MMSCF/d, 4.87 million Nm^3/d, 58.88 MJ/d. MMSCF/d: million standard cubic feet per day; Nm^3/d: normal cubic meter per day; MJ/d: megajoule per day. For definitions of units and conversion factors, please see Appendix A.

content, half of a million gallons, 0.14 percent, of the daily U.S. motor gasoline consumption.[63]

Table 3.1 System components of hydrogen production options evaluated in this study

Option	Energy source	Hydrogen production technology
VHTGR-SITC	VHTGR	Sulfur-Iodine thermochemical cycle
LWR-AE	LWR	Alkaline electrolysis

We use a simple spread sheet method to calculate the levelized cost of hydrogen. This model takes our efficiency and capital cost assumptions, and projects revenues and expenses to determine a cost per kilogram of hydrogen over the twenty-year lifespan of the project. The results are shown in Table 3.2, Table 3.3 and Table 3.4 at the end of this section. Our major findings are:

(1) There are no significant production cost differences between the thermochemical water splitting plant coupled to a VHTGR and the alkaline electrolysis plant coupled to a LWR. The levelized cost for the former option ranges between \$1.40-\$2.72/kg of H_2 (average \$1.95/kg) versus \$1.63-\$2.79/kg of H_2 (average \$2.21/kg) for the latter option.

(2) With optimistic production efficiency (50%), technological advances and improved capital costs, the levelized costs of the thermochemical production option become as low as \$1.40/kg (at the plant) and therefore competitive with current average gasoline prices at \$1.81/gal (at the pump)[64] provided that the transmission and delivery cost is less than \$0.41 kg of H_2.

[63] (a) 1 kg of H_2 ~ 1.18 gallon of gasoline in energy content. Energy content of a gallon of gasoline changes between 109,000 and 125,000 Btu. The average is about 114,000 Btu. This is approximately equal to a kilogram of hydrogen with energy content of 113,691 Btu (LHV) or 134,382 Btu (HHV).
(b) In 2003, U.S. motor gasoline consumption is approximately 359 million gallon per day calculated from weekly data of supplied gasoline products published by the U.S. Department of Energy, Energy Information Agency; see http://www.eia.doe.gov/oil_gas/petroleum/info_glance/gasoline.html.

[64] Average over all type of gasoline in the U.S. in March 2004. Source:U.S. Department of Energy, Energy Information Administration. Available at http://www.eia.doe.gov/emeu/mer/pdf/pages/sec9_6.pdf.

(3) Our results are relatively cautious with respect to the results of several other studies. The major difference is in the case of thermochemical hydrogen production. We believe the capital cost estimates of $350-$400 kWth used in several earlier studies for the VHTGR may be overly optimistic. Our estimates are in the range of $400 to $800/kWth.

(4) The two major uncertainties associated with large scale hydrogen production are capital cost and performance of interface systems connecting hydrogen production, storage and delivery.

(5) This study does not advocate or favor either thermochemical hydrogen production or hydrogen production via electrolysis. Our focus is to provide an objective and comparative technical assessment that is simple and explicit in all the baseline assumptions and methods used. Nevertheless, the results suggest that given the existing technical and cost uncertainties, developing the VHTGR technology solely for the use of thermochemical hydrogen production is not good energy (R&D) policy. Electrolysis is a more promising alternative provided a more efficient electrolysis technology can be coupled to an advanced nuclear energy (i.e., electricity) source at a reasonable cost.

Despite increasing public and private support, the future of hydrogen economy is not certain. There are a number of technological, economic and institutional barriers that obscure the vision of hydrogen economy even in the long term. Transition to a hydrogen energy infrastructure requires the creation of a market that is competitive with other fuels and energy sources. Yet there is no consensus on how this could be achieved. Nevertheless, hydrogen remains a promising energy carrier. We hope this study contributes to future planning towards a realistic tomorrow for hydrogen.

Table 3.2 The estimated costs of thermochemical hydrogen production using VHTGR-SITC. See Table 3.4 for details.

Very High Temperature Gas Reactor (VHTGR), 2400MWth, with thermochemical hydrogen conversion										
Production		I	II	III	IV	V	VI	VII	VIII	IX
Capacity, MW-th	(1)		2400			2400			2400	
Capacity, MW-H_2	(2)		720			960			1,200	
H_2 production, (000) MT/y	(3)		144.1			192.1			240.1	
Capital cost, $/kWth	(4)	400	600	800	400	600	800	400	600	800
Capital cost, $/kW-$H_2$	(5)	1,333	2,000	2,667	1,000	1,500	2,000	800	1,200	1,600
Capital charge, $/kW-$H_2$-y	(6)	156.6	234.9	313.2	117.5	176.2	234.9	94.0	141.0	187.9
O&M, $/kW-$H_2$-y[65]	(7)		78.8			78.8			78.8	
Conversion plant										
η_{conv}			30.0%			40.0%			50.0%	
Capital cost, (000) $	(8)		686,400			686,400			686,400	
H_2 conversion plant, $/kW-th	$(8)_1$		286.0			286.0			286.0	
H_2 conversion plant, $/kW-$H_2$	$(8)_2$		953.3			715.0			572.0	
Capital charge, $/kW-$H_2$-y	(9)		112.0			84.0			67.2	
O&M, $/kW-$H_2$-y	(10)		39.4			39.4			39.4	
Sub total, $/kW-$H_2$		2,287	2,953	3,620	1,715	2,215	2,715	1,372	1,772	2,172
Annual cost										
Capital charge, $/kW-$H_2$-y	(11)	268.6	346.9	425.2	201.4	260.2	318.9	161.2	208.1	255.1
O&M, $/kW-$H_2$-y	(12)		118.3			118.3			118.3	
Sub total annual total $/kW-$H_2$-y	(13)	386.9	465.2	543.5	319.7	378.4	437.2	279.4	326.4	373.4
H_2 cost at central plant, $/kg	(14)	1.93	2.32	2.72	1.60	1.89	2.18	1.40	1.63	1.87

Table 3.3 The estimated costs of electrolytic hydrogen production using LWR-AE. See Table 3.4 for details.

Light Water Reactor (LWR), 2400 MWth (800 MWe), electrolytic production of hydrogen										
Production		I'	II'	III'	IV'	V'	VI'	VII'	VIII'	IX'
Thermal efficiency η_{th}			33.3%			33.3%			33.3%	
Capacity, MW-th	(1')		2400			2400			2400	
Capacity, MW-H_2	(2')		640			640			640	
H_2 produced, (000) MT/y	(3')		128.1			128.1			128.1	
Capital cost, $/kWth	(4')	333	500	667	333	500	667	333	500	667
Capital cost, $/kWe	$(4')_1$	1,000	1,500	2,000	1,000	1,500	2,000	1,000	1,500	2,000
Capital cost, $/kW-$H_2$	(5')	1,250	1,875	2,500	1,250	1,875	2,500	1,250	1,875	2,500
Capital charge, $/kW-$H_2$-y	(6')	146.8	220.2	293.6	146.8	220.2	293.6	146.8	220.2	293.6
O&M, $/kW-$H_2$-y[65]	(7')		78.8			78.8			78.8	
Conversion plant										
η_{elec}			80.0%			80.0%			80.0%	
Capital cost, (000) $	(8')		928,000			696,000			464,000	
Electrolysis, $/kWe	$(8')_1$		1,160			870			580	
Electrolysis, $/kW-$H_2$	$(8')_2$		1,450			1,088			725	
Capital charge, $/kW-$H_2$-y	(9')		170.3			127.7			85.2	
O&M, $/kW-$H_2$-y	(10')		15.8			15.8			15.8	
Sub total, $/kW-$H_2$		2,700	3,325	3,950	2,338	2,963	3,588	1,975	2,600	3,225
Annual cost										
Capital charge, $/kW-$H_2$-y	(11')	317.1	390.6	464.0	274.6	348.0	421.4	232.0	305.4	378.8
O&M, $/kW-$H_2$-y	(12')		94.6			94.6			94.6	
COE of nuclear plant cents/kWe-h		2.9	3.8	4.7	2.9	3.8	4.7	2.9	3.8	4.7
Sub-total annual total $/kW-$H_2$-y	(13')	411.7	485.2	558.6	369.2	442.6	516.0	326.6	400.0	473.4
H_2 cost at central plant, $/kg	(14')	2.06	2.42	2.79	1.84	2.21	2.58	1.63	2.00	2.37

Table 3.4 Assumptions, definitions of variables and methods of calculation of values presented in Table 3.2 and Table 3.3. (1 MT = 1 metric tonnes; COE: Cost of Electricity)

	Table 3.2 (VHTGR)	Table 3.3 (LWR)	Assumptions, definitions of variables and methods of calculation	
Production			90% capacity	
Thermal efficiency, η_{th}				33.3% for LWR
Capacity, MW-th	(1)	(1')	(1) = (1') = 2400 MWth	
Capacity, MW-H_2	(2)	(2')	(2) = (1) x η_{conv}	(2')= (1') x η_{th} x η_{elec}
H_2 produced, (000) MT/y	(3)	(3')	(3) = (2) x 200.1	(3') = (2') x 200.1
Capital cost, $/kWth	(4)	(4')	(4) = $(4')_1$ x 1.2 given (4')	
Capital cost, $/kWe		$(4')_1$		(4') / η_{th}
Capital cost, $/kW-$H_2$	(5)	(5')	(5) = (4) x (1) / (2)	(5') = $(4')_1$ / η_{elec}
Capital charge, $/kW-$H_2$-y	(6)	(6')	(6) = (5) x 11.75%	(6') = (5') x 11.75%
O&M, $/kW-$H_2$-y	(7)	(7')	(7) = (7') = 78.8 $/kW-$H_2$-y[65]	
Conversion				
η_{conv}			30%; 40%; 50%	
η_{elec}				80%
Capital cost (000)$	(8)	(8')	(8) = $(8)_2$ x (2)	(8') = $(8')_1$ x (1') x η_{th}
H_2 conversion plant, $/kW-th	$(8)_1$		$(8)_1$ = (8) / (1)	
H_2 conversion plant, $/kW-$H_2$[66]	$(8)_2$	$(8')_2$	953.3; 715.0; 572.0	$(8')_2$ = (8') / (2')
Electrolysis, $/kWe[67]		$(8')_1$		$580; 870; $1,160
Capital charge, $/kW-$H_2$-y	(9)	(9')	(9) = (8') x 11.75%	(9') = $(8')_2$ x 11.75%
O&M, $/kW-$H_2$-y	(10)	(10')	(10) = 50% x (7)	(10') = 20% x (7')
Annual cost				
Capital charge, $/kW-$H_2$-y	(11)	(11')	(11) = (6) + (9)	(11') = (6') + (9')
O&M, $/kW-$H_2$-y	(12)	(12')	(12) = (7) + (10)	(12') = (7') + (10')
COE from LWR, cents/kWe-h			[(6') + (7')] / (365 x 24 x 0.9) x 100 cents / $	
Sub total annual, $/kW-$H_2$-y	(13)	(13')	(13) = (11) + (12)	(13') = (11') + (12')
H_2 cost at central plant, $/kg	(14)	(14')	(14) = (13) x (2) / [(3) x 1000] (14') = (13') x (2') / [(3') x 1000]	

[65] Based on 1 cent/kWe-h. Constant over all nine cases listed in Table 3.2 and 3.3. Depending on the capital cost, O&M cost accounts for the 2.96 % and 9.85% of the capital cost for the VHTGR, and 3.15% and 6.30% for the LWR, including fuel.

[66] (a) Brown *et al.*, (2003) reports a hydrogen plant capital cost of $572/kW-$H_2$. (See Footnote 68, Table Ex.1, p.vii; Table 3.13, p.3-34; Table 3-35, p.3-36)

(b) Our estimated overnight capital cost changes with efficiency: lower the efficiency higher the overnight capital cost. For 50% efficiency, the capital cost is $572/kW-$H_2$, same as that by Brown *et al.* For 40%, capital cost is $715/kW-$H_2$ (=$572 x 5/4); and for 30%, it is $953.3/kW-$H_2$ (=$572 x 5/3).

[67] Based on overnight capital cost of $400, $600 and $800/kWe and plus 20% for general facilities, 10 % for engineering, permitting & startup, 10% for contingencies, 5% for land & miscellaneous expenses.

3.2 Thermochemical hydrogen production

The thermochemical hydrogen production option employs a Very High Temperature Nuclear Reactor (VHTGR) to provide high temperature heat needed by a central conversion plant to thermochemically split water to produce hydrogen.

To keep our system design simple we did not include storage in our efficiency and cost analysis since storage technologies (either in compressed form in tanks or underground, or liquefied form stored in tanks), scale and costs strongly depend on the type of application, e.g., central or distributed storage. We also did not include a transmission or delivery system for hydrogen in our analysis. Nevertheless, we envision that central production can be connected to a gaseous hydrogen pipeline that delivers fuel to a city gate, which can further be connected with distributed energy plants via smaller pipelines. For pipeline design and efficiency considerations, see Appendix 3.C.

3.2.1 Technology

Thermochemical hydrogen production envisions use of a 2400-MWth VHTGR to supply high-temperature process heat for a hydrogen plant that produces hydrogen using thermochemical water splitting. Major systems components of the thermochemical hydrogen production are given in Figure 3.1. The VHTGR is composed of four 600-MWth Modular Helium Reactors (MHR), and the thermochemical process is the Sulfur-Iodine (S-I) Cycle. Estimated production rate at 90% capacity factor is 144.1 thousands tonnes/y at 30% conversion efficiency. (Table 3.2.)

The MHR-SI production scheme has been proposed by the team of General Atomics (GA), Sandia National Laboratories (SNL), and the University of Kentucky (UK) supported by the Nuclear Energy Research Initiative (NERI) Program for the U.S. Department of Energy.[68]

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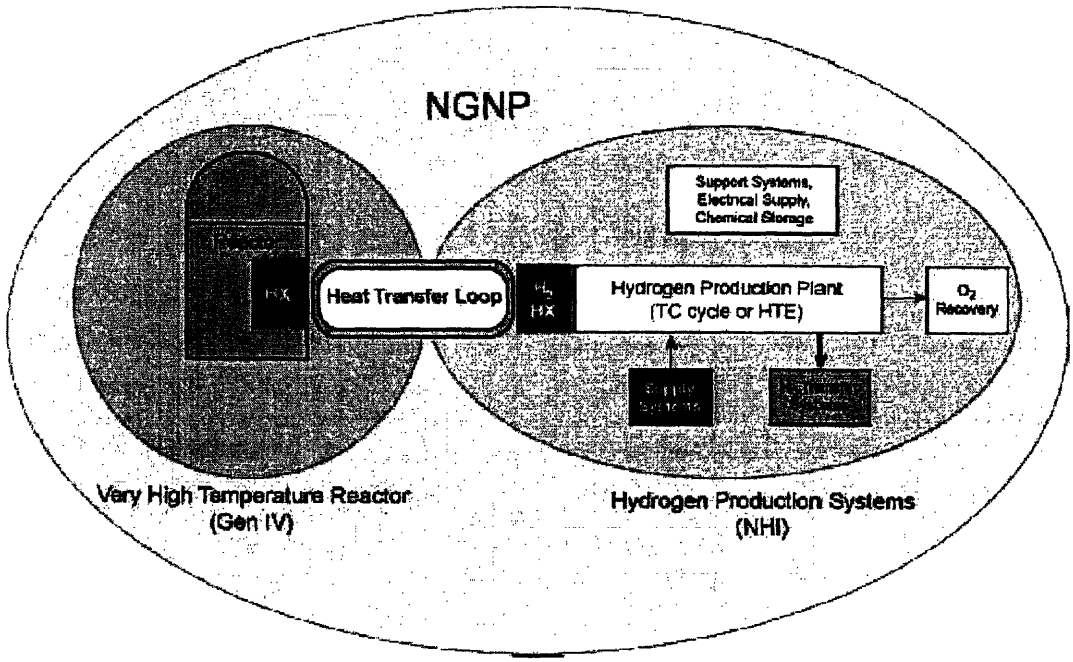
[68] Brown, L.C., Besenbruch, G. E., Lentsch, R. D.,Shultz, K. R., Funk, J. F., Pickard, P. S., Marshall, A. C., Showalter, S. K. "*High efficiency generation of hydrogen fuels using nuclear power*," GA-A24285 (2003); L.C Brown, J.F. Funk, S. K. Showalter, "*High efficiency generation of hydrogen fuels using nuclear power*," GA-A23451 (2000); A. C. Marshall, "*An assessment of reactor types for thermochemical hydrogen production*," SAND2002-0513 (2002).

