Hydrogen Economy: Opportunities and Challenges*

Phillip Tseng[a], John Lee[b], Paul Friley[b]

[a]Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC, USA
[b]Brookhaven National Laboratory, Upton, NY, USA
Corresponding author:<Phillip.Tseng@HQ.DOE.Gov>

Abstract

A hydrogen economy, the long-term goal of many nations, can potentially provide energy security, along with environmental and economic benefits. However, the transition from a conventional petroleum-based energy system to a hydrogen economy involves many uncertainties, such as the development of efficient fuel cell technologies, problems in hydrogen production and distribution infrastructure, and the response of petroleum markets. This study uses the U.S. MARKAL model to simulate the impacts of hydrogen technologies on the U.S. energy system and identify potential impediments to a successful transition. Preliminary findings identify potential market barriers facing the hydrogen economy, as well as opportunities in new R&D and product markets for bio-products. Quantitative analysis also offers insights on policy options for promoting hydrogen technologies.

1.0 Introduction

The objective of this paper is to study the transition from a petroleum-based energy system to a hydrogen economy, and ascertain the consequent opportunities and challenges. Insights from our quantitative analyses can provide valuable inputs to decision-makers in planning R&D, and in designing economic incentives. We used the U.S. MARKAL model to dynamically simulate the effects of a hydrogen economy on the energy sector, capture the interactions between hydrogen- and petroleum-based fuels, and identify the social costs and benefits of the transformation to a hydrogen economy.

To explore the opportunities and challenges associated with this transition, we assume that, as a result of successful research, development, and deployment, hydrogen production, system design, and fuel cell vehicles would be cost competitive with petroleum-based technologies. The economic and technical attributes used to characterize the hydrogen technologies represented in this study serve this purpose.

---

* DISCLAIMER
This study was conducted as an account of work sponsored by an agency of the United States Government. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government, or any agency, contractor or subcontractor thereof.

The U.S. MARKAL model used in this study can capture the impacts of the most extensive hydrogen economy on the U.S. energy system. However, to limit the scope of our analysis, we focus on hydrogen production from coal, natural gas, biomass, and electrolysis. On the demand side, we concentrate on fuel cell vehicles that use hydrogen. Although this approach is not a complete one, it allows us to demonstrate that opportunities abound for new technologies in a Hydrogen Economy.

It is also important to note that this paper does not address the chicken and egg problem in introducing hydrogen technologies into the U.S. energy system [1]. The existing infrastructure for petroleum-based fuel and vehicles clearly has an advantage over that for hydrogen and fuel cell vehicles. This lock-in effect for conventional technologies effectively locks out new ones. While building the required infrastructure is indeed a significant barrier to the hydrogen economy, the costs of producing hydrogen and fuel cell technologies are as important. A frugal consumer will not buy a hydrogen fuel cell vehicle if both it, and the fuel, cost more than conventional technologies [2].

Section 2 describes the U.S. MARKAL model and the analytical approach used. Section 3 presents the basic economic and technology assumptions for the Reference Case. The hydrogen economy scenarios, including technology assumptions used for analyzing the impacts of hydrogen technologies on the energy market, are considered in Section 4. Section 5 discusses findings from the model runs and the benefits of a hydrogen economy. Finally, Section 6 outlines opportunities and challenges in a hydrogen economy.

2.0 The U.S. MARKAL Model

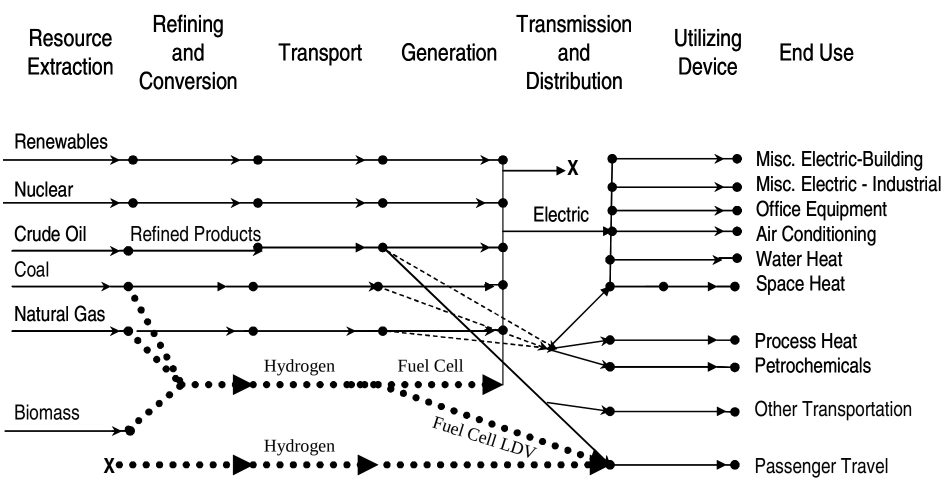
MARKAL is a partial equilibrium model of the U.S. energy systems [3,4]. It is a dynamic linear programming model that is run in 5-year intervals extending from 2000 through 2050. The objective function includes the capital costs of end-use (demand) technologies, capital costs of energy-conversion technologies (e.g., power plants, petroleum refineries), fuel and resource costs, infrastructure costs (such as pipelines), and operating and maintenance costs. The model tracks new investments and capital stocks between periods. It searches for a least-cost solution dynamically over the forecast period (2000-2050) to meet user-specified energy service demands, such as heating, cooling, lighting, and vehicle kilometers traveled. Because the model integrates both demand and supply technologies into a single energy market, the solution represents a partial equilibrium in which the energy system cost is minimized over the solution time period. The MARKAL model's output includes the least-cost configuration of the energy system, "shadow prices" for energy carriers and environmental emissions, and reduced costs for technologies that are constrained by bounds. It is especially useful in examining polices that change the technology menu, such as introducing hydrogen supply and fuel cell technologies to the transportation sector. Energy-efficiency regulations, caps on energy-related emissions, caps or floors on specific types of energy use are also examples of policies that could be modeled easily. Additionally, policies that explicitly or implicitly tax or subsidize specific technologies or energy forms can be modeled. The strength of MARKAL makes it very useful in analyzing the complexities involved in the transition towards a hydrogen economy.

