Hydrogen Economy: Oppp7(m)14.6 gs 0.0084c Brookhaven National Laboratory, Up
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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&D43ni. 387o To explore the transition, we assume that, ciated with the opportunities and challenges asso 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.

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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-

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

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

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

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

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

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.

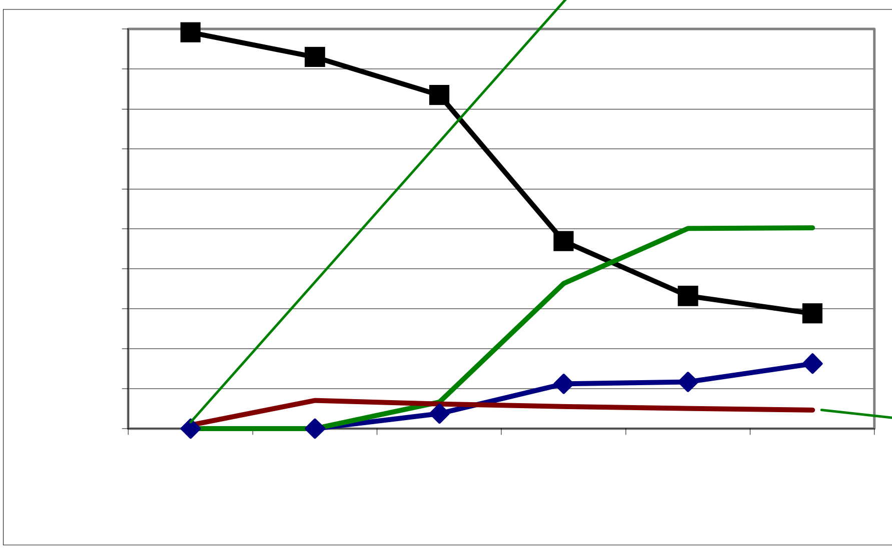
Four sensitivity model runs were used to examine the effects of a hydrogen economy on fuel choices for producing hydrogen, energy policy in encouraging the use of hydrogen, economic benefits of technologies, such as bio-refineries, on the prices of petroleum products, and the benefits of hydrogen economy 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

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



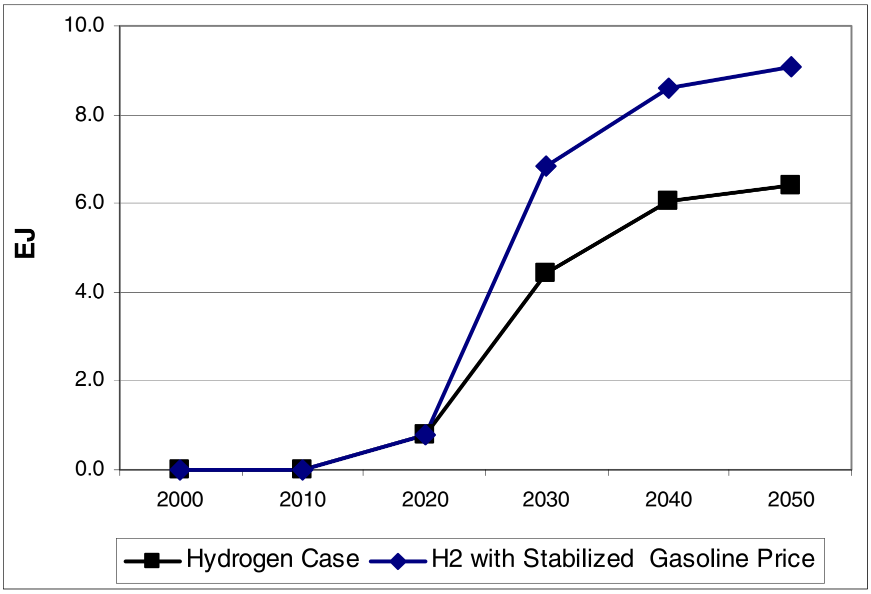
The prices of diesel fuel and petrochemical feedstocks for the Hydrogen Scenario are projected to increase. As demand for gasoline tumbles, refinery throughput will also decrease. Existing refinery technologies show that refiners have more flexibility in producing diesel fuels from intermediate products than petrochemical products. Accordingly, the imputed values of petrochemical products are projected to increase

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

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 to the energy system. The much greater reductions in CO_2 intensity in the Hydrogen Scenario with CO_2

- 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 masties f moprsea.7(i15.86(pr)-pr)6. .3(i)(

- 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 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.

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