Figure 3.1 Major systems components of the thermochemical hydrogen production[69]



NGNP: Next Generation Nuclear Plant (which is Very High Temperature Gas Reactor, VHTGR, in our case); Gen IV: Generation IV[70]; NHI: Nuclear Hydrogen Initiative; TC: Thermochemical; HTE: High Temperature Electrolysis; HX: Heat Exchange

3.2.1.1 Process reactions

Sulfur-Iodine cycle is a three-reaction thermochemical process that uses water (H_2O) and high heat (T>850 °C) to produce hydrogen and oxygen. (See Table 3.5 and Figure 3.2 for details.) Sulfuric acid (H_2SO_4) decomposes into oxygen (O_2), sulfur dioxide (SO_2), and water in Reaction I. After separation of oxygen, the products are combined with iodine (I_2) and water in Reaction II to produce hydrogen iodide (HI) and H_2SO_4, which is recycled back into Reaction I. In Reaction III, HI is decomposed into H_2 and I_2. The net reaction is thermochemical decomposition of H_2O into H_2 and O_2.

Available at http://www.osti.gov/dublincore/gpo/servlets/purl/821587-ThHkOV/native/821587.pdf.

[69] Taken from U.S. DOE, Office of Nuclear Energy, Science and Technology, Nuclear Energy Research Initiatives, "Nuclear Hydrogen R&D Plan – Draft" Figure 5-1, p 5-2. Last updated May 04, 2004. Available at http://neri.inel.gov/program_plans/pdfs/nhi_plan.pdf.

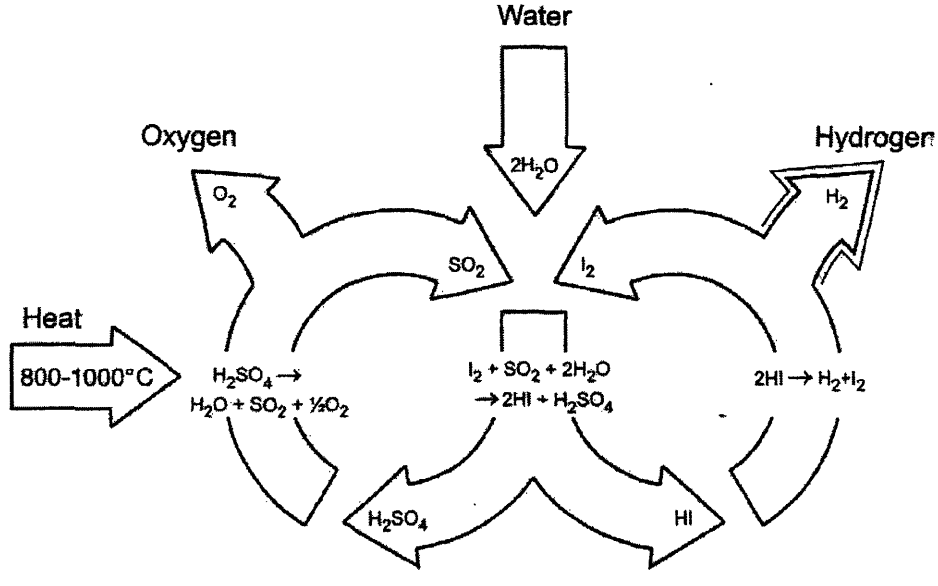
[70] "Generation IV refers to the development and demonstration of one or more [next] Generation IV nuclear energy systems that offer advantages in the areas of economics, safety and reliability, sustainability, and could be deployed commercially by 2030." Quoted from http://gen-iv.ne.doe.gov/ on November 12, 2004.

Table 3.5 Sulfur-Iodine cycle

	Reaction	T (°C)	ΔG (kJ/mol)	ΔH (kJ/mol)
I	$H_2SO_4(l) \rightarrow ½O_2(g)+SO_2(g) + H_2O(g)$	850	-66.7	+185.5
II	$I_2(g) + SO_2(g) + 2H_2O(g) \rightarrow H_2SO_4(l) + 2HI(g)$	120	-44.9	-220.2
III	$2HI(g) \rightarrow I_2(g) + H_2(g)$	450	+45.3	-17.6
I+II+III	$H_2O(g) \rightarrow H_2(g) + ½O_2(g)$	25	241.8	228.6

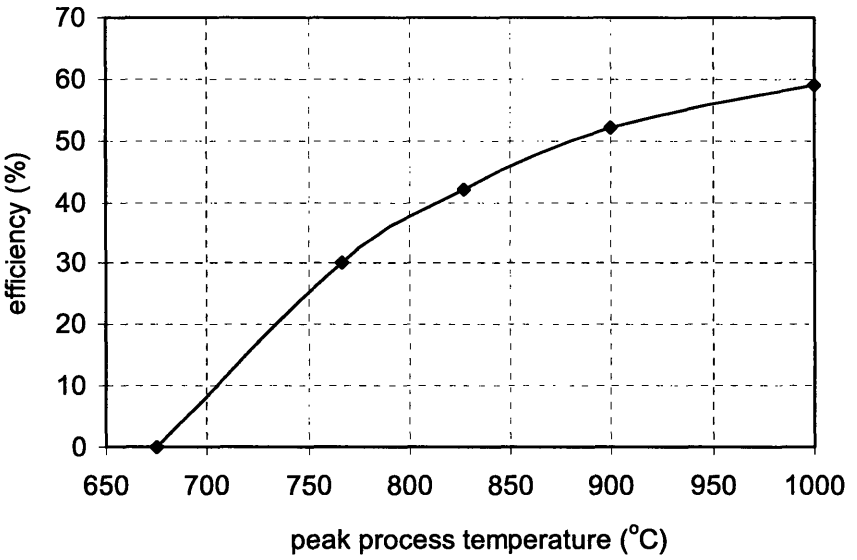
ΔG: Gibbs free energy; ΔH: Enthalpy. ΔG and ΔH values are defined for the specific temperatures given above. The reported reaction temperature ranges are T>800 °C for Reaction I, T>120 °C for Reaction II and T>300 °C for Reaction III. Note that for the net reaction ΔG and ΔH are not equal to the sum of reactions I, II and III, which is true only if ΔG's and ΔH's are defined for standard conditions for all reactions.

Figure 3.2 Sulfur-iodine cycle[71]



[71] Adapted from Forsberg, C. W., "Hydrogen, nuclear energy, and the advanced high-temperature reactor," *Intl. J. Hydrogen Economy*, 28, 1073 (2003).

Figure 3.3 Estimated hydrogen production efficiencies as a function of peak process temperatures[72]



3.2.1.2 Process efficiency

The S-I cycle requires process temperatures in the range of 750 to 880 °C for efficiencies between 30% and 50%. Brown *et al.* estimated an efficiency of 42% for a production rate of 213 thousands tonnes/y for a peak temperature of 827 °C in the process fluid.[68] For 52% production efficiency and 264 thousands tonnes/y production rate, a peak process temperature of 900 °C was estimated.[73]

Recent efficiency estimates by Brown *et al.* based on the thermochemical modeling and simulations conducted by Aspen Technologies[68, 74] are given in Figure 3.3. Note that Brown *et al.* generated this curve by extrapolating the calculated efficiency of 42% efficiency at T=827 °C to higher temperature to approach the Carnot efficiency of 80%

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[72] Brown *et al.* (2003) (Footnote 68), Figure 3-9 p. 3-24.

[73] For 42% of efficiency and 827 °C process temperature, the reactor outlet temperature is 850 °C, indicating a heat exchange efficiency of 97.3%. For 52% of overall efficiency and 900 °C process temperature, the reactor outlet temperature is 950 °C, indicating a heat exchange efficiency of 94.7%.

[74] See Footnote 68 (Brown *et al.*), Appendix C and D.

for temperatures above the kinetic limit. The other four points are interpolated by the author. Also note that below T=675 °C, the H_2SO_4 decomposition is negligible.

In our analysis, we assumed heat-to-hydrogen conversion efficiencies of 30%, 40% and 50%, which corresponds to hydrogen production rates of 144.1 million, 192.1 million and 240.1 million tonnes/y, or production capacity of 720, 960 and 1,200 MW-H_2 (with 90% capacity factor), respectively. Note that these efficiency values incorporate the uncertainties in the VHTGR outlet temperature as well as the uncertainties in the efficiency of the thermochemical conversion plant. We believe the conversion plant is a considerable source of efficiency and cost uncertainties since there is no pilot or commercial thermochemical water splitting plant that has ever operated.

This is an important factor in our cost projection because heat-to-hydrogen conversion efficiency affects the unit kW-H_2 cost of the thermochemical conversion plant. Brown *et al.* scaled the overall capital cost of the conversion plant linearly to the estimated production output and kept the unit capital cost per kW-H_2 constant. Therefore the overnight capital cost of the conversion plant changed according to the projected efficiency. That is, for a lower efficiency, i.e., a lower hydrogen production rate, the overnight capital cost of the conversion plant was lower.

Given the highly complex nature of the chemical processes involved, we take a different approach. We scaled the unit cost per kW-H_2 according to the efficiency: lower the efficiency, higher the unit cost. This scaling lead to a constant total capital cost for the conversion plant. See the text in the following section and Table 3.6 for more detail.

3.2.2 Production Cost

Our overnight capital cost assumptions for the VHTGR-SITC option are

(1) The overnight capital cost of VHTGR per kW-th is 20 % higher than that of the LWR that provides electricity to the electrolysis plant in the alternative electrolytic hydrogen production option[75], and

(2) The overnight capital of the thermochemical conversion plant per kW-H_2 changes with the heat-to-hydrogen conversion efficiency. The lower the efficiency the higher the unit capital cost per kW-H_2.

Table 3.6 Summary of capital cost assumptions for VHGTR and LWR-AE options[76]

	VHTGR-SITC option			**LWR-AE option**		
Production						
Thermal Efficiency				33.3%		
Capacity, MW-th		2400		2400		
Capacity, MWe				800		
Capacity, MW-H2	720	960	1,200	720		
Hydrogen production, (000) MT/y	144.1	192.1	240.1	160.1		
Capital Cost, $/kWth		400; 600; 800		333; 500; 667		
Capital Cost, $/kWe				1,000; 1,500; 2,000		
Capital Cost, $/kW-H2	1,333 2,000 2,667	1,000 1,500 2,000	800 1,000 1,200	1,250; 1,875; 2,500		
Conversion plant						
η_{conv}	30%	40%	50%			
η_{elec}				80%		
Capital cost, (000) $		686,400		928,000	696,000	464,000
Thermochemical conversion, $/kW-$H_2$	953.3	715.0	572.0			
Electrolysis, $/kWe				1,160	870	580
Electrolysis, $/kW-$H_2$				1,450	1,088	725

[75] The assumed capital cost of LWR includes electricity generation and transmission, which are estimated to be 20% of the overnight capital cost. The VHTGR does not produce electricity; therefore, does not require generation and transmission equipments, which would lower the overnight capital cost.

[76] For other cost assumptions, definitions of variables and methods of calculation see Tables 3.2, Table 3.3 and Table 3.4.

The overnight capital cost assumptions we used for the VHTGR are $400, $600 and $800/kW-th. These estimates are 20% more than our assumed overnight capital costs of a conventional LWR of 33% thermal efficiency, which are $333, $500 and $667/kW-th, respectively. We think of this additional 20% as the "technology premium" for the VHGTR.[75, 77]

For the thermochemical conversion plant, we estimated the overnight capital cost as follows. We used the used the Brown *et al.*'s estimate of $572/kW-$H_2$ as the overnight capital cost for our most optimistic conversion efficiency case (i.e., 50%). Then, we scaled the overnight (unit) capital cost ($/kW-$H_2$) according to the efficiency: lower the efficiency, higher the capital cost. That is for 40% efficiency, capital cost is $715/kW-$H_2$ (= $572 x 5/4); and for 30%, it is $953.3/kW-$H_2$ (= $572 x 5/3). Therefore, the total investment required to build the conversion plant stays constant at $686.4 million. The reason we adopted this method is because it is more realistic given the uncertainties in the conversion system's performance for such a complex thermochemical process with no commercial precedent.

The corresponding total capital costs for the VHTGR and the conversion plant are in the range of $2,287 to $3,620/kW-$H_2$ for 30% efficiency; $1,715 to $2,715/kW-$H_2$ for 40% efficiency; and $1,372 to $2,172/kW-$H_2$ for 50% efficiency. For O&M cost assumptions and other details, see Table 3.2 and Table 3.4

To assess the sensitivity of the hydrogen production cost to the overnight capital cost, we considered nine combinations: for each of the three conversion plant capital cost choices, we have three choices of VHTGR capital cost. We used a simple spread sheet method to calculate the cost per kg of hydrogen as shown in Table 3.2 and explained in Table 3.4. Other assumptions include capital charge of 11.75%, VHTGR O&M cost of 78.8 $/kW$H_2$-y and 39.4 $/kW$H_2$-y for the conversion plant.[78] (Also see Footnote 65)

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[77] Table 3.6 shows that the overnight capital costs for VHTGR are in the range of $400 to $800/kW-th compared to the original estimates of Brown *et al.* (Footnote 68), which range between $362 and $410 /kW-th. For 42% efficiency, Brown *et al.* reports a reactor overnight capital cost of $867.9 M ($362 /kWth or $861 /kW-$H_2$). For 52% efficiency capital cost is given as $984.2 M ($410 /kWth or 789 /kW-H_2).

