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Are Hydrogen Cars Good For America?

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POLICY STUDY 363

Reason Foundation

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Hydrogen cars have captured the imagination of politicians and the public alike. Governor Arnold Schwarzenegger, Senator John Kerry, and Energy Secretary Samuel Bodman have all hailed hydrogen as an important component of the nationwide effort to develop cleaner, greener, and more sustainable sources of energy. In addition to hydrogen's perceived efficiency and environmental friendliness, policymakers also have welcomed hydrogen as a source of energy that could wean the country off its dependence on oil and foreign sources of energy.

Hydrogen cars have been the most obvious symbol of efforts to move the country into a hydrogen-powered future. Policymakers envision a world in which the only emission from a car's tailpipe is water, the byproduct of hydrogen fuel cells.

As this policy report explains, however, hydrogen's promise as a truly clean and efficient alternative to oil is still only a promise. At present, hydrogen is not an efficient or environmentally friendly alternative to the gasoline that powers nearly all automobiles. Hydrogen fuel cells in the cars themselves produce virtually no pollution, aside from water. However, depending on the technology used, the manufacture of hydrogen fuel cells produces as much or more net pollution than the manufacture and use of gasoline.

Moreover, hydrogen would not significantly reduce the country's dependence on foreign sources of energy. The hydrogen manufacturing process requires substantial quantities of natural gas. Since production at known natural gas reserves in the United States and Canada has leveled off, the United States would need to look elsewhere for sources of natural gas to create the hydrogen for its hydrogen-powered future. Russia and countries in the Middle East are, as with oil, the largest producers of natural gas.

Policymakers' desire to reduce pollution is admirable, but hydrogen may not yet be the answer. Instead, other technologies – including clean coal processes and nuclear power – show promise.

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Part 1

Introduction

"They don't use gasoline or electricity, but these new Honda and Mercedes-Benz cars can whiz by at speeds up to 93 mph The new fuel cell cars are powered by hydrogen, the most abundant element in the universe, and they are pollution and noise free."- CNN [1]

I recently watched a well-known television news commentator interview an expert on hydrogen fuel-cell cars. While they talked, the network showed a video clip of a very stylish hydrogen-powered car racing around a test track. Their conversation centered on the design characteristics of the hydrogen car, its performance, and the fact that only water came out of the exhaust. Never once did the interviewer or his guest talk about whether the hydrogen-powered car was in any way better than its gasoline-powered cousin. They both simply assumed that hydrogen was the better fuel.

The hydrogen economy is a hot topic. In a 2007 interview in *Green Car Journal* California Gov. Arnold Schwarzenegger said that, "Hydrogen is fantastic because the only emission from the tailpipe is water. It is also a fuel that we can produce in California, instead of relying on oil from foreign countries." Governor Schwarzenegger's January 2007 California state budget allocated six million dollars to his Hydrogen Highway initiative.

On October 16, 2006, U.S. Department of Energy Secretary Samuel Bodman announced that, "We expect hydrogen to play an integral role in our energy portfolio and we are eager to see hydrogen fuel cell vehicles on the road in the near future." These are not mere words. Secretary Bodman's announcement was backed up by a $100 million commitment to fund 25 hydrogen research and development projects.

Car companies are also interested. Wikipedia lists over 25 fuel-cell vehicles from major manufacturers including Audi, BMW, Daimler Chrysler, Fiat, Ford, GM, Honda, Hyundai, Nissan, Peugeot, Toyota, and VW.

Many people have high hopes for hydrogen, not only as an environmentally friendly fuel, but also as a way to move our country in the direction of energy independence. Are these achievable goals? What do we need to do to ensure that hydrogen improves our environment while increasing our energy self-sufficiency?

Part 2

Background

When people discuss a hydrogen economy, it is commonly assumed that widespread use of hydrogen will result in the United States having to import less crude oil from the Middle East—a worthy goal given the current geopolitical climate. It is also assumed that hydrogen cars are environmentally friendly because they do not emit greenhouse gases such as CO_2. It is further assumed that hydrogen is readily available as a fuel, and that all we have to do is to build fueling stations to distribute this readily available clean fuel.