Using MARKAL for prospective assessments requires the judicious application of constraints and parameter settings to avoid optimal solutions that do not reflect behavioral factors or real diversity in the attributes of energy services. Applications that are not directly reflected in the technology representations are a tougher challenge. Special attention was paid to the expansion path of manufacturing capacity that produces hydrogen, fuel cell vehicles, and infrastructure.

2.1 Modeling the Hydrogen Economy in MARKAL

The energy system in MARKAL is represented as a reference energy system (RES), depicting all possible flows of energy carriers, from extracting the resource, through energy transformation, transmission, distribution, storage, and transport, to end-use devices (Figure 1). These end-use devices deliver energy services to meet demand from various sectors. Each link in the RES is characterized by a set of technical coefficients (e.g., capacity, efficiency), environmental emission coefficients (e.g., CO_2, SO_x, NO_x), and economic coefficients (e.g., capital costs, date of commercialization.). The specific segment of the hydrogen economy modeled in this study consists of a set of feedstock supply curves of natural gas, coal, and biomass. These feedstocks are sent to three process technologies: gas reforming, coal-, and biomass-gasification. Their output is joined with hydrogen production from electrolysis further downstream of the RES. Carbon sequestration is modeled as an option for gas reforming and coal gasification at additional cost. Both coal and biomass gasification generates by-products that can replace some petrochemical uses. The hydrogen produced is modeled to go through an intermediate delivery infrastructure and storage for meeting the demand of highway vehicles. Characteristically, the economic and technical attributes of the hydrogen fuel cell vehicles improve with time.

Figure 1.1: Modeling Hydrogen Economy in MARKAL Reference Energy System



Note that nuclear and other renewable energy technologies are not modeled here but the results give some approximate cost targets that other systems would have to meet.

2.2 Analytical Approach

The quantitative analyses generated in this study were based on the differences in the model's output between a Reference Case and a "Hydrogen Economy" scenario. Several steps are involved in estimating these differences:

1. Develop a Reference Case scenario based on a projected baseline that does not include any specific programs to accelerate the market competitiveness of the hydrogen economy.

2. Identify specific R&D programs that affect the market competitiveness of the hydrogen economy.

3. Develop a "Hydrogen Economy" scenario by incorporating the activities of some selected R&D programs into MARKAL wherein the technologies affected can be explicitly represented in terms of costs, availability, efficiency, and the level of consumer acceptance.

4. Generate and compare the differences representing the situation with and without the hydrogen and fuel cell technologies.

Many factors influence the solution. Representation of the technologies, market segments in which the hydrogen economy will compete (e.g., varying oil prices, and hydrogen delivery cost), the ability to model synergy among production processes and demand devices are all likely to impact the model's findings. Including hydrogen economy in the model solution depends on its cost competitiveness with respect to other available technologies. In this study, we applied a range of values to some key model instruments and alternative market conditions that may affect the economics of hydrogen technologies to identify market barriers and opportunities, as well as gain valuable insights on its successful adoption.

3.0 Reference Case Assumptions and Projections.

The Reference Case used to study the hydrogen economy in the U.S. MARKAL was benchmarked to the underlying assumptions made in the 2002 Annual Energy Outlook [5] published by the Energy Information Administration for the years 2000 to 2020. They cover projections for GDP, housing stock, commercial buildings' square footage, industrial output, and vehicle kilometers traveled. After 2020, various sources were drawn upon to compile a set of economic and technical assumptions. The primary economic drivers of GDP and population numbers were based on the real GDP growth rate from the Congressional Budget Office's Long-Term Budget Outlook [6], and population growth rates from the Social Security Administration's 2002 Annual Report to the Board of Trustees [7]. For energy prices, the reference case projections (world and domestic) in AEO2002 were used to generate a set of supply curves for fossil resources. At the sector level, both supply-side and demand-side technologies were characterized, as far as possible, to reflect the AEO2002 assumptions.

In the reference case, the GDP, based on the chain-type price index, is projected to increase at 3.0 percent per year from 2000 to 2020, and then slow to an average annual rate of 2.1 percent up to 2050. The population growth rate is projected to decline from an average annual rate of 0.8 percent between 2000 and 2020 to 0.4 percent to 2050. Table 3.1 shows the macroeconomic assumptions for the reference case.

Table 3.1: Reference Case Macroeconomic and Demographic Assumptions

	2000	2010	2020	2030	2040	2050
GDP (Bill. 2000$)	9,860	13,161	17,666	22,188	27,386	33,058
Population (Million)	275.7	300.2	325.3	344.7	359.6	371.2
Total Households (Million)	105.2	116.0	127.1	134.7	140.5	145.0
Commercial Floorspace (Bill. sq ft)	64.5	77.5	89.6	102.1	115.1	128.2
Industrial Production (2000=100)	100	130	167	208	255	306
Total Primary Energy Consumption (EJ)	104.9	122.7	137.0	150.8	163.7	173.6
Energy/GDP (MJ/ $ GDP)	10.6	9.3	7.8	6.8	6.0	5.3

Table 3.2 shows projected energy prices for the Reference Case. Natural gas prices are projected to drop between 2000 and 2005, and then increase at just over half a percent per year to 2020, before rising to an average annual increase of 1.2 percent from 2020 to 2050. Crude oil prices also are projected to drop between 2000 and 2005, increase at average annual rates of about one percent between 2005 and 2020, and increase at just over half a percent per year thereafter. Average coal prices at the mine-mouth are projected to continue to decline until about 2040. The Reference Case presents a picture of optimistic supply of fossil energy.