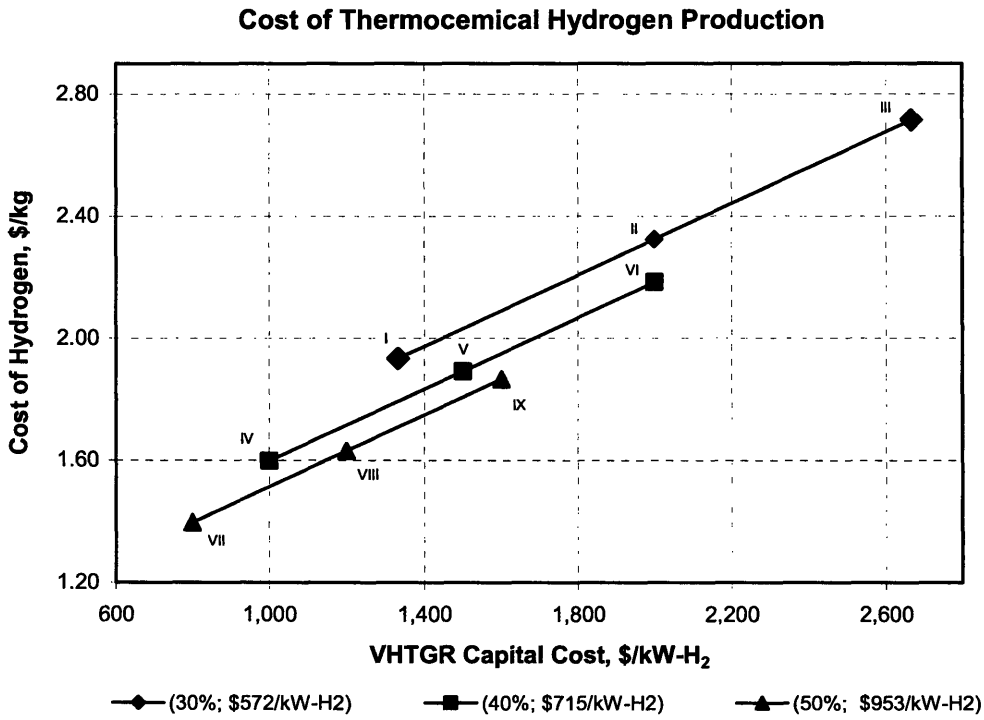
[78] Capital charge of 11.75% corresponds to 10% interest over 20 years of operation. The annual O&M cost of VHTGR is taken the same as that of LWR. Conversion O&M is taken as 50% of that of VHTGR.

Table 3.7 Levelized cost sensitivity matrix for central-thermochemical H_2 production. Production costs are given in \$/kg of H_2.

		Overnight capital cost of VHTGR, \$/kW-th		
		400	**600**	**800**
Thermochemical conversion plant efficiency	**30%**	\$ 1.93	\$ 2.32	\$ 2.72
	40%	1.60	1.89	2.18
	50%	1.40	1.63	1.87

For the conversion plant, the conversion efficiencies of 30%, 40% and 50% correspond to overnight capital costs of \$953, \$715, and \$572/kW-H_2 respectively.

Figure 3.4 Sensitivity of the hydrogen production cost to the capital cost of VHTGR as a function of heat-to-hydrogen conversion efficiency and total capital cost of the thermochemical conversion plant. Roman numbering follows the numbering of the columns in Table 3.2.



(%; \$/kW-H_2) = (conversion efficiency; the corresponding capital cost of the conversion plant)

The calculated levelized costs of hydrogen change in the range of $1.93 to $2.72/kg for 30% efficiency; $1.60 to $2.18/kg for 40% efficiency; and $1.40 to $1.87/kg for 50% efficiency. Table 3.7 displays these results as a function of overnight capital cost of VHTGR and the efficiency of the conversion plant. Figure 3.4 plots these results as a function of the production cost in $/kg and capital cost of the VHTGR in $/kW-$H_2$.

As expected, the production cost decreases with increasing efficiency: the average costs goes from $2.32 to $1.89, and then to $1.63 /kg as the conversion efficiency increases from 30% to 40% and then to 50%. Brown *et al.*'s original estimates are $1.53 /kg for 42% efficiency and $1.42 /kg for 52% efficiency, which are about 25% lower than our estimates on average.[79] In the worst-case scenario (with the highest capital cost requirements for the VHTGR and the conversion plant), the difference is as high as 55% ($2.72/kg estimated by this study compared to Brown *et al.*'s $1.53/kg.) The difference is mostly due to Brown *et al.*'s lower capital cost estimates for the VHTGR.

A comparison of the average total capital and production costs shows that for 1.5% decrease in total capital cost leads to a 1% decrease in the production cost.

[79] For 10.5% capital recovery factor (CRF). For 12.5% CRF, Brown *et al.* (Footnote 68) reports $1.69 /kg for 42% efficiency and $1.57 /kg for 52% efficiency. For 16.5% CRF, Brown *et al.* gives $2.01 /kg for 42% efficiency and $1.87 /kg for 52% efficiency. For more detail, see Brown *et al.* (2003), Table 3-16, p. 3.38

3.3 Electrolytic hydrogen production

Electrolytic hydrogen production option consists of central hydrogen production in a large electrolysis plant coupled to a conventional Light Water Reactor (LWR). As we did in the thermochemical hydrogen production option, we focus on the production and exclude other infrastructure components such as storage, transmission and delivery.

3.3.1 Technology

The electrolytic hydrogen production option models a large 800 MWe electrolysis plant with hydrogen production capacity of 720 MW-H_2 at 80% electrolysis efficiency. The electrolysis plant receives its electricity supply from a LWR of 2400 MW-th with 33.3% thermal efficiency (800 MWe). The corresponding production capacity is 160,081 tonnes/y.

We project that this large scale electrolysis plant will employ conventional alkaline (KOH: Potassium Hydroxide) electrolysis for there is greater experience with this technology in hydrogen production.[80, 81] The alternative PEM electrolysis is relatively new. It has been primarily used for small scale applications on the order of 5 *kW* (~3 kg/d) that are usually modeled for residential applications.[80]

In alkaline electrolysis of water, hydrogen is produced by passing electricity through the two electrodes (i.e., anode and cathode) in water. Hydrogen is produced at the anode:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-,$$

and oxygen is produced at cathode:

$$2OH^- \rightarrow \tfrac{1}{2}O_2 + 2H_2O + 2e^-.$$

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[80] Basye, L., Swaminathan, S. "Hydrogen production costs – a survey" U.S. Department of Energy, DOE/GO/10170-T18 (1997).
Available at http://www.osti.gov/dublincore/gpo/servlets/purl/674693-UIUZUy/webviewable/674693.pdf.

[81] Thomas, C. E., Kuhn, I. F., "Electrolytic hydrogen production infrastructure options evaluation. Final subcontract report," U.S. National Renewable Energy Laboratory, NREL/TP-463-7903 (1995).
Available at http://www.osti.gov/dublincore/gpo/servlets/purl/125028-MGPbw5/webviewable/125028.pdf.

3.3.1.1 Electrolysis Efficiency

The electrolysis plant uses alkaline electrolysis technology with 80% efficiency based on high heating value (HHV) of hydrogen. This production efficiency is similar to several other estimates in the literature, which on average assumed 80% energy efficiency.[80, 81, 82, 83, 84] The overall electrolytic hydrogen production efficiency is then 26.7%.[85]

When coupled to an advanced nuclear reactors that can provide both the electricity and the heat, high-temperature electrolysis (HTE, or steam electrolysis) technology may achieve close to 50% overall (heat-to-hydrogen) conversion efficiency. In HTE, high-temperature steam is separated at the anode as ions of oxygen pass through an ion conducting membrane away from the steam. The input stream to the electrolyzer is about 50:50 steam and hydrogen. The output is typically 75:25 hydrogen:steam by volume. Hydrogen can then be separated from the steam in a condensing unit. Additional steam is added after the removal of about 1/3 of the hydrogen to produce the 50:50 gas stream for the reintroduction to the electrolyzer. Recently Idaho National Engineering and Environmental Laboratory (INEEL), in collaboration with Cerametec Inc, Salt Lake City, UT), announced the experimental results that showed 50% heat-to-hydrogen conversion efficiency using HTE.[86] Another important point is the temperature sensitivity of the overall efficiency of such as VHTGR-HTE system is likely to be lower than that of a VHTGR-SITC system.[87]

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[82] The largest alkaline commercial alkaline electrolysis system today is the Norsk-Hydro's atmospheric pressure system Type No.5040, which delivers up to 381.9 tonnes/y with 80% conversion efficiency. See the reference in footnote 84, Table 3, p.8.

[83] The National Academy of Sciences (NAS), "*The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*" (Washington, DC: National Academy Press, 2004).
Prepublication copy available at http://books.nap.edu/books/0309091632/html/1.html.

[84] Ivy, J. "Summary of Electrolytic Hydrogen Production – Milestone Completion Report," U.S. National Renewable Energy Laboratory, NREL/MP-560-36734 (2004).
Available at www.nrel.gov/docs/fy04osti/36734.pdf

[85] 26.7% = 33.3% for LWR x 80% for electrolysis

[86] M. L. Wald, "Hydrogen Production Method Could Bolster Fuel Supplies," *New York Times*, 27 November 2004.

[87] See Yildiz & Kazimi, Footnote 96, Figure 14.

3.3.2 Production Cost

Our assumed overnight capital costs for a conventional LWR with 33% thermal efficiency are $333 ($1,000), $500 ($1,500) and $667 ($2,000) /kW-th (/kWe). For 80% electrolysis efficiency, these become $1,250, $1,876 and $2,500 /kW-$H_2$.

The capital cost estimates for alkaline electrolyzers given in the literature range from $400 to $1200 /kWe.[80, 81, 83] The three capital cost assumptions we used are $400, $600 and $800/kWe. To calculate the installed capital costs we assumed 20% for general facilities, 10 % for engineering, permitting & startup, 10% for contingencies, 5% for land & miscellaneous and obtained $580, $870, and $1,160/kWe.[88, 89] These in turn correspond to $725, $1,088 and $1,450/kW-$H_2$ taking into account the 80% electrolysis efficiency. We then have nine possible total capital costs for the coupled LWR-alkaline electrolysis system which ranges from $1,975 to $3,950/kW-$H_2$.[90] These costs are as listed in Table 3.3 and Table 3.6. We then calculated the nine different hydrogen production costs per kg of hydrogen using the same simple spread sheet method used in Table 3.3 and Table 3.4. Other major assumptions include capital charge of 11.75%[78], O&M cost of 1 cents/kWe-h (78.8 $/kW$H_2$-y) for the LWR plant and 0.2 cents/kWe-h (15.8 $/kW$H_2$-y) for the electrolysis plant. (Also see Footnote 65)

The calculated levelized costs of hydrogen change in the range of $1.63 to $2.79/kg with average of $2.21/kg. Table 3.8 lists these result as a function of overnight capital cost of LWR and the overnight capital cost of the electrolysis plant. Figure 3.5 plots

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[88] To calculate the installed capital costs, we followed the same approach as references in Footnote 83 and Footnote 97.

[89] Electrolysis does not benefit from economies of scale for applications above 200 kWe. Estimated from an empirical formula modeling the cost of hydrogen production per Nm^3 using electrolysis as a function of plant size in Nm^3/d in p.7, Eq.4 by Raissi *et al*, (2003).

$$Cost_{Electrolysis} = 0.224576 + 15.20497 \cdot (\text{Plant Size})^{-1.03149}$$

where $Cost_{Electrolysis}$=Production cost of hydrogen, $/$Nm^3$, and Plant Size=Hydrogen production capacity, Nm^3/d. (1 kg = 11.12 Nm^3; 1 kg of H_2=39.4 kWh.) Source: Raissi, T-, A., Gu, L., Huang, C., Elbaccouch, M., Robertson, T., "System analysis of hydrogen production and utilization at Kennedy Space Center," Florida Solar Energy Center (2003).
Available at http://www.fsec.ucf.edu/hydrogen/finalrpt-2002-2003.htm

[90] For each of the three capital cost estimates for LWR, there are three choices for the electrolyzer capital cost.

these results as a function of the production cost in $/kg versus capital cost of the VHTGR in $/kW-$H_2$.

A comparison of the average total capital and production costs shows that for 1.3% decrease in total capital cost leads to a 1% decrease in the production cost.

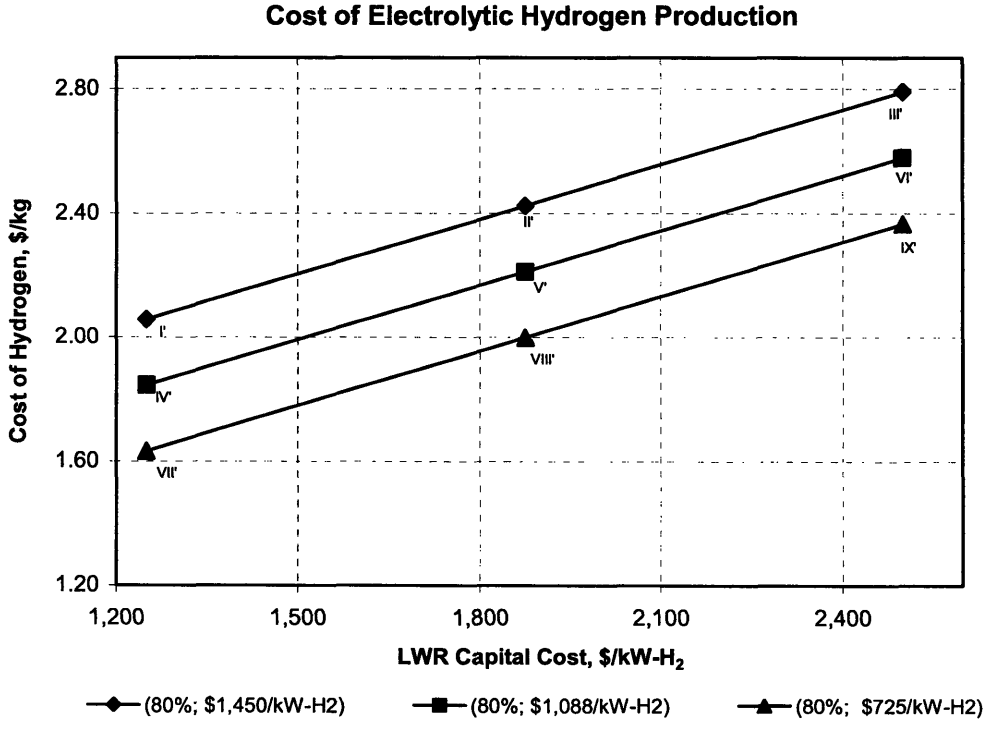
Although an explicit cost calculation is not included in this study, a VHTGR-HTE system is more advantageous in reducing the uncertainties in the hydrogen-production cost because the temperature sensitivity of the overall efficiency of a VHTGR-HTE system is likely to be lower than that of a VHTGR-SITC system.[87] Although the capital cost of VHTGR is expected to be more than that of a LWR, relatively higher output temperature (i.e., higher thermal efficiency) would lead to a comparable cost of electricity. In addition, higher capital cost of HTE is likely to be offset by the higher efficiency with respect to alkaline electrolysis. Therefore, in the mid- and long-term VHTGR-HTE option may be superior to both VHTGR-SITC and LWR-AE options.[96]

Table 3.8 Levelized cost sensitivity matrix for electrolytic hydrogen production option. Costs are given in \$/kg of H_2.