These key assumptions, which are seldom challenged or analyzed, form the basis of the recent national push to get hydrogen-fueled vehicles into the hands of consumers and on the road. This study seeks to examine these assumptions by asking simple questions. For example,

- Are hydrogen cars good for the environment?
- What additional raw materials must be imported in order to manufacture the needed hydrogen?
- If Americans switched to hydrogen cars, how much less crude oil would the United States have to import?
- What will it take to make hydrogen a successful alternative to conventional hydrocarbon-based transportation fuels?

Using hydrogen as a fuel involves making deliberate tradeoffs. Hydrogen must be manufactured and is therefore not a primary source of energy like coal, oil, natural gas or nuclear. While hydrogen powers cars very cleanly, the processes required to produce hydrogen in the first place can be dirty. In order to make a fair comparison with the environmental costs associated with oil, coal, or natural gas, policymakers must consider the manufacturing processes used to make hydrogen. How much oil, coal or natural gas does it take to make large quantities of hydrogen, and how much do these primary sources pollute? By manufacturing and using hydrogen on a large scale, can we truly lessen our dependence on foreign sources of oil or natural gas?

As will become clear, what underpins a successful hydrogen economy is a new mix of "clean" primary energy sources—ones that can minimize our reliance on other countries, and minimize our impact on the environment. What are these alternatives? One solution lies in our developing and deploying nuclear fusion on a large scale. Yet this technology perpetually hovers forty years in the future. In the meantime, our best immediate options appear to include nuclear fission-based reactors, solar and wind power, and "clean" coal technology.

Before embarking on an ambitious hydrogen strategy, policymakers should consider one further question:

> *What other alternatives are available to us that can put us on a course to increased energy independence?*

This study addresses these questions in quantitative terms. The work presented here is based on a prior study by the author, as well as the work of others.[2] A number of recent publications frame the issues surrounding hydrogen cars, including articles in *Popular Science* and *Scientific American*.[3]

Prior Study

This current study is an extension of previously published work examining the impact of hydrogen cars on environmental CO_2 emissions in California. *Fueling America: How Hydrogen Cars Affect the Environment* showed that even though hydrogen cars produce no CO_2 in the exhaust, the manufacture and distribution of hydrogen requires significant raw materials and energy.[4] In fact, almost as much CO_2 is generated by these hydrogen manufacturing and distribution processes, as is made by the equivalent processes for gasoline cars. One of the main conclusions of the prior study was that there are many less expensive ways to reduce atmospheric CO_2 emissions than switching to hydrogen-powered cars. For example, increasing the fuel efficiency of our existing gasoline cars is faster, simpler, and cheaper than building an entire hydrogen economy infrastructure.

Part 3

Exploring the Hydrogen Alternative

Today, hydrogen is being explored as an alternative to gasoline for use in automobiles. While it is common knowledge that gasoline is refined from crude oil, a widespread misperception is that hydrogen is somehow "harvested" from the air. In fact, there are two main industrial sources of hydrogen, both involving manufacturing processes. In the first, *electrolysis*, an electrical current is run through clean water, which then dissociates into its constituent molecules O_2 and H_2. The H_2 is collected, compressed and transported to users. The second source of commercial hydrogen is via the conversion of natural gas in a large industrial reactor (a process called *Steam Methane Reforming*). There are many variations of this process involving heating a light hydrocarbon stream (methane, ethane and propane are typically used as feedstocks) in the presence of a catalyst and water to produce a stream of H_2 (hydrogen), H_2O (water), CO (carbon monoxide) and CO_2 (carbon dioxide). After additional steps to remove CO, CO_2 and excess H_2O, nearly pure hydrogen is available for transmission to users. Notice that one of the main byproducts of the steam reforming process is CO_2, which is normally either vented to the atmosphere or sold to a user of the gas. The net hydrogen-producing reaction is shown in Equation 1.

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$$

Equation 1: Net Steam Methane Reforming Reaction

After its manufacture, hydrogen must be compressed to very high pressures in order to make its transportation economical. This is because the energy density of hydrogen at atmospheric pressure is far too low to make it worthwhile to transport.

A. Fuel Cells

The most efficient way to use hydrogen to power a car is to combine the gaseous hydrogen fuel with air in a fuel cell; this produces electricity that powers the car. The efficiency of a hydrogen fuel cell in isolation is around 80 percent, and the efficiency for an inverter/motor in isolation is around 80 percent. While the widely reported efficiency of fuel cell cars of 64 percent appears enticing, it ignores many other losses related to generating and transporting the hydrogen, which when taken together lower the hydrogen car's overall efficiency substantially. A gasoline-powered car, by contrast, converts around 20 to 25 percent of the energy available in gasoline into motion.