Table 3.2: Reference Case Energy Prices

2000 $s	2000	2010	2020	2030	2040	2050
World Oil Price ($/bbl)	28.69	25.06	27.40	28.37	30.44	32.12
Natural Gas Wellhead Price ($/Mcf)	3.87	3.13	3.37	3.96	4.38	4.82
Coal Minemouth Price ($/short ton)	17.01	14.11	13.41	11.95	11.77	12.18

4.0 The Hydrogen Economy Scenarios

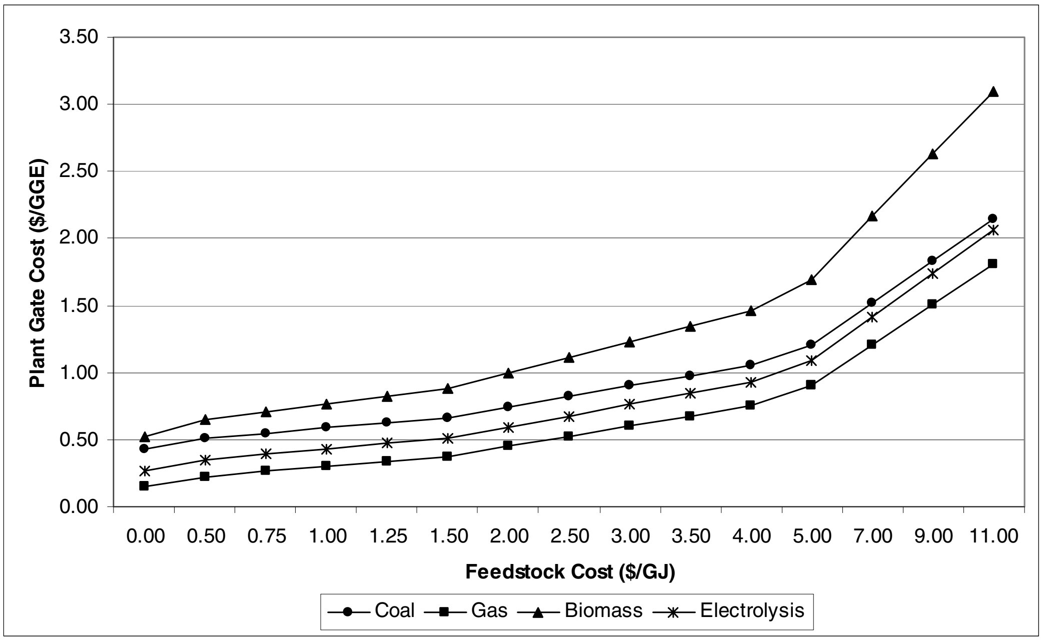
The transition from a petroleum-based energy system to a hydrogen economy requires constructing many new hydrogen plants and fueling stations. The new infrastructure must serve the emerging demand for hydrogen, and meanwhile, utilize the existing infrastructure, such as gas pipelines and railroads, to minimize the delivered price.

Early entry of a specific hydrogen technology might dominate the market if infrastructure is established to accommodate it. For example, if natural gas becomes the dominant fuel for hydrogen production, a more complete network of pipelines could be built to facilitate transporting gas and manufacturing hydrogen. Both coal and biomass could be gasified and carried via this network. Under such a scenario, technology learning could further lower the cost of producing hydrogen and make gas-based hydrogen technology the dominant one. Alternatively, railroads, gas pipelines, biomass collection systems, nuclear thermochemical, and solar thermochemical could be developed in regional markets where these energy sources are economically advantageous. Technology lock-in under this scenario is less likely.

The price of hydrogen delivered to customers depends on factors such as the size of the hydrogen plants, distance to load centers, and availability of inputs to the hydrogen plan. The designs of hydrogen infrastructure and systems must account for existing infrastructure for moving natural gas, coal, biomass, water, and possibly, other renewable energy sources. The fact that transporting these resources is a lot cheaper than constructing hydrogen pipelines affects the optimal design of the hydrogen production and delivery system. In the United States, hydrogen plants plausibly will be situated close to the load center and to rail or pipeline terminals to minimize the expenses of transportation. In areas where there is an abundant biomass supply but no easy access to coal, natural gas, or other cost-effective energy sources, biomass could have a significant niche [8].

Choices of inputs for producing hydrogen also could be time-dependent and price-sensitive. As demand for natural gas increases, prices will rise, and alternative technologies may become competitive. Furthermore, requirements for gas storage capacity will increase. The availability of natural gas could be problematic if overall demand is not matched with an adequate production, delivery, and storage system. For coal, the capacity of freight rail may be the limiting factor. With a greater demand for hydrogen from coal, shipments of coal from the mine-mouth to the terminal where hydrogen is produced will rise, and a lack of freight capacity could limit the production of hydrogen [9].

Figure 4.1: Hydrogen Plant Gate Cost by Feedstock Cost*



*In MARKAL, the cost of a feedstock is based on a set of time dependent supply curves, which varies as demand changes. For electrolysis, the feedstock cost represents the cost of electricity, ranging from 0.1 cent to 4 cents per kWh in the figure.

The "Hydrogen Economy" scenario was based on achieving a production cost of $0.50 to $1.00 per gallon of gasoline equivalent (GGE) at gate. The price varies with capital cost, efficiencies, and cost of the feedstock used (i.e., natural gas, coal and biomass). Costs and operational characteristics for hydrogen production plants were based on published data from the National Energy Technology Laboratory and U.S. Department of Energy Office of Power Technologies [10,11]. For electrolysis, production cost is highly correlated to the cost of electricity. Figure 4.1 depicts the projected cost of hydrogen production at gate for the four conversion technologies we modeled. At $0.75 per GGE, the respective feedstock costs for natural gas, coal, and biomass are $3.5, $2.0, and $1.0 per GJ. For electrolysis, the corresponding cost of electricity is below 2 cents per kWh. Clearly, biomass conversion and electrolysis are reasonable sources of hydrogen provided there is cheap biomass available near the site, and excess off-peak electricity. For transporting (via pipeline) and storing hydrogen (in gas form), we assume approximately $0.65 to $0.85 per GGE based on an average delivery distance of 50 to 100 miles between production facilities (and throughput capacities of 75,000 to 114,000 kg/day capacity) and demand centers, and about $0.40 per GGE for less than 25 miles [12].