		Overnight capital cost of LWR, \$/kW-th)		
		333	**500**	**667**
Overnight capital cost of electrolyzer, \$/kW-H_2	**725**	\$ 1.63	\$ 2.00	\$ 2.37
	1,088	1.84	2.21	2.58
	1,450	2.06	2.42	2.79

To obtain the capital cost in \$/kWe multiply by 0.8, which is the assumed electrolysis efficiency.

Figure 3.5 Sensitivity of the hydrogen production cost to the capital cost of LWR as a function of the capital cost of electrolyzers. Roman numbering follows the numbering of the columns in Table 3.3.

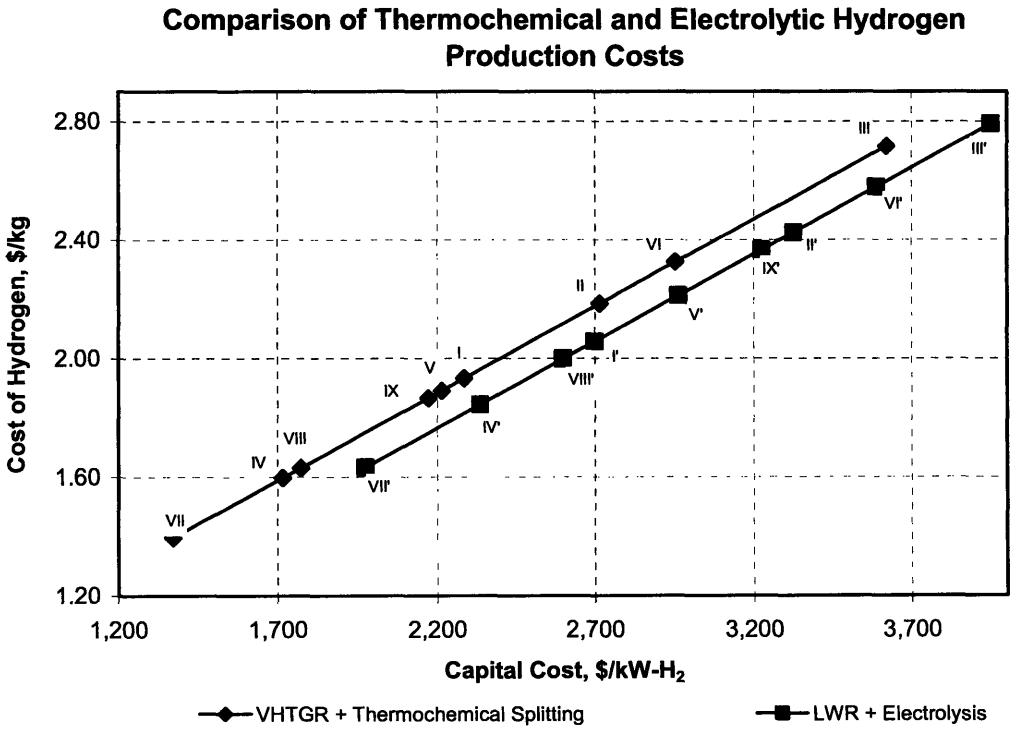


(%; \$/kW-H_2) = (electrolysis efficiency; the corresponding capital cost of the electrolysis plant)

3.4 Overall cost comparison

Figure 3.6 shows the comparison for thermochemical hydrogen production (squares) and electrolytic hydrogen production (diamonds) costs as a function of overnight capital cost in \$/kW-H_2. Each line has nine points representing the nine capital cost estimates used in the sensitivity analysis of the respective options. (See Table 3.2 and Table 3.4) Because the simple cost model we used is a linear model, the nine points in each case nicely fall on a straight line.

Figure 3.6 Comparison of the hydrogen production costs between thermochemical hydrogen production (squares) and electrolytic hydrogen production (diamonds) options. Each line has nine points representing the nine capital cost estimates used in the sensitivity analysis of the respective options. Roman numbering follows the numbering of the columns in Table 3.2 and Table 3.3. Note that because the simple cost model we used is a linear model, the nine points in each case fall on a straight line.



Our major results are

(1) There are no significant production cost differences between the thermochemical water splitting plant coupled to a VHTGR and the alkaline electrolysis plant coupled to a LWR within on our capital cost and efficiency estimates.

   (a) The levelized cost for the VHTGR-SITC option ranges between $1.40-$2.72/kg of H_2 (average $1.95/kg) versus $1.63-$2.79/kg of H_2 (average $2.21/kg) for that of LWR-AE option.

   (b) The production cost differences are negligible for conversion efficiencies up to 40% for the VHTGR-SITC option. If the conversion plant reaches efficiency above 40%, then the VHTGR-SITC option is superior to the electrolysis option.

   (c) For a given hydrogen production cost, the thermochemical hydrogen production option requires slightly less (~10%) capital investment. Considering the technological uncertainties associated with this option, the savings in capital investment are negligible.

(2) With optimistic production efficiency (50%), technological advances and improved capital costs, the levelized costs of the VHTGR-SITC production option become as low as $1.40/kg (at the plant) and therefore competitive with current average gasoline prices at $1.81/gal (at the pump)[64] provided that the transmission and delivery cost is less than $0.41 kg of H_2.

(3) Our conclusions are cautious compared to the results of several other studies. (See Section 5.) The major difference is in the case of thermochemical hydrogen production. We believe the capital cost estimates of $350-$400 kWth used in several earlier studies for the VHTGR may be overly optimistic. Our estimates are in the range of $400 to $800/kWth.

3.5 Comparison to recent studies

Although the hydrogen economy has recently become popular, it is not a new concept. The ideas of large scale hydrogen production using nuclear technology and electrolysis have been revisited occasionally as technology and public policymakers invested time, attention and money in hydrogen R&D.[91, 92] A search on the U.S. DOE's Office of Technology and Information database shows that there have been a total of 8719 entries related to these topics between 1948 and 2004.[93] A similar search using the search engine Google.com resulted in 96,810 hits.[94]

Hydrogen's increasing popularity as an alternative fuel for the future, the promise of new production technologies and increasing financial support for R&D have motivated systems analyses that evaluated the economic feasibility of different infrastructure pathways.[68, 80, 81, 83, 84, 95, 96, 97] We provide short descriptions of these studies in Tables 3.11 and 3.14.

Comparison of our assumptions and results with other studies are presented in Table 3.9 through Table 3.11 for electrolytic hydrogen production and in Table 3.12 through Table 3-14 for thermochemical hydrogen production.

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[91] Dickson, E. M., Ryan, J. W., Smulyan, M. H. "*The Hydrogen Energy Economy : A Realistic Appraisal of Prospects and Impacts*" (New York: Praeger Publishers, 1977)

[92] Winter, J. C., Nitsch, J., eds. "*Hydrogen As An Energy Carrier: Technologies, Systems, Economy*" (Berlin: Springer-Verlag,1988)

[93] Search conducted using the following expressions: "hydrogen economy" (1984 entries), "nuclear hydrogen production" or "nuclear energy and hydrogen production" (6066 entries total) and "electrolytic hydrogen production" or "electrolysis and hydrogen production" (669 entries total). Source: U.S. DOE, Office of Technology and Information at http://www.osti.gov/bridge/. Last accessed on June 15, 2004.

[94] Search with the same keywords as in Footnote 93. Source: http://www.google.com. Last accessed on June 15, 2004.

[95] Ogden, J. M.,"Prospects for building a hydrogen energy infrastructure," *Annu. Rev. Energy Environ.* **24**, 227 (1999)

[96] Yildiz, B., Kazimi S. M., "Nuclear Energy Options for Hydrogen and Hydrogen-based Liquid Fuel Production" MIT Center for Advanced Nuclear Energy Systems, MIT-NES-TR-001 (2003)

[97] Simbeck, D., Chang, E., "Hydrogen supply: cost estimate for hydrogen pathways – scoping analysis," U.S. National Renewable Energy Laboratory, NREL/SR-540-32525 (2002).
Available at http://www.nrel.gov/docs/fy03osti/32525.pdf.

3.5.1 Electrolytic hydrogen production studies

For the six studies listed in Table 3.9, the cost of electrolytic hydrogen production ranges between $1.63 (this study) and $5.13 /kg (Simbeck & Chang) for central production and $3.93 (NAS) and $12.1/kg (Simbeck & Chang) for distributed production. The 'average' cost of central electrolytic hydrogen production is $3.46/kg. The 'average' for distributed electrolytic production pathways is 9.34 /kg. With future technologies, the average estimated production costs are $2.10/kg for central electrolysis, and to $3.93/kg for distributed electrolysis.

Although the differences among these cost estimates may seem large, such variation can be explained by the differences in efficiency and cost assumptions.[98] To illustrate this assertion and to check the validity of our cost calculation method, we used the efficiency and cost assumptions of the latest three studies and calculated 'new' hydrogen production costs.[99] The results in Table 3.10 show that the differences between the previously reported hydrogen production costs and our estimates are attributed to the differences between the corresponding efficiency and capital cost assumptions.

The production rate for central electrolytic pathways changes between 150,000 tonnes/d (Simbeck & Chang)[97] and 395,000 tonnes/d (this study). The estimated cost of transmission by gaseous hydrogen pipeline is around $0.40/kg. For distributed pathways, the assumed production rate is about 480 kg/d (NAS).[83] All studies used capacity factor of 90% except Simbeck & Chang, who assumed 70% for distributed electrolysis. The assumptions for the cost of on-peak electricity ranges between 3.0 and 6.7 cents/kWe-h for central production and 6.0 and 9.2 cents/kWe-h for distributed electrolysis.

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[98] (a) For example, Ogden assumed moderately high electrolysis efficiency (85%), low electrolyzer capital cost ($300/kWe) and relatively lower cost of electricity (3 cents/kWe-h).

(b) Simbeck & Chang reported the highest cost for distributed electrolytic hydrogen production ($12.1/kg) due to a capital cost for electrolysis ($2,000/kWe), a relatively lower efficiency (75%), and high-cost electricity (9 cents/kWe-h on-peak, 4 cents/kWe-h off-peak).

[99] These 'new' costs are calculated by our method using the same capital and O&M cost, efficiency, capacity utilization, and capital recovery rate assumptions of the studies of Simbeck & Chang, NAS, and Yildiz & Kazimi). Note that several studies reported their total investment or operation costs, not the unit costs. The unit costs presented in Table 3.9 through Table 3.13 are deduced from these total costs by using the best available numbers (in the author's judgment). Therefore, the author is fully responsible from the discrepancies/errors in the conversion.

Table 3.9 Cost of electrolytic hydrogen production using alkaline electrolysis and corresponding assumptions for various studies

	Basye *et al.* (1997)	**Ogden (1999)**	**Simbeck & Chang (2002)**		**NAS (2004)**				**Yildiz & Kazimi (2003)**		**This study (2004)**	
Production option	C	C	C	D	C		D		C		C	
					High	Low	High	Low	High	Low	High	Low
Production cost, $/kg	3.66	1.70	5.13	12.1	4.70	2.30	6.58	3.93	4.48	2.75	2.79	1.63
Transmission cost, $/kg	na	~0.4		na	0.42	0.31	na		na		na	
Electrolysis eff. (HHV), %	80	85	75	75	75	85	75	85	65	90	80	
Production, MT/d	255	233	150	0.47	24	24	0.48	0.48	150		395	
Electrolyzer capital cost, $/kWe	ns	300	1,000	2,000	800	100	1,000	125	1,000	500	1,160	580
Compressor capital cost, $/kW	ns	ns	2,000	3,000	2,000	1,000	3,000	1,500	2,000		na	
Electrolysis plant capital cost, $K /kg/hr	23.54	28.80	90.62	211.7	84.8	9.72	127.0	28.58	60.6	21.9	63.5	38.1
Capacity factor, %	90	ns	90	70	90				90		90	
CRF, %	20	ns	18	18	16		14		13.1		11.75	
Output pressure, psi	ns	1,000	1,102	5,878	1,102		5,878		ns		na	
Electricity (off-peak), c/kWe-h	5.0	3.0	6.0 (2.0)	9.0 (4.0)	6.0 (2.0)				4.5	3.5	4.7	2.9

MT: 1,000 tonnes; C: Central; D: Distributed; na: not applicable; ns: not specified; CRF: Capital recovery factor. Output pressures are given at the point of storage or pipeline inlet. Not all numbers listed in this table are originally reported in their respective units. We used the factors in Table A1 through A3 in Appendix A to convert them to the units we used in this report. Production costs do not include transmission.

Table 3. 10 The 'alternative' cost of hydrogen calculated using the assumptions given by Simbeck & Chang, NAS, and Yildiz & Kazimi and our calculation method presented in Table 3.3 and Table 3.4. The results show that the differences among the cost estimates can be explained by the different set of assumptions used in other studies within 12% on average.[99]

	This study (2004)		Simbeck & Chang (2002)	NAS (2004)		Yildiz & Kazimi (2003)	
Price range	Low	High	High	Low	High	Low	High
MW-th	2400		365	46	53	304	421
Rated capacity in MW-H_2	640		274	39		274	
Production, (000) MT/y	128.1		54.8	7.9		54.8	
η_{elec}	80.0%		75.0%	85.0%	75.0%	90.0%	65.0%
Electrolysis plant, \$/kWe[100]	580	1,160	1,470	169	1,357	500	1,000
Electrolysis plant, \$/kW-H_2	725	1,450	1,960	199	1,809	556	1,538
Capital charge, \$/kW-H_2-y	85.2	170.4	352.8	31.8	289.5	72.8	201.5
O&M, \$/kW-H_2-y[101]	241.4	388.3	565.6	436.4	615.4	303.7	568.2
Total cost, \$/kW-H_2-y	326.6	558.7	918.4	468.2	904.9	376.5	769.7
H_2 cost at central plant, \$/kg	1.63	2.79	4.59	2.34	4.52	1.88	3.85
Original reported cost, \$/kg			5.13	2.30	4.70	2.75	4.48
Other assumptions							
COE, cents/kWe-h	2.9	4.7	4.5	4.5	4.5	3.5	4.5
Non-fuel O&M cost, cents/kWe-h	0.20		1.6	0.50	2.50	0.35	0.98
Capacity factor	90.0%		90.0%	90.0%		90.0%	
Capital recovery factor	11.8%		18.0%	16.0%		13.1%	

[100] Electrolyzer costs taken as \$400/kWe (low) and \$800/kWe (high) by this study; \$1000/kWe by Simbeck & Chang; \$100/kWe (low) and \$800/kWe (high) by NAS; \$500/kWe (low) and \$1,000/kWe (high) by Yildiz & Kazimi. Plant cost includes additional expenses for general facilities (20%), engineering & permitting (10%), contingencies (10%), and land & miscellaneous (5%; 7% by Simbeck & Chang and NAS) except by Yildiz & Kazimi.

[101] For this study, we collapsed the capital charge and the operating costs of the LWR plant as the electricity cost for the electrolyzer plant since the electrolyzer plant receives its electricity exclusively form the LWR plant.

Table 3.11 Supplementary information on studies listed in Table 3.9 excluding this study.