Hybrid gasoline/electric cars, which have recently become popular, are significantly more efficient than their gasoline-only equivalents. For example, the 2007 Toyota Camry hybrid gets 40/38 mpg (city/highway) versus the gasoline-only Toyota Camry, which gets 24/34 mpg (city/highway).[5] This makes the hybrid Toyota 67 percent more efficient for city driving and 12 percent more efficient for highway driving.

B. The Link Between Hydrogen and CO_2

Clearly, burning gasoline yields carbon dioxide, as illustrated in Equation 2.

$$C_8H_{18} + 12\frac{1}{2}\ O_2 \rightarrow 9H_2O + 8CO_2$$

Equation 2: Combustion of gasoline (iso-octane)

But, as Equation 1 shows, making hydrogen by reforming also results in carbon dioxide. (Note that the electricity generation steps which precede electrolysis also produce CO_2 indirectly.)

The production of all types of fuels, including hydrogen and gasoline, requires energy in the form of electricity. One of the most common ways to make electricity in the United States is to burn hydrocarbons, namely, coal, fuel oil and natural gas to produce steam to drive steam turbine generators. Burning these hydrocarbons produces CO_2. With rare exceptions then, it turns out that making hydrogen, compressing and transporting it ends up indirectly generating significant amounts of carbon dioxide through the electricity consumed in the process.

When a driver powers a car with hydrogen, it's a fact that he won't be leaving any CO_2 behind in the exhaust. However, in getting the hydrogen manufactured and transported to his car, the driver will have already been responsible for creating plenty of CO_2.

The central question is "What is the total amount of CO_2 generated per mile of driving for a gasoline-powered car, compared to a hydrogen-powered one?" As one would expect, the answer is… "It depends."

C. Analyzing Hydrogen Use in Cars

In order to make a valid comparison between hydrogen and gasoline as fuels, it's necessary to draw the correct envelope around the process under consideration. Cleary, if one draws the envelope only around the vehicle itself (Figure 1), the hydrogen car is the hands-down winner because it produces zero atmospheric CO_2. For simplicity, the effects of other tailpipe emissions such as oxides of sulfur and nitrogen, and unburned hydrocarbons are excluded from this study. In well-running engines, these components appear in small amounts relative to the water and carbon dioxide in the exhaust.

For comparison, if all processes are included in the analysis (Figure 2), the comparison becomes richer and more valid. Figure 2 shows that the process to create hydrogen and get it to the car requires many steps, and that each step burns some fuel and generates its own CO_2. For example, drilling for natural gas (first step) requires power to run the drill, and other equipment such as compressors and pumps. Frequently such power comes from burning diesel fuel. Transporting natural gas through pipelines (step 2) requires large compressors, which themselves rely ultimately on combustion of hydrocarbons as a source of power. In manufacturing hydrogen from natural gas, large amounts of carbon contained in the natural gas feed end up in the air as carbon dioxide. The other steps of generating electricity, transporting electricity and transporting hydrogen each produce significant carbon dioxide emissions in similar fashion.

Figure 3 shows that making, transporting and burning gasoline generates CO_2 in a similar fashion to hydrogen fuel. Each step in the process requires energy, which usually results in CO_2 as an end product.

Figure 1: Envelope Only Around Car. Top: Hydrogen-fueled. Bottom: Gasoline-fueled.