In the next five years, the U.S. government will provide R&D funding of about $1.7 billion for hydrogen and fuel cell technology. International collaboration between many OECD countries through the International Energy Agency's Implementing Agreement also could accelerate an improvement in costs and efficiency.

Table 4.1 reports the assumptions on the costs of vehicles and efficiencies, for conventional vehicles, hydrogen fuel cell, hybrid gasoline, and hybrid with advanced diesel vehicles, relative to the average of conventional gasoline vehicles of 2000 vintage. These assumptions are helpful in analyzing transition issues. The cost of hydrogen and fuel cell technologies could be higher and still penetrate the market if the world supply of petroleum were much more limited and crude oil prices higher than the Reference Case. The transition issues presented in this paper most likely would not be affected.

Table 4.1: Projected Costs and Efficiencies by vehicle type*

	2015	2020	2030	2050
Conventional Gasoline				
Capital Cost	1.00	1.00	1.00	1.00
O&M Cost	1.00	1.00	1.00	1.00
Efficiency	1.08	1.11	1.15	1.27
Hydrogen Fuel Cell				
Capital Cost	1.15	1.15	1.15	1.10
O&M Cost	1.10	1.05	0.90	0.90
Efficiency	2.20	2.50	2.90	2.90
Hybrid Gasoline				
Capital Cost	1.03	1.01	1.01	1.01
O&M Cost	1.05	1.00	0.90	0.90
Efficiency	1.45	1.50	1.50	1.50
Hybrid Advanced Diesel				
Capital Cost	1.15	1.10	1.05	1.05
O&M Cost	1.05	1.05	1.00	1.00
Efficiency	1.75	1.85	2.00	2.00

*In multipliers of 2000 vintage gasoline cars (efficiency = 28.6 miles per gallon, capital cost = $18,000 per vehicle).

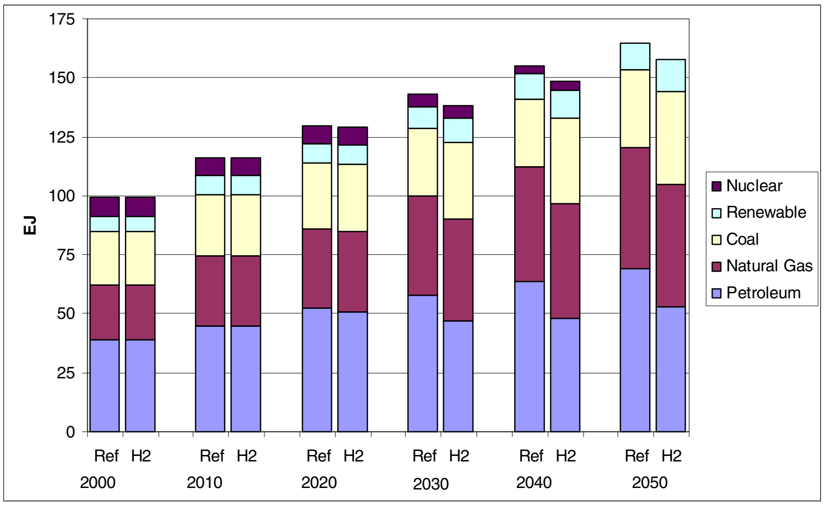
5.0 Analysis of Results

The transition from a petroleum-based energy system to a hydrogen economy will reduce demand for petroleum, lower oil prices, and reduce crude oil throughputs into petroleum refineries. Energy security will improve as sources become more diversified. Emissions of carbon dioxide also are projected to decline because of drastic improvements in fuel efficiency in the transport sector. A very important finding is that the value of gasoline will decline as the demand for it decreases. However, the value of other petroleum products will increase in the energy system because their supply will fall with lower refinery throughput. The rest of this section presents model results that would shed insights in planning of R&D work.

Four sensitivity model runs were used to examine the effects of a hydrogen economy on fuel choices for producing hydrogen, energy policy in encouraging the use of hydrogen, economic benefits of technologies, such as bio-refineries, on the prices of petroleum products, and the benefits of hydrogen economy in reducing GHG intensity. We note that biomass is used as a representative technology for renewable energy. With further technology, the contribution of other renewable technologies and nuclear power to a hydrogen economy also can be explored within the U.S. MARKAL modeling framework.

Hydrogen economy improves overall energy efficiency. Figure 5.1 shows that market penetration of hydrogen technologies will significantly lower the consumption of total primary energy and petroleum. The decline in primary energy consumption is projected to be about 5 EJ in 2030 and almost 7.5 EJ by 2050. The reduction in petroleum consumption is more dramatic, falling by 11.5 EJ in 2030 and by just over 17 EJ by 2050, i.e., almost three fold below the reduction of primary energy consumption. This difference reflects the impacts of two factors. First, petroleum consumption is less due to the adoption of more efficient fuel cell vehicles and its displacement by hydrogen. While overall primary energy consumption benefits from improved efficiency in the transportation sector, producing hydrogen requires energy to convert coal, natural gas, and biomass.