Study	Notes
Basye *et al.* (1997)	A report on large-scale hydrogen production costs. This report includes hydrogen production by steam reforming of natural gas (SMR), coal gasification, partial oxidation of fuel oil, biomass gasification and alkaline electrolysis. It also provides a literature survey on capital and operating costs of these technologies. Basye *et al.* provides an explicit model for cost calculation. All calculations are done on HHV basis. Plant life time=20 yrs. Prepared by Sentech Inc. for the U.S. DOE.
Ogden (1999)	A review paper on hydrogen energy infrastructure options. This paper provides a comparative discussion of various hydrogen production methods, e.g., SMR, biomass gasification, coal gasification, electrolysis and their costs. No model for cost calculation is provided. Cost components are not listed separately. Therefore, the cost values in Table 3.2 are taken from the corresponding figures. This paper briefly describes hydrogen storage and transmission technologies. Ogden also discusses city-scale infrastructure scenarios based on central hydrogen production.
Simbeck & Chang (2002)	A comprehensive economic study of hydrogen production (e.g., methanol reforming, SMR, gasoline reforming biomass gasification, coal gasification, petroleum coke gasification and electrolysis), storage (e.g., liquid and compressed) and transmission (e.g. liquid, high pressure tube and pipeline) pathways. This report explicitly shows the cost components and calculation details. Simbeck & Chang provided efficiency values only for production. Both central and distributed pathways are considered. Comparison of different hydrogen pathways is based on cost considerations alone. All calculations are done on LHV basis. Life times for different pathways are not specified. Prepared by SFA Pacific, Inc. for the U.S. NREL.
NAS (2004)	A comprehensive study on the hydrogen economy, including infrastructure costs, barriers and R&D needs. It discusses central and distributed supply chains for hydrogen production, e.g., electrolysis (grid, wind and photovoltaic), SMR, coal gasification, and biomass gasification. The supply chains are evaluated for current and future technologies. The calculation method is same as that of Simbeck & Chang with slightly different cost and efficiency assumptions. This study also discusses hydrogen economy from a public policy perspective and provides a list of recommendations.
Yildiz & Kazimi (2003)	A study concentrating on hydrogen production using nuclear energy. Emphasis is on efficiency performance of different nuclear options, e.g. conventional and high-temperature electrolysis using electricity from different reactor technologies. This study provides a simple economic model. The numbers reported in Table 3.9 were kindly provided by Yildiz. Plant life time is 15 years. Production parameters are similar to those of Brown *et al.*

3.5.2 Nuclear thermochemical hydrogen production studies

For the four studies listed in Table 3.12, the cost of nuclear heat assisted thermochemical hydrogen production ranges between $1.53 (Brown *et al.*[68]) and $2.72/kg (this study) with an average of $2.06/kg. With future technologies (i.e., with lower capital cost and higher conversion efficiency), the estimated range becomes $1.13 (Yildiz & Kazimi) to $1.42/kg (Brown *et al.*) with an average of $1.40/kg.

Except this study, the baseline capital cost estimates for the VHTGR are basically the same (around $400/kWth) as those used by Brown *et al.* The hydrogen production efficiencies are also similar around 40% to 50% following Brown *et al.*'s original estimates. Our assumptions about nuclear hydrogen production are more cautious. As we noted in Section 3.2, we assume the cost of VHTGR to be 20% more than a LWR. This brings our baseline estimate for VHTGR capital cost to the range of $400 to 800/kW-th compared to ~400/kW-th of the other three studies.

The differences among the hydrogen production costs by the four studies listed in Table 3.12 (i.e., Brown *et al.*, NAS, and Yildiz & Kazimi) are small. To compare these differences and also to check the validity of our calculation method, we used the efficiency and cost assumptions of the other three studies, and calculated 'new' hydrogen production costs. The results in Table 3.13 show that the differences between the previously reported hydrogen production costs and the 'new' estimates are small. These differences mainly come from the variation of the efficiency and capital cost estimates.[99]

The capital costs of thermochemical hydrogen production plant for the first three studies and the high efficiency (50%) case we considered are approximately the same. Note that we used a lower baseline production efficiency of 30% compared to the 42% of Brown *et al.*, 60% of the NAS study, and 38% of Yildiz & Kazimi Consequently our baseline hydrogen production cost is the highest at $2.72/kg. The estimated production rates change between 395,000 tonnes/d (this study) and 1,200,000 tonnes/d (NAS). The estimated cost of transmission by gaseous hydrogen pipeline is only given by the NAS study as 0.39/kg of hydrogen. The capacity factor assessed is 90% for all studies. For more detail, please see Table 3.12, 3.13 and 3.14.

Table 3.12 Cost of thermochemical hydrogen production using nuclear heat and corresponding assumptions for various similar studies

	Brown *et al.* (2003)		**NAS (2004)**	**Yildiz & Kazimi (2003)**		**This study (2004)**		
Production option	C		C	C		C		
	High	Low		High	Low	High	Medium	Low
Production cost, $/kg	1.53	1.42	1.63	2.37	1.13	2.72	1.63	1.40
Transmission cost, $/kg	na		0.39	na			na	
Overall process efficiency, %	42	52	60	0.38	0.52	30	40	50
Production, MT/d	584	723	1,200	527	723	395	526	658
VHTGR capital cost, $/kWth	362	410	ns	400	325	800	600	400
Conversion plant cost, $K/kg/hr	23.70	23.70	ns	45.9	16.7	41.72	31.3	25.04
Total capital cost, $/kg/hr	59.40	56.34	49.37	89.6	42.6	158.44	96.97	60.06
Capacity factor, %	90		90	90			90	
CRF, %	10.5		15.9	13.1			11.75	
Output pressure, psi	320		1,102	ns		ns	ns	ns

MT: 1,000 tonnes; C: Central; na: not applicable; ns: not specified; CRF: Capital Recovery Factor. Output pressures are given at the point of storage or pipeline inlet. Not all numbers listed in this table are originally reported in their respective units. We used the factors in Table 3.A.1 through 3.A.3 in Appendix 3.A to convert them to the units we used in this report. Production costs do not include transmission.

Table 3.13 The 'alternative' cost of hydrogen calculated using the assumptions given by Brown *et al.*, NAS, and Yildiz & Kazimi and our calculation method given in Table 3.2 and Table 3.4. The results show that the differences among the cost estimates can be explained by the different set of assumptions used in other studies within 4% on average.[99] (ns: not specified)

	This study		Brown *et al.* (2003)		NAS (2004)	Yildiz & Kazimi (2003)	
Price range	Low	High	Low	High	Low	Low	High
MW-th	2400		2400		3283	2400	
Rated capacity in MW-H_2	1200	720	1248	1008	1970	1248	912
Production, (000) MT/y	240.1	144.1	249.7	201.7	394.2	249.7	182.5
η_{conv}	50.0%	30.0%	52.0%	42.0%	60.0%	52.0%	38.0%
VHTGR Plant							
Capital, $/kW-th	400	800	410	362	ns	325	400
Capital, $/kW-H2	800	2,667	789	861	ns	625	1,053
Capital charge, $/kW-H2-y	94.0	313.3	82.8	90.4	ns	81.9	137.9
O&M, $/kW-H2-y	78.84	78.84	74.8	89.5	ns	62.5	105.3
Conversion Plant							
(Total) Capital, $/kW-th	286.0	286.0	297.4	240.2	(677.4)	210.0	400.0
(Total) Capital, $/kW-H2	572.0	953.3	571.9	571.9	(1128.9)	403.8	1052.6
(Total) Capital charge, $/kW-H2-y	67.2	112.0	60.1	60.1	(179.5)	52.9	137.9
(Total) O&M, $/kW-$H_2$-y	39.4	39.4	50.2	50.2	(132.0)	28.3	73.7
Total cost, $/kW-$H_2$-y	279.5	543.6	267.9	290.1	311.5	225.5	454.7
H_2 cost at central plant, $/kg	1.40	2.72	1.34	1.45	1.56	1.13	2.27
Original reported cost, $/kg			1.42	1.53	1.63	1.13	2.37
Other Assumptions							
VHTGR O&M, cents/kWe-hr	1.0		0.9	1.1		0.8	1.3
Conversion (total) O&M, cents/kWe-hr	0.5		0.6	0.6	(1.7)	0.4	0.9
Capacity factor	90.0%		90.0%		90.0%	90.0%	
Capital recovery factor	11.8%		10.5%		15.9%	13.1%	

Table 3.14 Supplementary information on studies listed in Table 3.12 excluding this study.

Study	Notes
Brown *et al.* (2003)	A detailed report on hydrogen production technologies using nuclear power. This report provides an evaluation of thermochemical water splitting cycles and nuclear technologies that can potentially be coupled to these cycles. Detail chemical process modeling and cost components are given for Sulfur-Iodine cycle coupled to a Very High Temperature Nuclear Reactor. Plant lifetime is 15 years.
NAS (2004)	A new, comprehensive study on hydrogen economy including infrastructure costs, barriers and R&D needs. It discusses central and distributed supply chains for hydrogen, e.g., electrolysis (grid, wind and photovoltaic), SMR, coal gasification, and biomass gasification. The supply chains are evaluated for current and future technologies. The calculation method is same as that of Simbeck & Chang. with slightly different baseline assumptions. This book also discusses hydrogen economy a public policy perspective and provides a list of recommendations.
Yildiz & Kazimi (2003)	A study concentrating on hydrogen production using nuclear energy. Emphasis is on efficiency performance of different nuclear options, e.g. thermochemical production using S-I cycle, conventional electrolysis (using electricity from LWR, Advanced LWR, Helium Gas Cooled Reactor, GT-MHR, Super Critical Water Reactor, SCWR), high-temperature electrolysis of steam, HTES, using GT-MHR and Super Critical CO_2 cycle, SCO2-AGR. This study provides a simple economic model. The numbers reported in Table 3.11 were kindly provided by Yildiz. Plant life time is 15 years. Production parameters are similar to those of Brown *et al.*

3.6 Outlook and policy implications

Hydrogen as an energy carrier is politically an irresistible cause to advocate. If a non-fossil fuel based production pathway is achieved, hydrogen will be fuel of the 21st century. It will reverse America's dependence on foreign oil, considerably decrease the emissions of greenhouse gases and provide the cleanest alternative to our energy problem.

A transition to hydrogen economy will also encourage technological innovation across industries and lead to the introduction of numerous new technologies. Hydrogen will become what "steam" was for the 19th century and the fuel cell will be the "steam engine" for hydrogen.

The Bush Administration and other governments around the world rightly recognized hydrogen as the fuel of future, and launched a range of R&D initiatives to bring government and private resources together. Between FY2002-FY2004, the U.S government dedicated about $1.2 billion to DOE's Hydrogen Program. (See Appendix B for allocation details. Also see Appendix A of Footnote 40.)

The three most recent publications that present the U.S. efforts towards hydrogen economy and nuclear energy based hydrogen production in particular are

(1) **Hydrogen Posture Plan** – An Integrated Research, Development and Demonstration Plan by U.S. DOE[102]

(2) **Hydrogen, Fuel Cells & Infrastructure Technologies Program** – Multi-Year Research, Development and Demonstration Plan for 2003-2010 by U.S. DOE Office of Energy Efficiency and Renewable Energy[103]

(3) **Nuclear Hydrogen R&D Plan** – Draft by U.S. DOE Office of Nuclear Energy, Science and Technology[104]

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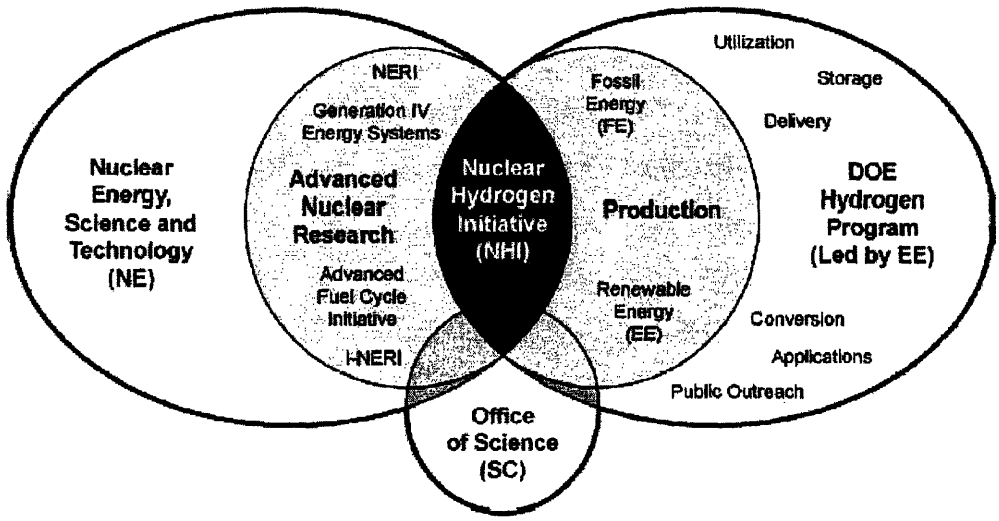
[102] Adapted from U.S. DOE, "Hydrogen Posture Plan – An Integrated Research, Development and Demonstration Plan" (2004).
Available at http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogen_posture_plan.pdf.

[103] U.S. DOE, Office of Energy Efficiency and Renewable Energy Hydrogen, Fuel Cells & Infrastructure Technologies Program – Multi-Year Research, Development and Demonstration Plan for 2003-2010. Last updated June 3, 2003. Available at http://www.eere.energy.gov/hydrogenandfuelcells/mypp/.

Figure 3.7 U.S. DOE's integrated program to develop technologies for hydrogen production.[105]



NERI: Nuclear Energy Research Initiatives; Gen IV: Generation IV70

The three primary goals of the DOE's Hydrogen Program are to:[106]

(1) be produced from domestic sources,

(2) avoid the production of greenhouse gases, and

(3) be cost-competitive with gasoline in the implementation timeframe.

The Nuclear Hydrogen Initiative (NHI) is an integral part of the DOE's Hydrogen Program. (See Figure 3.7 and Figure 3.8.) As the results of our cost evaluation indicate, nuclear option (either through thermochemical water splitting or electrolysis) can produce hydrogen at large amounts and competitive prices provided certain capital cost, efficiency, scalability and infrastructure criteria are met simultaneously.

On the other hand, there are considerable technical and economic risks associated with the development and performance of nuclear hydrogen production options. As indicated in the DOE's Nuclear Hydrogen R&D Plan: "Laboratory demonstration of a

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[104] U.S. DOE, Office of Nuclear Energy, Science and Technology, Nuclear Energy Research Initiatives, "Nuclear Hydrogen R&D Plan – Draft". Last updated May 04, 2004.
Available at http://neri.inel.gov/program_plans/pdfs/nhi_plan.pdf

[105] Footnote 104, Figure 1-4.

[106] Footnote 104. Quoted from p.1-2.

process may not assure cost effectiveness; however, the performance and cost uncertainties can be reduced. None of the process reviewed have been demonstrated on a scale that would be necessary for reliable cost estimates."[107]

The current target of the DOE's Hydrogen Program is to complete R&D by 2015 and to accomplish transition to a hydrogen marketplace by 2025. (See Figure 3.9) More specifically for NHI, there are two important milestones: (1) the decision of which thermochemical cycle would be used in a pilot plant is planned for 2007,[108] and (2) the engineering decision for the demonstration process is scheduled for 2010. (See Figure 3.10 for more details.)