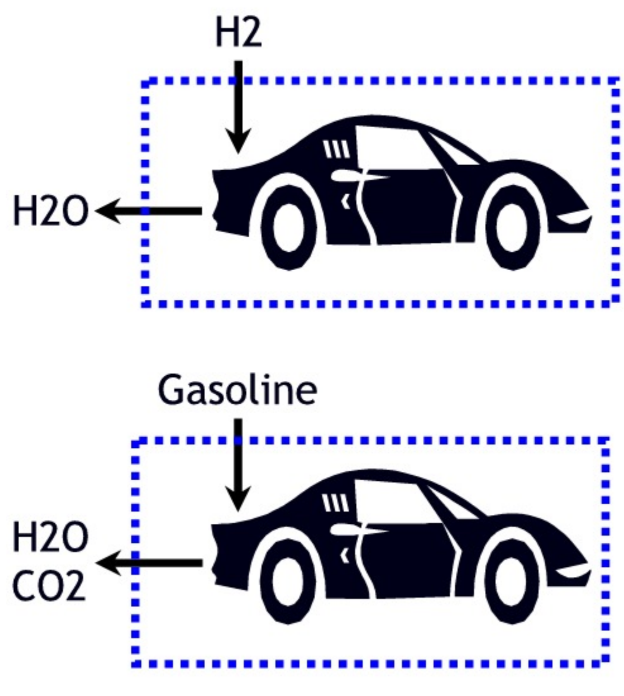


Figure 2: Manufacturing Hydrogen and Transporting It Makes CO_2

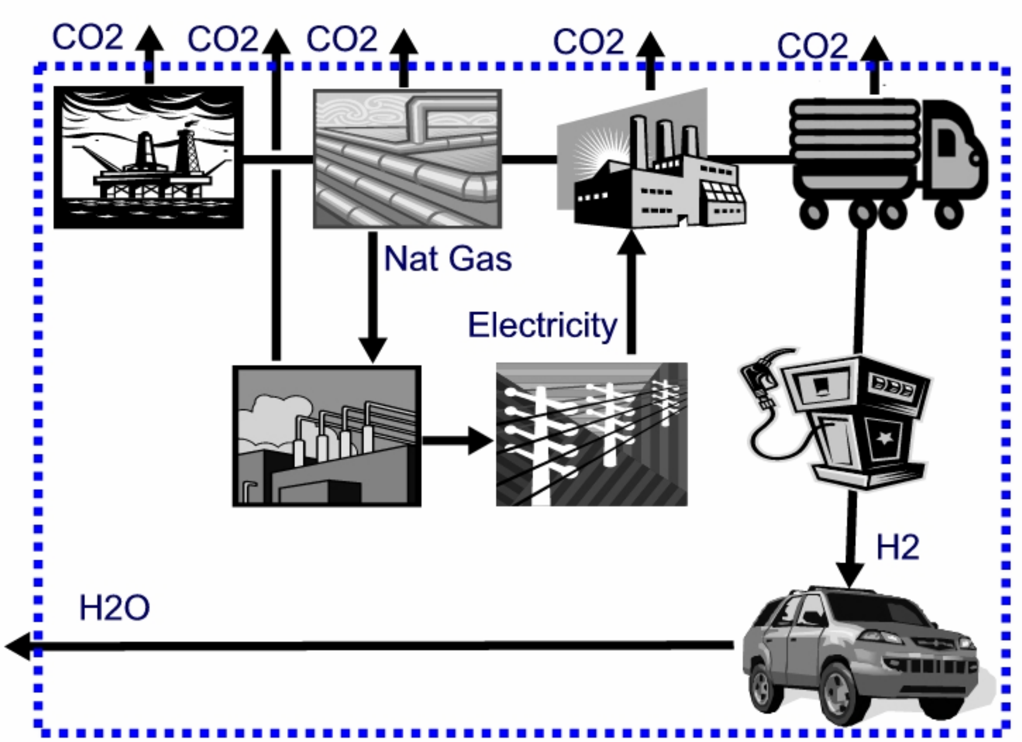
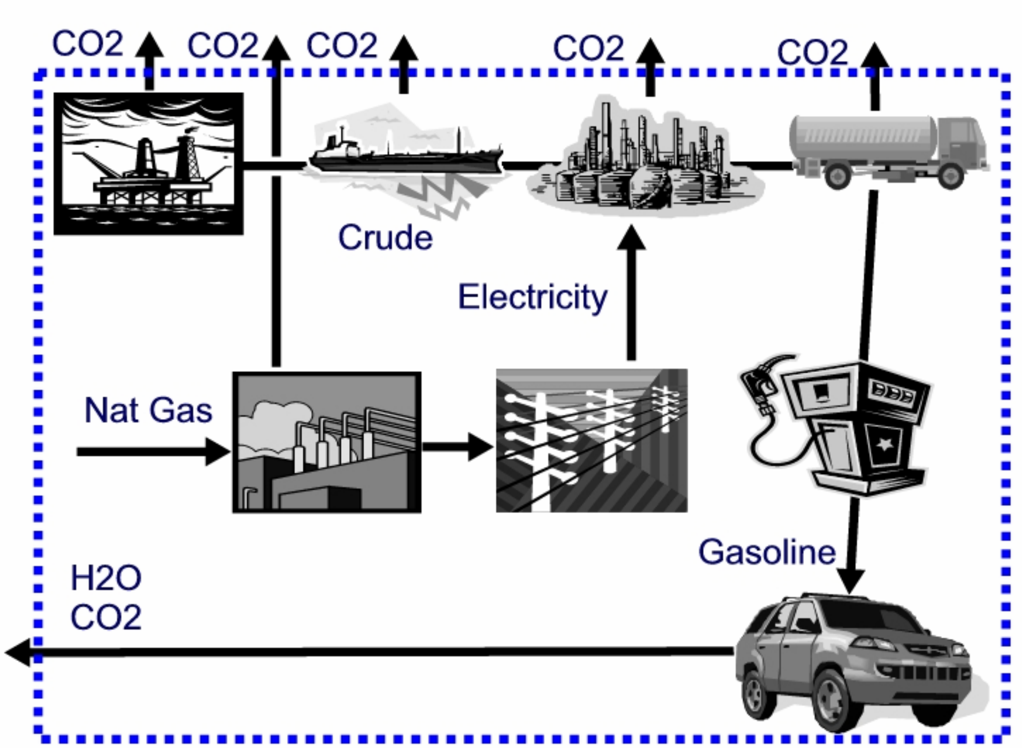