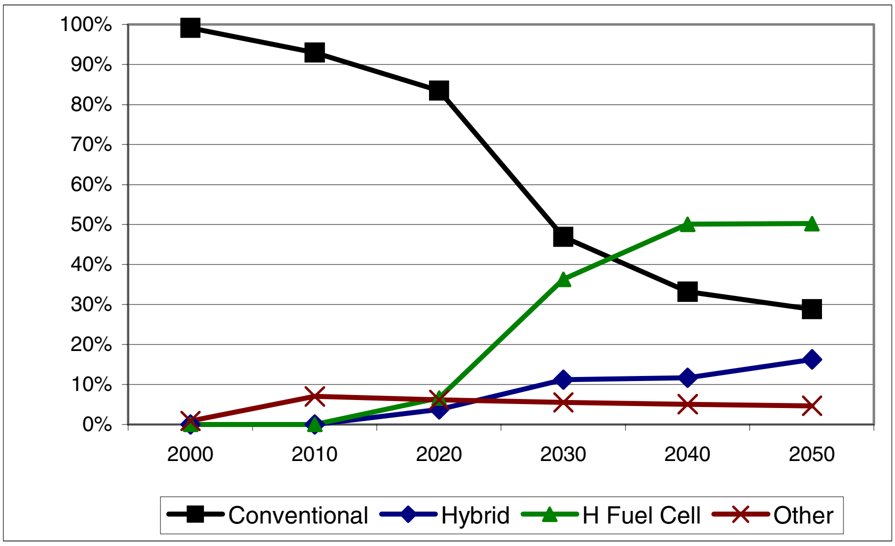
Figure 5.1: Primary Energy Consumption by Fuel



Given the assumptions on hydrogen conversion technologies and resource costs, coal appears to be the most competitive way to produce hydrogen without considerations about carbon emissions. Biomass and natural gas are projected to show some penetration, although much less. Their penetration patterns in the hydrogen economy require further regional analysis of the costs associated with transporting hydrogen from plant gates to fueling stations. The model results reported here reflect assumptions that supply curves for both natural gas and biomass are much steeper than that for coal.

On the demand side, the model's results show that hydrogen fuel cell vehicles compete well against conventional and hybrid vehicles. Their market penetration is the highest among the competing technologies due to a high efficiency that more than offsets a higher capital cost. This is the main reason for the overall energy efficiency improvements observed in a hydrogen economy. Figure 5.2 depicts the relative market share by vehicle type under the Hydrogen Scenario. It is important to note that our purpose was analyzing the transition from a petroleum-based energy system to a hydrogen economy. Therefore, the assumptions made in Table 4.1 were to ensure cost-effectiveness throughout the life cycle of hydrogen fuel cell vehicles that could happen if technologies were to improve more or oil markets become much tighter than those described in the input assumptions.

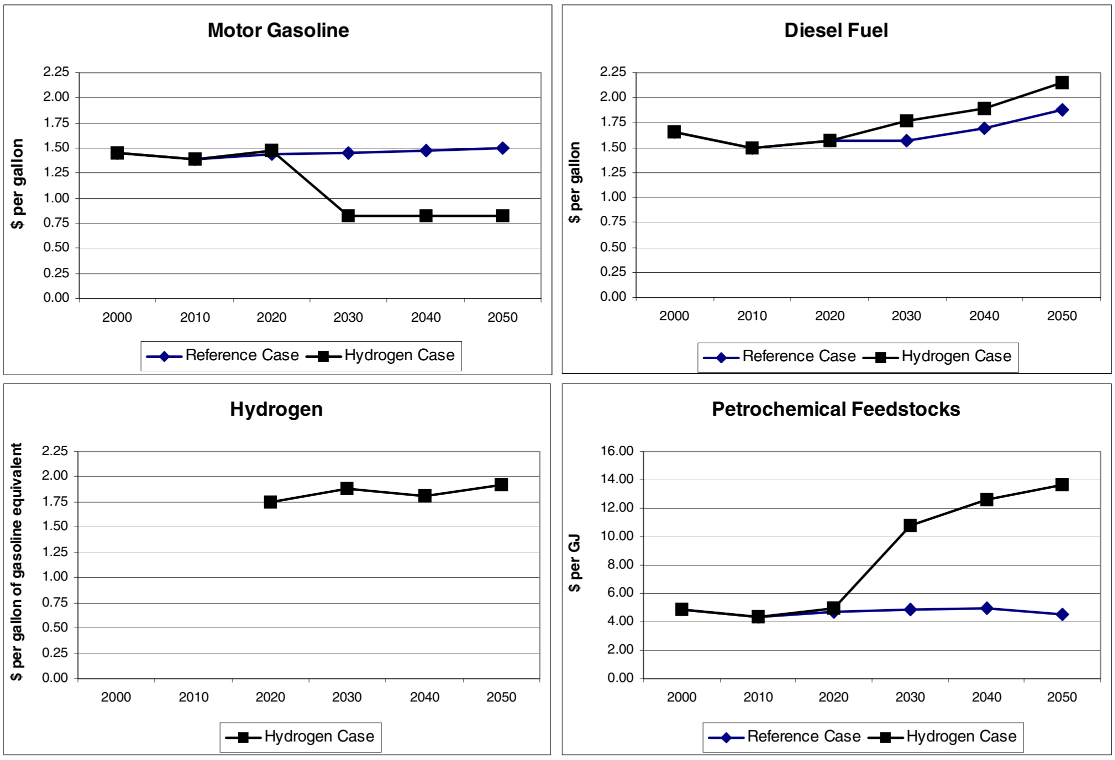
Figure 5.2: Passenger Travel Market Share by Vehicle Type



Imputed value of petroleum products changes as refinery output of gasoline decreases. Figure 5.3 shows the imputed value of gasoline, diesel fuel, petrochemical products, and hydrogen. Gasoline price is projected to decline along with a decrease in demand. By 2030, gasoline price is projected to have fallen by more than 50% for the Hydrogen Scenario compared with the Reference Case. This reduced demand changes its role as a premium fuel at refineries in the Reference Case, to a joint or byproduct in the Hydrogen Scenario.