NHI also considers high-temperature electrolysis (HTE) as an option to produce hydrogen. In high-temperature electrolysis, the steam is generated by the thermal energy provided by an advanced nuclear reactor. This high-temperature steam (~950 °C) decreases the electrical energy requirement and therefore increases electrolysis efficiency.**Error! Bookmark not defined.** According to NHI, the pilot plant decision will be made by the end of 2006 and the decision for the engineering demonstration process will be made by the end of 2010.[109] (See Figure 3.10 for more details.)

The DOE's projected target costs for high temperature electrolysis are $2.50/kg in 2008 and $2.00/kg in 2016. It is interesting to note that the most pessimistic point in our sensitivity analysis for LWR-coupled alkaline electrolysis option is not too far off from the 2008 target. With modest improvement in or capital cost assumptions, the LWR-coupled alkaline electrolysis – a technology that is available today – already meets the 2016 cost target for hydrogen production.

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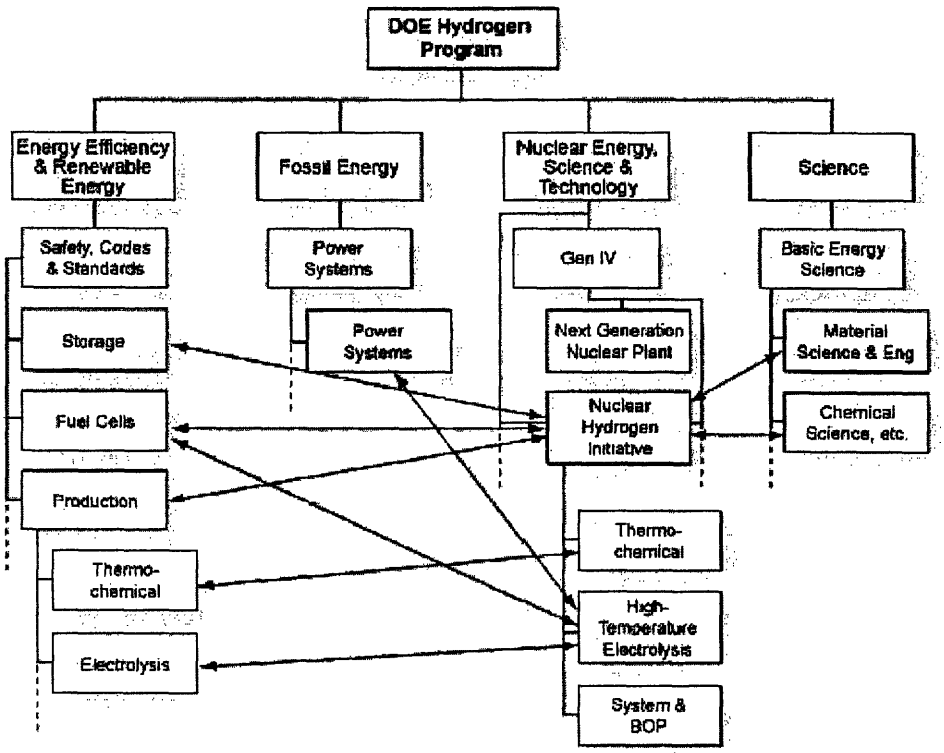
[107] Footnote 104. Quoted from p.2-3.

[108] We only included Sulfur-Iodine cycle in this study since it is the most well-understood process. There are other thermochemical cycles such as Sulfur-Bromine and Calcium-Bromine. For more information on these and other cycles, see Footnote 68, (Brown *et al.*) p. 2-1 – 2.13; or Funk J.E., "Thermochemical Hydrogen production: Past and Present," *Intl. J. Hydrogen Economy*, 26, 185 (2001).

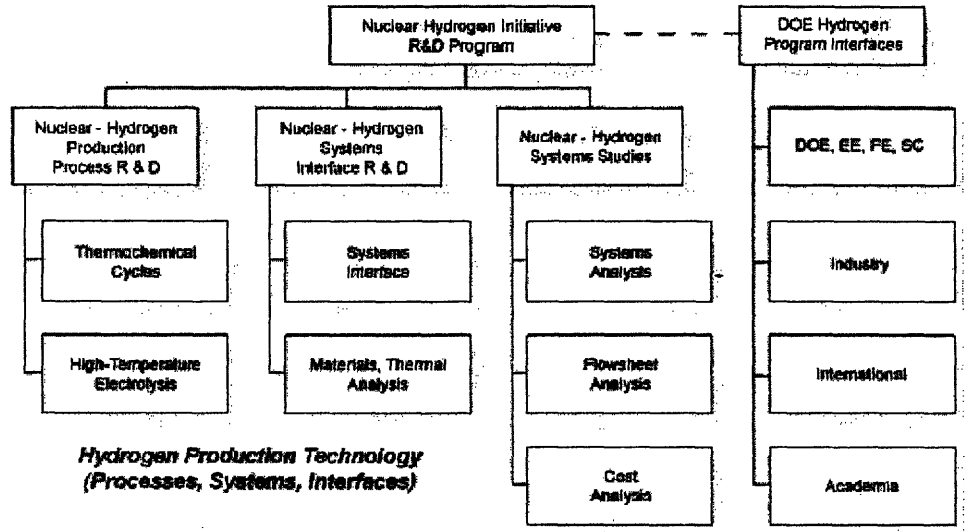
[109] *Ibid.*, Section 4, p.4-1.

Figure 3.8 The stakeholders and their interactions in the DOE's integrated program to develop technologies for hydrogen production.[110]

(a)



(b)



[110] Footnote 104, Figure 1-3 for (a) and 1-5 for (b)

Figure 3.9 The time frame of the DOE's integrated program to develop technologies for hydrogen production.[111]

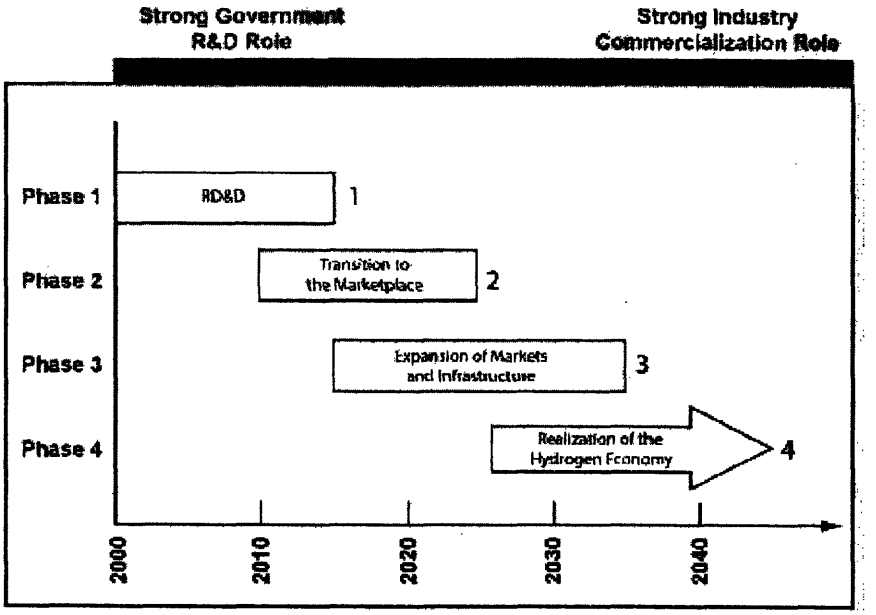
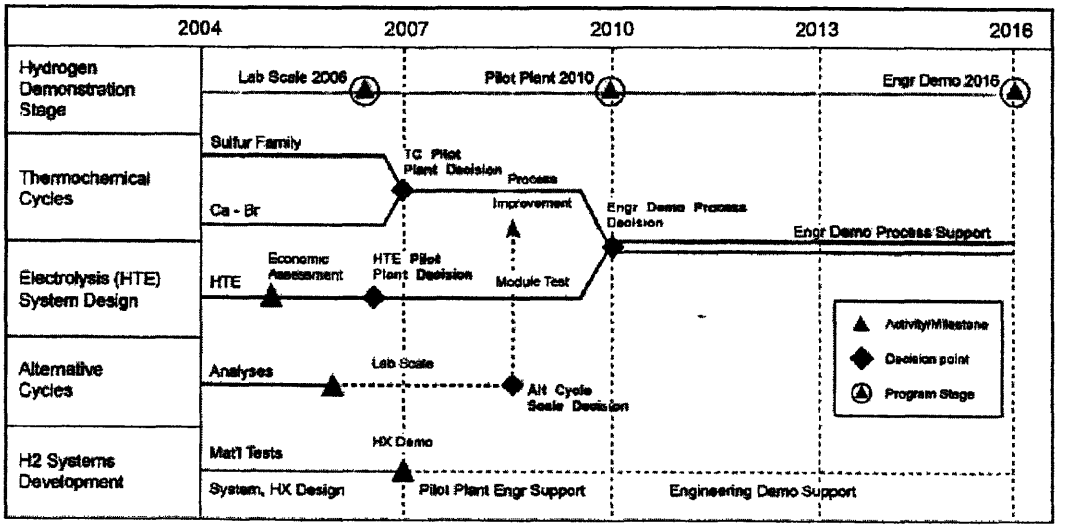


Figure 3.10 The summary of Nuclear Hydrogen R&D plan activities and sequence.[112]



[111] Footnote 104, Figure 1-1.

[112] Footnote 104, Figure 2-1

Fully developed market and infrastructure for hydrogen will be achieved when hydrogen based power and transport systems will become commercially available at competitive costs across the U.S. The DOE's target date for a substantial transition to hydrogen economy is 2040 and beyond. This is an ambitious target. A useful example that explain the vast scale of hydrogen the U.S. need to produce to reach this target is given in Table 3.15.

The National Hydrogen Posture Plan calculated the amount of U.S. energy resources that have to be dedicated to produce 40 million short tons of hydrogen per year to fuel 150 million vehicles with average fuel economy of 60.5 mpg gasoline equivalent.[113] The production options include reforming/partial oxidation of from natural gas, biomass and coal; water electrolysis using electricity from wind, solar and nuclear energy; and thermochemical conversion using an advanced nuclear reactor similar to the VHTGR technology discussed above. According to Table 3.15, fueling 150 million fuel cell vehicles requires 200 Light Water Reactors each with 1000-1,200 MWe capacity producing electricity needed for water electrolysis, or 125 advanced high-temperature nuclear reactors each with 2,400 MWth capacity.[114]

Independent technology assessment of the nuclear hydrogen production and the nuclear hydrogen systems interface are the focus of the NHI. As our production cost analysis indicate, capital cost is one of the two major source of uncertainty in any technological assessment. This uncertainty is especially large with hydrogen production technologies that are not here today such as advanced high-temperature nuclear reactor, thermochemical splitting of water and high temperature electrolysis. The second major source of uncertainty is associated with interface of hydrogen production, storage and delivery systems.

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[113] Currently only 9 million short tons of industrial hydrogen are produced annually. Source: "Hydrogen," *Chemical Market Reporter*, 263, 8, 43 (2003)

[114] (a) This estimate assumes 50% heat-to-hydrogen conversion efficiency for the advanced high-temperature reactor and the thermochemical conversion complex.

(b) We calculated that to produce enough hydrogen to replace the entire motor gasoline use in the U.S. (in energy equivalent terms), we need to build 430 Very High Temperature Gas reactors (VHTGR) each and thermochemical conversion plant complex each with 2,400 MWth capacity at 50% efficiency.

Table 3.15 Examples of U.S. resources that could be used to produce 40 million short ton/y (40 x 2000 lbs/y) of hydrogen to fuel 150 million vehicles.[115] (Values shown are based on that resource being used to produce the full 40 million tons. Currently only 9 million short tons of industrial hydrogen are produced annually.)

Resource	Needed for Hydrogen[a]	Availability	Current Consumption	Consumption with Hydrogen Production (factor times current)	Construction/ Footprint Required
REFORMING AND/OR PARTIAL OXIDATION[b]					
Natural Gas	95 million tons/year	28 billion tons (technically recoverable as of 1/2000)	475 million tons/year	1.2	400 dedicated hydrogen plants (100 MMSCF of hydrogen per day)
Biomass	400-800 million tons/year	800 million tons/year of biomass residue and waste, plus 300 million tons/year of dedicated crops[c]	200 million tons/year (3 quads for heat, power & electricity)	2-4	400-600 dedicated hydrogen plants
Coal	310 million tons/year	126 billion tons (recoverable bituminous coal)	1100 million tons/year (all grades)	1.3	280 dedicated hydrogen plants
WATER ELECTROLYSIS[d]					
Wind	555 GW_e	3250 GW_e	4 GW_e	140	Available capacity of North Dakota (Class 3 and above)
Solar	740 GW_e	SW U.S.: 2,300 kWh/m^2-year	<1 GW_e	>740 times current	3750 sq. miles (approx. footprint of White Sands Missile Range, NM)
Nuclear	216 GW_e	n/a	98 GW_e	3.2	200 dedicated plants (1-1.2 GW_e)
THERMO-CHEMICAL					
Nuclear	300 GW_{th}	n/a	0 GW	n/a	125 dedicated plants (2.4 GW_{th})

[a] Examples of domestic resources that can be used to produce the 40 million short tons/y of hydrogen needed for 150 million vehicles; assumes a 2.2x improvement in efficiency over 27.5 mpg baseline fuel economy for fuel cell vehicles.

[b] Calculations were made for the exclusive production for the amount of hydrogen requested.

[c] Includes only that biomass not currently used for food, feed or fiber products.

[d] Other renewable power generation technologies such as geothermal can also serve as a resource for water electrolysis.

[115] Taken from Footnote 104 Table I, p. 29.

The DOE's R&D efforts aim to reduce these uncertainties by going ahead with laboratory scale experiments. Laboratory scale experiments may or may not help resolve these technical and economic uncertainties that may persists at the pilot and demonstration plant level. Even one may chose to be optimistic about the scalability of the capital costs; there is less reason to do so with the scalability of the overall system efficiency. In short, by concentrating to reduce the risk associated with future hydrogen production technologies, DOE seems to underestimate the 'option value' of current technologies for large scale hydrogen production such as a traditional nuclear reactor dedicated to alkaline electrolysis.