Figure 3: Manufacturing Gasoline and Transporting It Makes CO_2



The results presented here are derived from a series of computer simulations. Each simulation is based on publicly available data for different combinations of vehicle types and fuels, which assume that the candidate vehicles are driven 300 miles (about one tank of fuel). The stimulation is based on two vehicles with similar horsepower, as shown in Table 1 and Table 2.

Table 1: Gasoline Car Characteristics	
Internal Combustion Engine Vehicle	
Car type	**Ford Focus**
Curb Weight (lb)	2,564
Engine Size (liters)	2
Fuel Tank Capacity (gallons)	13.2
Horsepower	110
Miles Per Gallon: City	28
Miles Per Gallon: Highway	36
Overall Length (inches)	174.9
Torque (foot pounds)	125
Transmission Type	5M
Vehicle Width (inches)	66.9
Wheelbase (inches)	103
BTU consumed / mile driven	3,424

Table 2: Hydrogen Fuel-Cell Vehicle Characteristics	
Hydrogen Fuel-Cell Vehicle	
Car type	**Necar**
Curb Weight (lb)	3,476
Horsepower	94
Motor type	Ballard twin-stack PEM fuel cell
BTU consumed / mile driven	2,033

In conducting the simulations, the energy and raw materials requirements are calculated for every step involved in manufacturing, distributing and using the gasoline and hydrogen fuels. These essential steps are:

- Production and recovery of raw materials;
- Transportation of raw materials;
- Production of intermediates and finished fuels;
- Pumping, compressing and transporting intermediates and fuels;
- Storage of fuels;
- Refilling of vehicle; and
- Driving of vehicle a standard distance (300 miles).

The complete list of the fuel manufacturing, distribution and consumption processes is shown in Table 3. By way of general overview, each step in Table 3 can be considered a “building block” for the various processes that create fuels (hydrogen and gasoline), transport them and consume them. By combining these building blocks in different ways, we assembled a set of simulations whose results we summarize here.

Some of the terminology in Table 3 requires explanation.

- SMR means Steam Methane Reforming and is the main industrial process for manufacturing hydrogen. SMR uses natural gas as the raw material to make hydrogen. Electrolysis is the other industrial process for making hydrogen. In this process, electricity passes through water to make hydrogen.

- CH_4 stands for methane, the primary component of natural gas, which is one of the main raw materials for making hydrogen (the other is water).

- Gas Cogen refers to an efficient way to generate electricity by burning natural gas. Most new power plants being built in the United States are of this type.

- Single Cycle refers to an older, less efficient way to generate electricity by burning natural gas.

- ICE refers to Internal Combustion Engine (a gasoline-powered car).

A set of 12 simulation cases was constructed, based on the processes shown in Table 3. The 11 computer simulations plus a base case are summarized in Table 4. Each is based on a different set of assumptions for what type of car is used (gasoline or fuel cell), where the fuel comes from (which manufacturing process for hydrogen), and how electricity is made (e.g. coal, natural gas, nuclear, hydroelectric). The simulations included processes for manufacturing and distributing fuels, making electricity, and driving the cars, as per Table 3. For each simulation case the total CO_2 emissions and fuel requirements are calculated.