The prices of diesel fuel and petrochemical feedstocks for the Hydrogen Scenario are projected to increase. As demand for gasoline tumbles, refinery throughput will also decrease. Existing refinery technologies show that refiners have more flexibility in producing diesel fuels from intermediate products than petrochemical products. Accordingly, the imputed values of petrochemical products are projected to increase more significantly with a lower level of refinery throughput. In addition, to maintain refinery profit margin, prices of refined products must increase to compensate for reduced selling price of gasoline.

Figure 5.3: Imputed Value of Selected Fuels



A decrease in refinery throughput and an increase in the prices of some petroleum products signal changes in the economics of petroleum refining. These changes provide possible market opportunities for internationally tradable products or new technologies. In a world where hydrogen technologies become prevalent, domestic technologies that can produce petrochemical products or diesel fuels could benefit from reduced refinery throughput and higher prices for refined petroleum products.

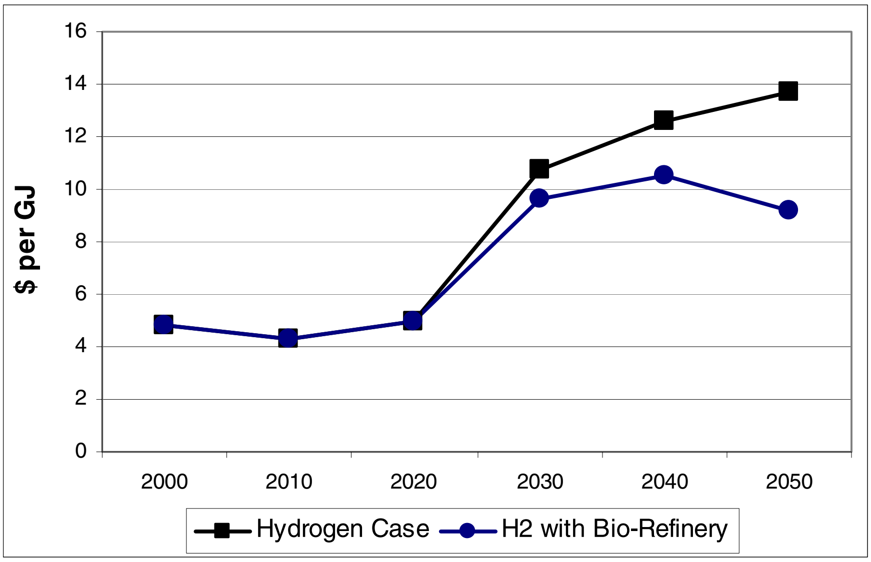
The imputed prices of hydrogen, as well as other end-use fuels, are determined endogenously and reflect the investment and operational costs of the conversion technologies, as well as delivery costs, fuel taxes and the total supply and demand for the resource/feedstock inputs. Thus, holding all other factors constant, the price of hydrogen will increase with demand as the demand and price for the resource/feedstock inputs increase.

In the current model runs, the world price of oil is not projected to decline drastically. This representation of the supply assumes that the long-term capacity for oil production may not expand if demand is not projected to grow. Consequently, the impacts of a hydrogen economy in the world oil market may be a drastic reduction in oil demand but a limited reduction in oil prices. However, oil producers probably would try to maintain market share and keep supply at levels where the marginal cost of producing oil equals the market price. Thereupon, oil prices in the hydrogen-economy scenario could drop significantly and the equilibrium point where new technologies compete with exiting technologies also will be very different.

Economic benefits of bio-refineries on prices of petroleum products in a hydrogen economy. Potential bio-products from biomass include bio-diesel, bio-chemical products, bio-fuel for transportation, and bio-gas for power or further processing for transportation fuel, such as hydrogen. A bio-refinery could integrate different processes and produce a slate of products that could change in response to market conditions. Similar analyses can be undertaken for other technologies, such as nuclear thermochemical and solar thermochemical from the production of hydrogen.

Given the assumptions on bio-refinery economics and output, model results show that biochemical products could replace some petrochemical products lost through reduced refinery throughput. Since biochemical products command a higher price on an energy-content basis, a bio-refinery could effectively reduce the imputed cost of producing hydrogen as a joint product. Figure 5.4 shows the changes in imputed value of petrochemical products as a result of increased supply of biochemical products.

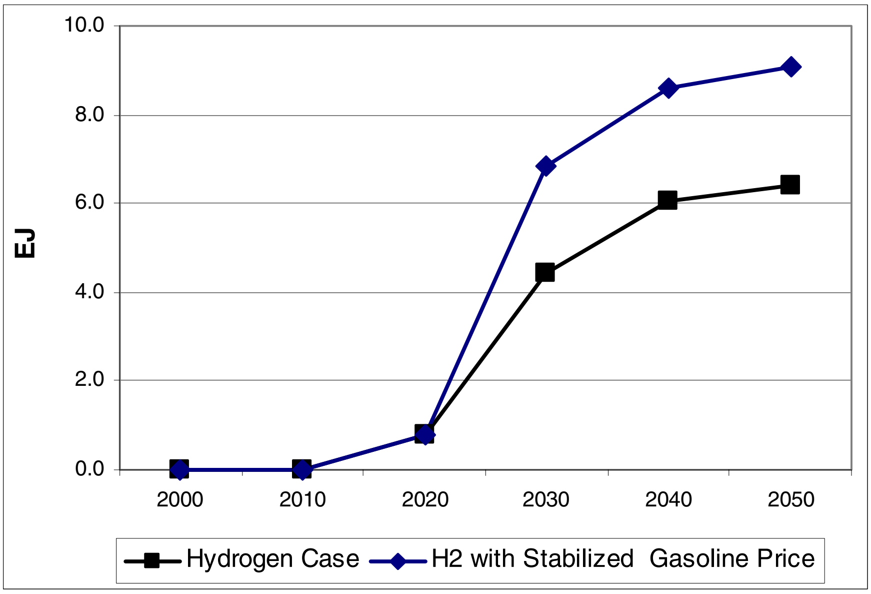
Figure 5.4: Imputed Value of Petrochemical Feedstocks



Balancing energy security and increased use of hydrogen. While the life cycle costs of driving a hydrogen fuel cell vehicle are projected to decline because of improved technology and lower costs, those of driving a traditional gasoline vehicle also might drop as gasoline prices start to fall in response to the reduction in demand. Therefore, within the energy system, drivers of gasoline-powered vehicles could experience declining fuel prices resulting from the penetration of hydrogen technologies. One of the objectives of having a Hydrogen Economy is energy security. Hence, it is important to know the point at which our energy security can be improved without completely moving to hydrogen technologies. Policy handles can be implemented to change the relative economics of the petroleum-based technologies vis-à-vis hydrogen and fuel cell technologies, and raise the market share of the new ones.