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Appendix 3.A. Conversion factors

Table 3.A.1 Units of measure

1 kg	=	2.205 lbs	1 m^3	=	35.315 SCF
1 kJ	=	0.948 Btu 0.239 kcal	1 atm =	=	101,325 Pa
1 kW	=	1.341 HP	1 psi =	=	6,894.8 Pa
1 kW-hr	=	3,600 MJ 3,412 Btu 860 kcal	1 km =	=	0.622 mile

Table 3.A.2 Energy parameters for hydrogen and natural gas*

		Hydrogen			Natural Gas		
		# of moles	LHV	HHV	# of moles	GHV	
		1.00	241.82	285.83	1.00	1,053.28	kJ
1 kg	=	496.03	119.95	141.78	59.23	62.39	MJ
1 lb	=	225.00	54.41	64.31	26.87	28.30	MJ
1 Nm^3	=	44.61	10.79	12.75	44.61	23.61	MJ
1 SCF	=	1.20	0.29	0.34	1.20	1.26	MJ

* LHV: Low Heating Value; HHV: High Heating Value. Nm^3 is measured at 1 atm and 273.15 K (32 °F, 0 °C). SCF is measured at 1 atm and 288.71 K (60 °F, 15.56 °C). GHV: The gross heating value is the total heat obtained by complete combustion at constant pressure of a unit volume of gas in air, including the heat released by condensing the water vapor in the combustion products. Gas, air, and combustion products taken at standard temperature (60 °F, 15.56 °C) and pressure (1 atm). Source: http://www.uniongas.com/aboutus/aboutng/composition.asp

Table 3.A.3 Conversion parameters for 1 MMSCF of hydrogen based on HHV

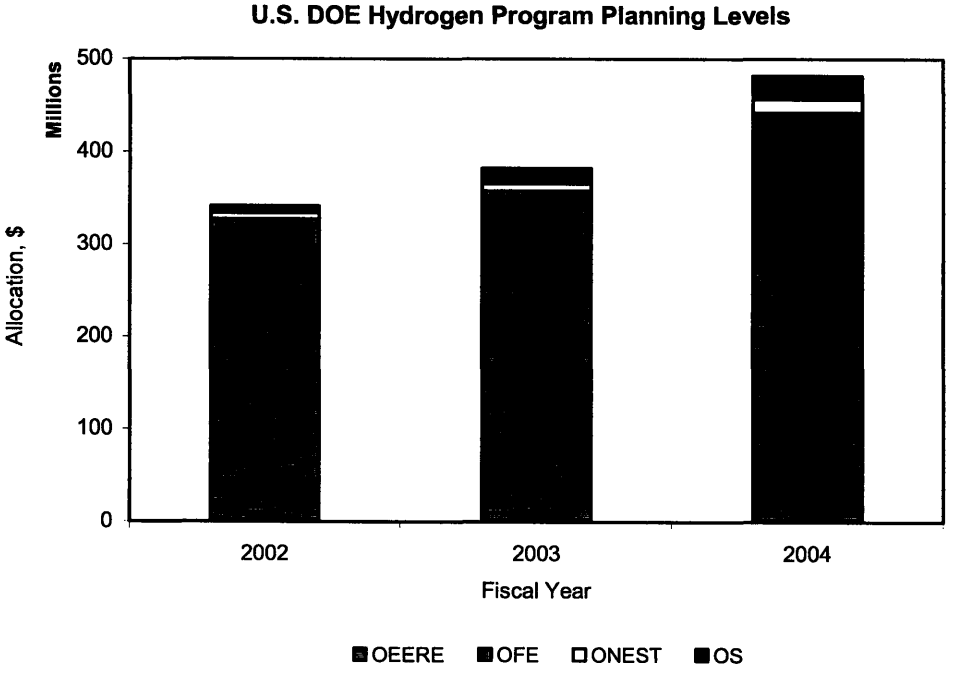
		SCF	Nm^3	MJ	Btu (000)
1kg of H_2	=	415.01	11.12	141.78	134.41

SCF: standard cubic feet; MJ: gigajoules; Btu: British thermal units

Appendix 3.B DOE Hydrogen Program Planning Levels

The U.S. DOE's Hydrogen Program planning levels increased from $342.3 millions in 2002 to $482.5 million in 2004, a 41% increase over two years as shown in Figure E1. In 2004, $66.2 million is requested for R&D on hydrogen production, delivery, storage, and infrastructure validation, roughly a three-fold increase from 2002. The budget request for nuclear hydrogen R&D under, or associated with, DOE Office of Nuclear Energy Science and Technology amounts to $16.2 million, 81% increase from 2003 appropriation. The R&D on distributed generation systems using fuel cells received $63.8 million in associated grants in 2003 under DOE Office of Fossil Energy.

Figure 3.B.1 U.S. DOE Hydrogen Program Planning Levels, FY2002-FY2004.



OEERE: Office of Energy Efficiency and Renewable Energy; OFE: Office of Fossil Energy; ONEST: Office of Nuclear Energy Science and Technology; OS: Office of Science. Source: NAS (2003). Appendix D, Table C-1.

Appendix 3.C Hydrogen Transmission

3.C.1 Gaseous hydrogen pipeline

We assume compressed gas pipeline transmission due to short distance (100 km) to the city gate delivery point and large quantity of hydrogen that needs to be transported Table 3.C.1 summarizes the technical specifications for our pipeline design. We calculated the operating parameters using the pipeline equations derived in Section 3.C.2 of this appendix. The results are given in Table 3.C.2 and Table 3.C.3.

To keep our system analysis simple, we did not include a distribution infrastructure that uses smaller pipelines after the city gate to deliver the hydrogen to individual distributed energy plants. We assume that existing low pressure natural gas infrastructure in urban areas could be used to deliver hydrogen with minor changes as suggested by several other studies.[116]

Assuming that the losses due to leakage are zero, we calculated transmission efficiency as the ratio of energy needed for compression for a given hydrogen delivery rate to the energy content of hydrogen delivered. In the central-thermochemical-H_2-production option, hydrogen is produced at 323 psi (2.23 MPa).[117] Table C.3.2 shows that for the production rates of 144.1 million, 192.1 and 240.1 million kg/y at output pressure, p_L, of 200 psi (1.38 MPa) at the city gate, hydrogen from conversion plant in the VHTGR-SITC option needs to be compressed to input pressures, p_H, of 632 (4.36), 824 (5.68) and 1,019 (7.02) psi (MPa), respectively, for a 100-km pipeline with 30-cm inside diameter. The corresponding compression power accounts for the 0.7%, 0.9% and 1.1% of the energy content of the transmitted hydrogen. These values correspond to transmission efficiency of 99.3%, 99.1% an d98.9% assuming no pipeline leakage.

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[116] Blazek, C. F., Biederman, R.T., Foh, S. E., Jasionowski, W. "Underground storage and transmission of hydrogen" *Proc. 3rd Annu. US. Hydrogen Meet.* (Technol. Transit. Corp., Washington, DC, 1992), p.4-203-21.; Buenger, U., Zittel, W., Schmalschlager, T. "Hydrogen in the public gas grid – a feasibility study about its applicability and limitations for admixtures within a demonstration project for the city of Munich" *Proc. 10th World Hydrogen Energy Conf.* (Int. Assoc. Hydrogen Energy, 1994)

[117] Footnote 68 (Brown *et al.*), Table 3-3, p. 3.11

Table 3.C.1 Hydrogen pipeline specifications for the central hydrogen production options[118]

	Central-thermochemical-H_2-production option			Central-electrolytic-H_2-production option
Production efficiency	30%	40%	50%	26.7%
Transmission efficiency	99.3%	99.1%	98.9	96.4%
Flow rate, million tonnes/y (MMSCF/d)	144.1 (163.9)	192.1 (218.6)	240.1 (273.2)	128.1 (145.6)
Input pressure, MPA (psi)	4.36 (632)	5.68 (824)	7.02 (1,019)	3.92 (569)
Compressor power, kW (HP)	3,457 (4,636)	6,430 (8,623)	9,861 (13,224)	16,727 (22,431)

Pipeline length=100 km (62.5 mi); Output pressure=200 psi (1.38 MPa); Pipeline inside diameter=30 cm (11.8 inch); Compressor efficiency=80%; Number of compressors=1.

For the electrolytic hydrogen production option at 200 (1.38) psi (MPa) outlet pressure at the city gate, the required input pressure is 569 (3.92) psi (MPa). For electrolytic hydrogen production option, the compression power needed accounts for 3.6% of the transmitted power since the hydrogen is at the electrolyzer output at atmospheric pressure. Then, the corresponding transmission efficiency is 96.4%.

Note that we did not model any 'booster' compression stations along the pipeline since the transmission distance is short. Also note that if the same amount of energy is delivered by natural gas, keeping all the other pipeline parameters constant, approximately 3.4 times less energy is used for compression as shown in Figure 3.C.2. Today's natural gas pipeline infrastructure in the U.S. uses approximately 0.5% of the energy for compression per 100 km.

[118] Transmission (pipeline) efficiencies are calculated as the ratio of energy needed for compression to the energy delivered.

Table 3.C.2 Operation parameters and transmission efficiencies for a 100-km gaseous hydrogen pipeline with 30 cm inside diameter.

Operation parameters		**LWR & electrolysis**		**VHTGR &thermochemical water splitting**						**Units**	
		SI	**Imperial**	**SI**	**Imperial**	**SI**	**Imperial**	**SI**	**Imperial**	**SI**	**Imperial**
Production efficiency	(1)	30%		30%		40%		50%			
Transmission											
Mass flow rate	(2)	4.06	773,773	4.57	871,023	6.10	1,161,364	7.62	1,451,706	kg/s	lb/d
	(2')	128,085	126,084	144,183	141,930	192,244	189,240	240,305	236,550	tonnes/y	tons/y
Volume flow rate	(3)	49.3	145.6	55.5	163.9	74.0	218.6	92.5	273.2	Nm^3/s	MMSCF/d
Energy flow rate	(4)	49,753	47,157	56,007	53,084	74,675	70,779	93,344	88,473	GJ/d	MMBtu/d
Mass velocity, g	(5)	57.5	1,016,977	64.7	1,144,794	86.2	1,526,392	107.8	1,907,991	kg/s m^2	lb/d ft^2
Inlet pressure, p_H	(6)	3.92	569	4.36	632	5.68	824	7.02	1,019	MPa	psi
Outlet pressure, p_L	(7)	1.38	200	1.38	200	1.38	200	1.38	200	MPa	psi
Average pressure, p_{ave}	(8)	2.85	414	3.13	453	3.97	575	4.83	701	MPa	psi
Base pressure, p_B	(9)	0.10	15	0.10	15	0.10	15	0.10	15	MPa	psi
Inside diameter	(10)	0.30	11.81	0.30	11.81	0.30	11.81	0.30	11.81	m	inch
Pipeline length	(11)	100.00	62.15	100.00	62.15	100.00	62.15	100.00	62.15	km	mile
Transmission coefficient	(12)	2.72E-03		2.72E-03		2.72E-03		2.72E-03			
Reynolds number	(13)	2,102,163		2,366,370		3,155,160		3,943,950			
Pipe roughness, K_e	(14)	1.78E-05	7.00E-04	1.78E-05	7.00E-04	1.78E-05	7.00E-04	1.78E-05	7.00E-04	m	inch
Compression											
Compression efficiency	(16)	80%		80%		80%		80%			
Compressor power	(16)	16,727	22,431	3,457	4,636	6,430	8,623	9,861	13,224	kW	HP
Fuel equivalent	(17)	1.79	5.46	0.37	1.13	0.69	2.10	1.06	3.22	m^3/s	MMSCF/d
Compression losses	(18)	3.63%		0.67%		0.93%		1.14%			
Efficiency											
Pipeline efficiency	(19)	96.37%		99.33%		99.07%		98.86%			
Overall	(20)	25.70%		29.80%		39.63		49.43			

Table 3.C.3 Definitions of variables and method of calculation of values given in Table 3.C.2 given only for SI units. (For more detail on the derivations of equations please see the text.)

Operation parameters	Table 3.C.2 #	Definitions of variables and method of calculation	SI Units
Production efficiency	(1)	30%;40%;50%	
Transmission			
Mass flow rate	(2)	(2') x 1000 kg/tonnes / (365 x 24 x 3600 s/yr)	kg/s
	(2')	Given; See Table 3.2 &3.3	tonnes/y
Volume flow rate	(3)	(2) x 11.12 Nm^3/kg	Nm^3/s
Energy flow rate	(4)	(2) x 141.78 x 10^{-3} GJ/kg x (24 x 3600 s/d)	GJ/d
Mass velocity, g[119]	(5)	(2) / [π x $(10)^2$ / 4]	kg/s m^2
Inlet pressure, p_H[120]	(6)	$\{[(7) \times 10^6 \text{ Pa/MPa}]^2 - (5)^2 \times R \times (11) \times [(11) \times 1000 \text{ m/km}] \times (12) / [M \times 10]\}^{1/2} / [10^6 \text{ Pa/MPa}]$	MPa
Outlet pressure, p_L	(7)	1.38 (200 psi); Assumed	MPa
Average pressure, p_{ave}	(8)	(2/3) x {(6) + (7) – (6) x (7) /[(6) + (7)]}	MPa
Base pressure, p_B	(9)	0.1 (1 atm); Assumed	MPa
Inside diameter	(10)	0.3 m; Given	m
Temperature	T	0 °C = 273.15 K; Assumed	K
Pipeline length	(11)	100 km; Assumed	km
Transmission coefficient[121]	(12)	$[4 \times \log (3.7 \times (10) / (15)]^{-2}$	
Reynolds number[122]	(13)	(10) x (5) / η	
Pipe roughness, K_e	(14)	1.78 x 10^{-5}; Assumed	m
Gas Constant	R	8.1345	m^3 Pa/K mol
Molecular Weight	M	0.002	kg/mol
Viscosity	η	8.2 x 10^{-6}	kg/m s
Compression			
Compression efficiency	(15)	80%; Assumed	
Compressor power[123]	(16)	$\pi \times [(5) / M] \times [(10) / 2]^2 \times R \times T \times \ln[(6) / (9)] /$ (1000 W/kW)	kW
Fuel equivalent	(17)	(16) / (15) / (1000 kW/MW) / (12.75 MJ/m^3)	m^3/s
Compression losses	(18)	(17) / (3) x 100	%
Efficiency			
Pipeline efficiency	(19)	100 – (18)	%
Overall	(20)	(1) x (19)	%

[119] See Section 3.2.2 for definition of mass velocity.

[120] See Equation 3.C.11.

[121] See Equation 3.C.17.

[122] See Equation 3.C.14 for definition of Reynolds number.

[123] Assuming isothermal compression. See Equation 3.C.19.