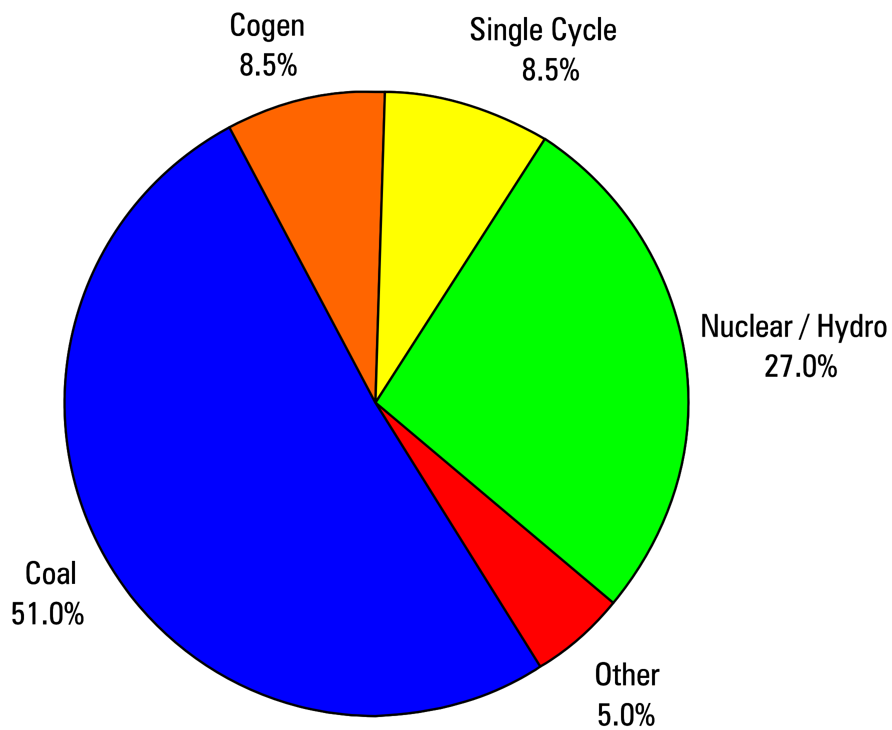
The detailed simulation work incorporates published results and methodologies developed by others[6] as well as detailed modeling technology developed by the author.[7] The results for a single vehicle were subsequently expanded to simulate the CO_2 generation and raw materials requirements for all of the vehicles in the United States, driven for one year.

Table 3: Summary of Simulation Processes	
Process	**Description**
1	Natural gas production & recovery
2	Compress & transport natural gas by pipeline
3	Crude oil production & recovery in Middle East
4	Crude oil transport by Tanker
5	Mine coal
6	Coal transport
7	Gasoline production at refinery
8	Gasoline transport by truck
9	H_2 generation by Central SMR- CH_4 feed
10	H_2 generation by Central Electrolysis
11	Compress and transport H_2 via Truck
12	H_2 storage at filling station
13	H_2 refueling at filling station
14	Gasoline storage at filling station
15	Gasoline refueling at filling station
16	Generate electricity by natural gas cogen
17	Generate electricity by natural gas single cycle
18	Generate electricity by nuclear or hydro
19	Generate electricity by coal
20	Transport electricity
21	Drive ICE car
22	Drive H_2 fuel cell car

Table 4: Summary of Simulation Case Studies				
Case	**Car**	**Electricity**	**H_2 source**	**Processes**
Base	Gasoline	Coal	n/a	3,4,5,6,7,8,14,15,19,20,21
1	Gasoline	Gas cogen	n/a	1,2,3,4,7,8,14,15,16,20,21
2	Gasoline	Gas single cycle	n/a	1,2,3,4,7,8,14,15,17,20,21
3	Gasoline	Nuclear or Hydro	n/a	3,4,7,8,14,15,18,20,21
4	Fuel cell	Coal	SMR- CH_4	1,2,5,6,9,11,12,13,19,20,22
5	Fuel cell	Gas cogen	SMR- CH_4	1,2,9,11,12,13,16,20,22
6	Fuel cell	Gas single cycle	SMR- CH_4	1,2,9,11,12,13,17,20,22
7	Fuel cell	Nuclear or Hydro	SMR- CH_4	1,2,9,11,12,13,18,20,22
8	Fuel cell	Coal	Electrolysis	5,6,10,11,12,13,19,20,22
9	Fuel cell	Gas cogen	Electrolysis	1,2,10,11,12,13,16,20,22
10	Fuel cell	Gas single cycle	Electrolysis	1,2,10,11,12,13,17,20,22
11	Fuel cell	Nuclear or Hydro	Electrolysis	10,11,12,13,18,20,22