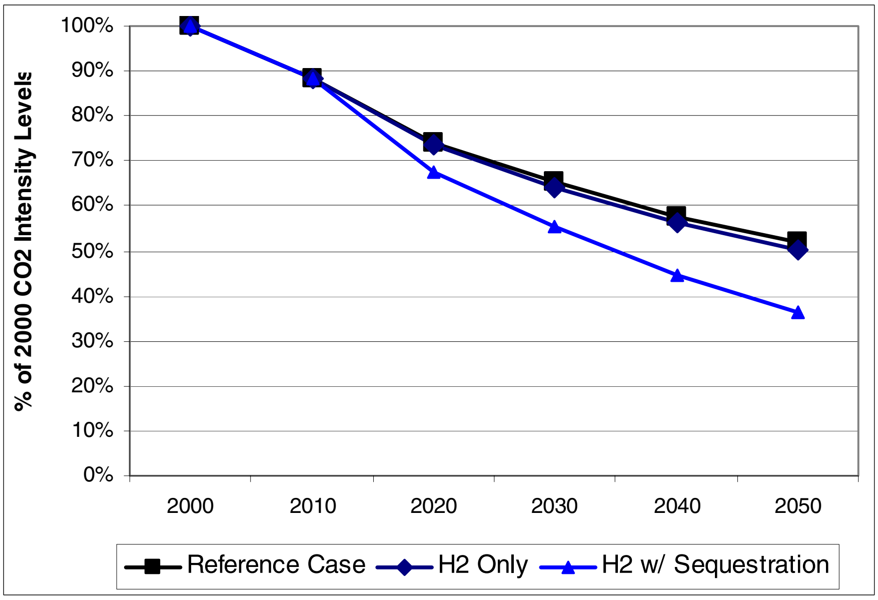
Figure 5.5 shows that by maintaining the gasoline price at the pump, or keeping the life cycle cost a both types of technologies comparable through tax incentives, total hydrogen demand could increase by more than 50 percent relative to the hydrogen case in 2030.

Figure 5.5: Hydrogen Demand under Stable Gasoline Price Case



Environmental Benefits of a Hydrogen Economy. Hydrogen technologies can reduce carbon emissions if hydrogen is produced from renewable technologies or nuclear energy. Hydrogen from fossil fuel with carbon sequestration can also help in reducing carbon emissions. One advantage of hydrogen production through reforming or gasification processes is that the carbon dioxide produced can be readily extracted for storage. Recent studies showed that capturing CO_2 adds about 25-30% to the cost of producing hydrogen [13]. Figure 5.6 depicts the reduction in carbon intensity as a percentage of the 2000 intensity level for the Reference Case, the Hydrogen Scenario, and the Hydrogen Scenario with CO_2 sequestration. The CO_2 intensities in the Hydrogen Scenario are slightly lower than those in the Reference Case due to the higher overall efficiency of the energy system. Those reductions were achieved with no additional cost to the energy system. The much greater reductions in CO_2 intensity in the Hydrogen Scenario with CO_2 sequestration may be attained if R&D on carbon sequestration is successful and policies or market conditions favor such technologies.

Figure 5.6: Reduction in CO_2 Intensity by Scenario



6.0 Opportunities and Challenges

A hydrogen-based economy would dramatically change the petroleum refining sector and the output mix of petroleum products. In the Hydrogen Case, the reduced demand for gasoline not only impinges on demand for oil, but also changes the refinery's economics and turns gasoline from premium fuel into a joint product in the petroleum refining process. As refiners reduce throughput in response to a fall in the demand for gasoline, the supply of diesel fuel, petrochemical products, and other byproducts also drops. Changes in the supply/demand mix create market opportunities for a range of products and technologies, which could include products from biomass, coal, and other renewable energies. The findings from the analyses in Section 5 are summarized below:

Opportunities

Many new technological opportunities arise as a result of changes in the energy system. The prospect of future oil supply plays a significant role in the development and the economics of many of them.

In a world where conventional oil and gas are abundant, the transition from a petroleum-based economy to a hydrogen-based economy between now and 2050, and beyond, could offer more technology opportunities to the petroleum-refining industry than to the natural gas-, biomass-, and coal-industries.

- Petroleum refiners could develop new technologies to minimize the production of gasoline, and optimize that of distillate, jet fuel, petrochemical products, and other products, such as asphalt and road oil. The economics of petroleum refining as well as the pricing of crude oil would change. Lighter crude oil with higher gasoline yield may command less than before the transition, while heavier oil may become relatively more valuable.

- Hydrogen derived from biomass is a higher value-added product. The delivered costs of hydrogen to end-users depend on both the costs of production and relatively high costs of transportation. In a Hydrogen Economy, biomass might be more cost-effective in niche markets where hydrogen from coal and natural gas may not be competitive due to the high expense of transporting them.

- Hydrogen production technologies from bio-refineries are more transferable to non-oil producing countries because they provide a flexible, cost-effective framework in meeting the changing market demand. Internationally, it could create export opportunities for these technologies. Diversification of demand for transportation fuels reduces market power of oil producers, therefore, could improve energy security and stabilize prices.