3.C.2 Flow in pipes

3.C.2.1 Incompressible fluid

For steady flow of an incompressible fluid in a circular pipe of radius R, at uniform elevation, the Navier-Stokes equation is:

$$\eta\nabla^2\vec{v}(\vec{r}) = -\vec{\nabla}p \tag{3.C.1}$$

where $\vec{v}$ is the local velocity, p the pressure and η the shear viscosity. For flow in a pipe of uniform cross section of inner diameter D, this equation becomes:

$$\eta\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial v_z(r)}{\partial r} = -\frac{\partial p}{\partial z}. \tag{3.C.2}$$

Integrating twice with respect to the radius r and using the boundary conditions that v'$_z$ is finite at $r = 0$ and $v_Z(R) = 0$, we obtain the Poiseuille formula:

$$v_z(r) = \frac{1}{4\eta}\left(\frac{\partial p}{\partial z}\right)\left[R^2 - r^2\right]. \tag{3.C.3}$$

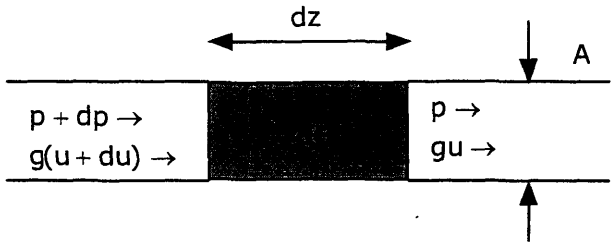
The average flow velocity is $u = \frac{1}{\pi R^2}\int_0^R v_z(r)2\pi r dr$, and the average flow rate is $Q = 2\pi Ru$ Thus we find

$$u = -\frac{R^2}{8\eta}\left(\frac{dp}{dz}\right) \text{ or } -\left(\frac{dp}{dz}\right) = \frac{8\eta}{R^2}u. \tag{3.C.4}$$

3.C.2.2 Compressible fluid

For the steady flow of a compressible gas in a circular pipe of inside diameter D, at uniform elevation, with constant mass velocity $g = u(z)\rho(z)$ down the pipe the force balance on a volume of size Adz must include the pressure-volume work on the volume element, change of kinetic energy in the flow, and the frictional loss in the volume element:

Figure 3.C.1 Force balance for a compressible fluid



The force balance is $Adp + A(\rho u)du = -dF$. For turbulent flow the frictional force is given by the Fanning equation that says the frictional loss at the pipe walls is proportional to the surface area of the walls and the kinetic energy of the fluid in the pipe. In the Fanning equation, the dimensionless constant of proportionality is the friction coefficient "*f*."

$$dF = f\frac{1}{2}\rho u^2 dS = f\frac{1}{2}\rho u^2 \pi dZ . \tag{3.C.5}$$

Therefore we have the equation:

$$vdp + udu = f\frac{2}{d}u^2 dz \tag{3.C.6}$$

where $v = 1/\rho$.

This expression can be integrated for flow along the pipe. For an ideal gas, under isothermal conditions [adiabatic conditions could be handled as well], the equation of state is

$$pV = \frac{R_{gas}T}{M}. \tag{3.C.7}$$

The relation between the pressure and gas velocity is:

$$u = \frac{gR_{gas}T}{Mp}. \tag{3.C.8}$$

Substitution in the force balance equation, leads the relation:

$$\frac{M}{g^2 R_{gas} T} p dp - \frac{dp}{p} = -\frac{2f}{D} dz \,. \tag{3.C.9}$$

This equation can be integrated along the pipe of length L, from an initial high pressure p_H to a lower downstream pressure p_L to obtain the result:

$$p_H^2 - p_L^2 = \frac{4g^2 R_{gas} TfL}{DM}\left[1 + \frac{D}{2fL}\ln\left(\frac{p_1}{p_2}\right)\right] \tag{3.C.10}$$

where "gas constant" $R_{gas} = 8.3145\ m^3 Pa/K\ mol$, or $10.73\ psi\, ft^3/lbmoles\,^\circ R$. Ordinarily, the frictional loss dominates (f large) and the compression term can be neglected. In this circumstance, the equation simplifies to:

$$p_H^2 - p_L^2 = \frac{4g^2 R_{gas} TfL}{DM} \qquad \text{"The gas equation"} \tag{3.C.11}$$

Frequently, this expression is written as:

$$p_H - p_L = \frac{2g^2 fL}{DM^2 \rho_{av}} \text{ where } \rho_{av} = \frac{\rho_1 + \rho_2}{2}. \tag{3.C.12}$$

3.C.2.3 Frictional losses

The frictional loss per unit cross sectional area can be written as:

$$\frac{1}{A}\frac{dF}{dz} = \frac{2f\rho}{D}u^2 = -\frac{dp_f}{dz} \tag{3.C.13}$$

If, we compare this expression with the incompressible flow result that is correct for low Reynolds number flow, we find:

$$\frac{2f\rho}{D}u^2 = \frac{8\eta u}{(D/2)^2} \text{ so } f = \frac{16\eta}{\rho D u} = \frac{16}{Re\#} \tag{3.C.14}$$

We see that the friction coefficient will depend upon Reynolds number, Re#. There are many alternative forms to the pressure equation that amount to different assumptions about how the friction coefficient varies with Re#. These refinements

include the "Weymouth," "Panhandle," and "AGA" equation. For turbulent flow, high Re#, f is fairly constant.

The Weymouth equation is suitable for systems with large diameter, high flow rate and high pressure, for which f is given by

$$\sqrt{\frac{1}{f}} = 11.19 D^{1/6}. \tag{3.C.15}$$

The Panhandle equation is used for pipelines with very large diameters (>24 cm), high flow rate and high pressure. The friction coefficient is

$$\sqrt{\frac{1}{f}} = 16.49(\text{Re\#})^{0.01961} \tag{3.C.16}.$$

The AGA equation is suitable for and the most frequently used equation for in the fully turbulent regime for pipelines with medium to large diameter, high pressure and flow rates. The friction coefficient is used in AGA equation is

$$\sqrt{\frac{1}{f}} = 4 log \frac{3.7D}{K_e} \tag{3.C.17}$$

where K_e is the "roughness" in inch. For our pipeline calculations we used AGA equation with $K_e = 0.0007$ inch. A more detailed study of pipeline design equations and characteristics is given by Mohitpour *et al.*[124]

3.C.2.4 Compression

The basic pressure loss equation can be used to solve several problems of interest. For example, what is the ratio of power required to send two different gases [denoted "a" and "b"] delivering equal energy flow down a the same pipeline with fixed D, p_L. Here is how this problem is solved:

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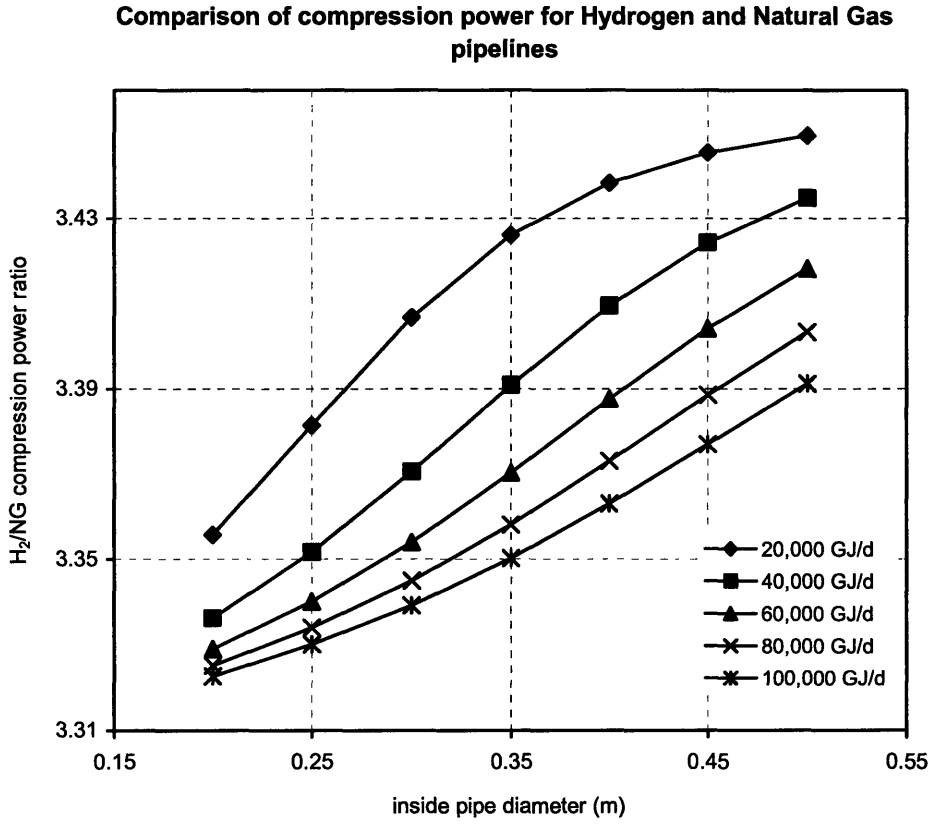
[124] Mohitpour, M., Golshan, H., Murray, A. "*Pipeline design & construction: a practical approach*" (ASME Press, New York, 2000)

Figure 3.C.2 The ratio of power needed for compression hydrogen and natural gas for flow equal energy flow rates and outlet pressures as a function of inside pipeline diameter.



1. The relationship between the two flow rates is: $g_a \Delta h_a = g_b \Delta h_b$
2. The "gas equation" is used to determine p_H^a , p_H^b for the two gases using the respective mass velocities and friction coefficients {recall f depends on shear viscosity, as well as Re#; for turbulent flow the Re# dependence is not important.)
3. The work requires to produce the high pressure may be calculated according to the appropriate conditions; for example, isothermal or adiabatic reversible compression. The case where intermediate compression stations exist along the

pipeline would be addressed in an analogous manner. For isothermal compression the work is:

$$W_a = \frac{m_a}{M_a} R_{gas} T \ln\left(\frac{p_H^a}{p_L}\right) \tag{3.C.18}$$

and the corresponding expression for power is:

$$\wp_a = \frac{g_a}{M_a} \pi \left(\frac{D}{2}\right)^2 R_{gas} T \ln\left(\frac{p_H^a}{p_L}\right). \tag{3.C.19}$$

Thus, the ratio of the power requirement for the two gases is:

$$\frac{\wp_a}{\wp_b} = \frac{\frac{g_a}{M_a} T \ln\left(\frac{p_H^a}{p_L}\right)}{\frac{g_b}{M_b} T \ln\left(\frac{p_H^b}{p_L}\right)}. \tag{3.C.20}$$

Curriculum Vitae

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Technology and Policy Program, Massachusetts Institute of Technology — Cambridge, MA
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- Evaluated two major studies by MIT Laboratory for Energy and Environment and General Motors/Argonne National Laboratory on advanced automobiles.
- Analyzed political and economical aspects of advanced electric hybrid vehicles versus fuel cell vehicles. (Report published in Science magazine.)
- Performed efficiency and cost analysis of hydrogen production, transmission and distribution systems with a focus on nuclear energy sector.

Department of Chemistry, Massachusetts Institute of Technology — Cambridge, MA
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- Developed pioneering optical techniques for chemical analysis and imaging.
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- Authored sixteen refereed publications and presented nine conference papers.

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Department of Nuclear Engineering, Massachusetts Institute of Technology — Cambridge, MA
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- Helped teach Applications of Technology in Energy and Environment (MIT wide engineering elective class administered by the Nuclear Engineering
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Department of Chemistry, Massachusetts Institute of Technology — Cambridge, MA
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- Taught Thermodynamics and Kinetics.
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- Taught Turkish, History and Math to second graders.
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WORK EXPERIENCE

Claude Delorme Research Center, Air Liquide-France — Paris, France
Researcher — Summer 2004

- Constructed a comprehensive database on new and emerging iron and steel making technologies for global corporate R&D.

- Built technology and market scenarios to guide investment strategies in iron making markets for Air Liquide.
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Massachusetts Institute of Technology — Cambridge, MA
Conflict Resolution Mediator — USA
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- Trained and certified in the Commonwealth of Massachusetts in conflict resolution.
- Provided resources for easing workplace friction and stress to students, post-doctoral fellows and staff.

Bridgestone Sabancı Tire Company, BRISA (LASSA) — İzmit, Turkey
Intern Analytical Chemist — Summer 1997

- Performed quantitative measurements used in rubber production and quality control.

SKILLS and INTERESTS

Technical:

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- Femtosecond solid state laser (Ti:Sapphire, Regenerative Amplifier, and Optical Parametric Amplification-Difference Frequency Mixing (OPA-DFG)) system operation and maintenance.
- Designed and built of experimental non-linear optical components and interferometers

Data analysis

- Proficient in FORTRAN, Matlab, Mathematica and Mathcad programming on Unix, Linux and Windows platforms
- Developed non-linear least squares data fitting routines implementing correlated interactions of coupled, stochastic multivariate systems.

Technical writing, graphics and presentations

- Experienced with MS Word, MS Excel, MS PowerPoint, and graphic design using Origin, Adobe Illustrator, and CorelDraw. Experienced with Windows XP, Macintosh, Linux and Unix.

Languages: Turkish (native); English (fluent) and French (fluent); German (beginner).

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- Full-Tuition Scholarship, 1993-1998.

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- Scholarship for Education of Young Scientists, 1993-1998.

PUBLICATIONS

Energy Technology and Policy

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5. "Correlated Vibrational Dynamics Revealed by Two-Dimensional Infrared Spectroscopy," N. Demirdöven, M. Khalil, A. Tokmakoff, *Physical Review Letters* 89, 237401 (2002).
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7. "Coherent Two-Dimensional Fourier Transform Infrared Spectroscopy," M. Khalil, N. Demirdöven, A. Tokmakoff, *Trends in Optics and Photonics*, 72, 148 (2002).
8. "Dispersion Compensation with Optical Materials for Compression of Intense Sub-100 Femtosecond Mid-infrared Pulses," N. Demirdöven, M. Khalil, O. Golonzka, A. Tokmakoff, *Optics Letters* 27, 433 (2002).
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16. "Polarization-Selective Femtosecond Raman Spectroscopy of Isotropic and Anisotropic Vibrational Dynamics in Liquids," M. Khalil, O. Golonzka, N. Demirdöven, C. J. Fecko, A. Tokmakoff, *Chemical Physics Letters*, 321, 231 (2000).

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1. March 2003, American Physical Society National Meeting, Austin, TX USA. Paper Presented: "Signatures of β-Sheet Secondary Structures in Two-Dimensional Infrared Spectroscopy," Abstract Number N11 3.
2. October 2002, Optical Society of America Annual Meeting-Laser Science 18th Conference, Orlando, FL USA. Paper Presented: "Two Dimensional Line Shape Analysis to Study Vibrational Solvation Dynamics Using Two-Dimensional Infrared Correlation Spectroscopy," Abstract Number WL5
3. August 2002, Vibrational Spectroscopy and Molecular Dynamics, Gordon Research Conference, Newport, RI USA. Poster Presented: "Correlated Vibrational Dynamics Studied by Two-Dimensional Infrared Spectroscopy," Abstract Number 22.
4. May 2002, 13th International Conference in Ultrafast Phenomena, Vancouver, Canada. Poster Presented: "Correlated Vibrational Dynamics in Solution Studied by Two-Dimensional Fourier Transform Infrared Spectroscopy," Abstract Number TuE27.
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6. June 2001, Max Born Institute Summer School on Ultrafast Vibrational Spectroscopy: Structure and Dynamics, Berlin, Germany. Poster Presented: "Correlation Effects in the Two-Dimensional Vibrational Spectroscopy of Coupled Vibrations."
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8. August 2000, 220th American Chemical Society National Meeting - Division of Physical Chemistry," Washington, DC USA Poster Presented: "Femtosecond Infrared Study of the Dephasing and Population Relaxation of Anharmonically Coupled Vibrations in Solution," Abstract Number 420.
9. August 2000, Vibrational Spectroscopy and Molecular Dynamics, Gordon Research Conference, Newport, RI USA. Poster Presented: "Femtosecond Infrared Study of the Dephasing and Population Relaxation of Anharmonically Coupled Vibrations in Solution," Abstract Number 18.

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