One of the most important considerations in carrying out the simulation work is to understand how electricity is generated in the United States. Different methods of electrical power generation require different fuels, and produce different amounts of CO_2 per kilowatt hour of electricity. Although the share of natural gas-based electricity is expected to increase over the coming years, this trend was analyzed and found to have little impact on the study results. The analysis is therefore based entirely on the 2003 power generation data shown in Figure 4.

Figure 4: Types of Electricity Generation in the United States in 2003[8]



There is a strong desire to move the United States in the direction of "clean energy." In regard to electricity, clean energy generally refers to solar and wind generation. A well-known study by David Pimental of Cornell and others, summarizes well a number of the opportunities and practical issues associated with bringing these alternate energy sources closer to reality.[9]

> *Renewable energy technologies will introduce new conflicts. For example, a basic parameter controlling renewable energy supplies is the availability of land. At present more than 99% of the US and world food supply comes from the land (FAO 1991). In addition, the harvest of forest resources is presently insufficient to meet US needs and thus the United States imports some of its forest products (USBC 1992a). With approximately 75% of the total US land area exploited for agriculture and forestry, there is relatively little land available for other uses, such as biomass production and solar technologies. Population growth is expected to further exacerbate the demands for land. Therefore, future land conflicts could be intense.*

Notwithstanding land constraints, opportunities exist for satisfying our electrical needs with both wind and solar. The Pimental study states that 13 percent of the U.S. contiguous land area is sufficiently windy that we could generate 20 percent of our current electrical needs from wind. Although wind power is a fundamentally clean source of electricity, it does have drawbacks, including its effect on bird populations, noise, and its cosmetic impact on residential areas.

Photovoltaic solar power holds great promise. Pimental estimates that our total electricity needs can be met by using only 0.6 percent of our land. The main drawbacks associated with solar power include its high cost, the durability of the solar cells themselves, and the toxic nature of the materials used in their manufacture. According to Pimental, the current cost is 30¢/KWH (four to six times the cost of conventional electricity), but this is expected to drop to 10¢/KWH by the end of the decade and then to 4¢/KWH by 2030. Expected life for photovoltaic panels now runs about 20 years. This short life combined with the toxic materials needed to make the cells (cadmium sulfide and gallium arsenide) pose environmental risks that must be carefully considered.

D. Results Summary

Simulation results are summarized here. For clarity, the calculations done by the author are referenced separately from the work done by others.[10]

As expected, gasoline cars require gasoline as fuel (Table 5) and produce CO_2 emissions (Table 6). SMR-based hydrogen fuel-cell cars on the other hand require almost no gasoline, but do require a lot of natural gas which is a raw material for making hydrogen. Interestingly, SMR/hydrogen fuel-cell cars make almost as much CO_2 as gasoline ones (1.51 vs 1.67 billion Ton/yr). Electrolysis-based hydrogen cars also require a significant amount of natural gas, almost twice as much as gasoline cars. This is due to the natural gas required to make the electricity for electrolysis. Remarkably, electrolysis-based hydrogen cars produce enormous amounts of CO_2, mainly due to the combustion of coal in the electric utility plants needed to power electrolysis.

In effect, by replacing gasoline cars with hydrogen ones, we will reduce our crude oil requirements by using less gasoline, but increase our need for natural gas. In terms of CO_2 emissions, hydrogen cars on average produce more than gasoline cars, especially if the hydrogen is made by electrolysis.