- Bio-refineries producing bio-chemical products, biogas for power generation, and hydrogen, could offer a flexible framework in meeting demand. Domestically produced bio-chemical products also have an added edge in competing with imported petrochemical products, due to transportation costs. Some residual products from bio-refineries, such as particulate and ashes may substitute for road materials that are currently based on asphalt from petroleum refiners.

- The use of energy carriers, especially those that reduce or avoid emissions of greenhouse gases, is likely to increase in the future. Gasification of fossil feedstocks could sequester CO_2 at a cost lower than those of other adjustments in the energy system to achieve a carbon intensity goal. Storage costs could be a binding factor in CO_2 sequestration, however.

In a world where conventional oil and gas are not abundant, then between now, 2050, and beyond, the transition from a petroleum-based economy to a hydrogen-based economy could provide more new technology opportunities to the biomass, coal, and other energy industries. Higher oil and gas prices in the U.S. energy market call up economic incentives to adopt new technologies.

- As economics favors hydrogen technologies because of higher prices for petroleum products, more hydrogen would be produced from coal and biomass in the midterm. Nuclear and other renewable energy also may play a very significant role in the long term as thermochemical production technology improves.

- Bio-refineries producing bio-chemical products and hydrogen could be more cost competitive because of higher prices for petroleum products in the domestic market. Consequently, more biomass will be used.

- Using coal for producing hydrogen with the concomitant sequestration of carbon emissions may be more cost-effective when the prices of petroleum products are higher, and there is a requirement to reduce the intensity of greenhouse gas emissions. We note that carbon emissions can be captured more cost-effectively when coal is gasified.

- In a world where petroleum becomes increasingly scarcer, hydrogen technologies could significantly and quickly reduce energy system costs, improve GHG intensity, and help achieve sustainable economic development.

Challenges

- Lowering hydrogen price at the pump to $1.50 - $2.00/GGE requires improvements throughout the entire hydrogen economy, from production, processing, transportation, and storage, to distribution. The improvement in fuel cell vehicle technologies requires revolutionary breakthroughs in fuel cell technologies, and evolving improvements in drive train. The development of vehicle technologies and hydrogen production technologies must proceed in tandem to break the chicken and egg problem.

- Transitioning to a hydrogen economy requires designing and implementing an economic incentive system to encourage the building of hydrogen infrastructures and market development of fuel cell vehicles. Initially, niche markets must be identified where hydrogen technologies can penetrate the market with limited economic incentives. As technology learning and economy of scale drive down technology and fuel costs, hydrogen technologies will expand.

- Transporting hydrogen is a very significant part of the cost of the delivered product. The design of an infrastructure, including gas pipelines and rail lines for delivering inputs for producing hydrogen will be a very important integral part of the delivery system. The challenges in achieving the best delivery system for hydrogen are to match the resources for hydrogen inputs and delivery system, to select the site for hydrogen production, and to establish a viable transportation network.

- Petroleum refiners have produced hydrogen for decades. Reducing the costs of producing hydrogen also would also lower the expense of producing gasoline. The reduction in gasoline demand will further reduce its imputed cost. In an oil-abundant world, low gasoline prices could impede hydrogen technologies.

- Government policies must play a role in transforming the energy system to a hydrogen economy. Hybrid vehicles, which share many common technologies with fuel cell technologies, are becoming more energy efficient and cost-effective, as are the fuel cell vehicles. However, as hydrogen technologies penetrate the market, gasoline prices will decline, and hybrid vehicles could be more competitive than the fuel cell vehicles, dampening the penetration of hydrogen technologies.

References

[1] W. Melaina, Initiating Hydrogen Infrastructures: The Role of the Chicken and Egg Problem in Increasing Energy Security and Reducing Greenhouse Gas Emissions in the U.S., Unpublished paper, 2003.

[2] L.A. Barreto, K. Makihira, and Riahi, The hydrogen economy in the 21st century: a sustainable development scenario. In Press, International Journal of Hydrogen Energy, 2002.

[3] L. Fishbone, and H. Abilock, A Linear Programming Model for Energy Systems Analysis: Technical Description of the BNL Version, *Energy Research*, Volume 5, 1981. pp. 369-379.

[4] L.D. Hamilton, , G.A. Goldstein, J.C. Lee, A.S. Manne, W. Marcuse, S.C. Morris, and C-O Wene, "MARKAL-MACRO: An Overview, BNL-48377, Brookhaven National Laboratory, Upton, New York, November 1992.

[5] Annual Energy Outlook 2002, Energy Information Administration, U.S. Department of Energy, December 2001.

[6] The Long-Term Budget Outlook, Congressional Budget Office, October 2000.

[7] The 2002 Annual Report of the Board of Trustees of the Federal Old-Age and Survivors Insurance and Disability Insurance Trust Funds, Social Security Administration, March 2002.

[8] K. Manitatis, Pathways for the Production of Bio-Hydrogen: Opportunities and Challenges, IEA Bioenergy, March 2003.

[9] J. Ogden and E. Kaijuka, New Methods for Modeling Regional Hydrogen Infrastructure Development, Unpublished paper, 2003.

[10] M.G. Klett, J.S. White, R.L. Schoff, and T.L. Buchanan, Hydrogen Production Facilities Plant Performance and Cost Comparisons, Final Report, National Energy Technology Laboratory, The United States Department of Energy, March 2002.

[11] D.B. Myers, G.D.Ariff, B.D. James, J.S.Lettow, C.E. Thomas, and R.S. Kuhn, Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances, Task 2

Report, Hydrogen Program Office, Office of Power Technologies, United States Department of Energy, April 2002.

[12] W.A. Amos, J.M. Lane, M.K. Mann, and P.L. Spath, Update of Hydrogen from Biomass – Determination of the Delivered Cost of Hydrogen, NREL, Golden, Colorado, April 2000.

[13] D. Hart, P. Freund, and A. Smith, Using Hydrogen – Today and Tomorrow, IEA Greenhouse Gas R&D Programme, Cheltenham, UK, 1999.