Table 5: Fuel Results After Including the Effect of Electricity Generation [10]						
		CH_4	Coal	Gasoline	Diesel	Resid.
Car type	H_2 generation	Billion standard cubic feet per year	Million Tons per year	Million barrels per year	Million barrels per year	Million barrels per year
ICE	None	4,351	26	3,300	40	67
Fuel cell	SMR	18,037	227	1	13	1
Fuel cell	Electrolysis	8,975	1,575	0	8	0

Table 6: CO_2 Results After Including the Effect of Electricity Generation [10]		
Car type	H_2 generation	CO_2 Billion Ton/yr
ICE	None	1.67
Fuel cell	SMR	1.51
Fuel cell	Electrolysis	4.01

E. Detailed Review of Results

Table 7 shows how much of each type of fuel is required for each scenario. For example, in the base case, it takes 4,050 billion cubic feet of natural gas, 49 million tons of coal and small amounts of diesel and residual fuel to produce the 3,300 million barrels of gasoline necessary to power all of the cars in America for the year 2003. These are the fuels required to make and transport the gasoline that eventually ends up being burned in the engines of the cars we drive. By comparison, Case 4 shows that if all the cars in the United States were hydrogen fuel-cell cars, powering these requires much more natural gas (16,885 billion cubic feet), but much less gasoline (1 million barrels) to produce the fuel to drive the cars.

Table 8 shows how much CO_2 is generated by each of the 11 simulation scenarios. The base case CO_2 generated is 1.707 billion tons per year. This comes mainly from car exhaust. By contrast, Case 4 shows that hydrogen-powered fuel-cell vehicles produce 1.877 billion tons of CO_2 per year. While at first glance this may seem surprising (hydrogen cars only produce water in the exhaust!), the explanation is that making hydrogen and compressing it ends up making a lot of CO_2, particularly when coal is the main electricity source.

Table 7: Detailed Results Summary of Fuels [10]

	Car type	Electricity type	H_2 generation	CH_4 used Billion standard cubic feet per year	Coal used Million Tons per year	Gasoline used Million barrels per year	Diesel used Million barrels per year	Resid used Million barrels / year
Base	ICE	Coal	None	4,050	49	3,300	40	67
Case 1	ICE	Gas cogen	None	5,321	0	3,300	40	68
Case 2	ICE	Gas single	None	6,144	0	3,300	40	68
Case 3	ICE	Nuclear/Hydro	None	4,050	0	3,300	40	67
Case 4	Fuel cell	Coal	SMR	16,885	422	1	13	1
Case 5	Fuel cell	Gas cogen	SMR	22,363	0	1	16	1
Case 6	Fuel cell	Gas single	SMR	25,925	0	1	18	1
Case 7	Fuel cell	Nuclear/Hydro	SMR	16,369	0	1	9	0
Case 8	Fuel cell	Coal	Electrolysis	0	2,933	0	3	0
Case 9	Fuel cell	Gas cogen	Electrolysis	37,897	0	0	26	0
Case 10	Fuel cell	Gas single	Electrolysis	62,418	0	0	40	0
Case 11	Fuel cell	Nuclear/Hydro	Electrolysis	0	0	0	3	0

Table 8: Detailed Results Summary of CO_2[10]

				Billion Tons CO_2 / yr			
	Car type	Electricity	H_2 generation	Fuel production & transportation	Electricity generation & transmission	Driving car	TOTAL CO_2
Base	ICE	Coal	None	0.292	0.109	1.307	1.707
Case 1	ICE	Gas cogen	None	0.295	0.034	1.307	1.636
Case 2	ICE	Gas single	None	0.294	0.056	1.307	1.656
Case 3	ICE	Nuclear/Hydro	None	0.292	0.000	1.307	1.599
Case 4	Fuel cell	Coal	SMR	0.944	0.933	0.000	1.877
Case 5	Fuel cell	Gas cogen	SMR	0.971	0.294	0.000	1.265
Case 6	Fuel cell	Gas single	SMR	0.988	0.485	0.000	1.473
Case 7	Fuel cell	Nuclear/Hydro	SMR	0.912	0.000	0.000	0.912
Case 8	Fuel cell	Coal	Electrolysis	0.001	6.485	0.000	6.486
Case 9	Fuel cell	Gas cogen	Electrolysis	0.188	2.035	0.000	2.223
Case 10	Fuel cell	Gas single	Electrolysis	0.309	3.352	0.000	3.661
Case 11	Fuel cell	Nuclear/Hydro	Electrolysis	0.001	0.000	0.000	0.001

F. Note on Electrolysis

The results shown in Table 7 and 8 show that electrolysis is currently not an efficient way to manufacture hydrogen, both in terms of the natural gas used to produce the necessary electricity and in terms of the CO_2 emissions produced. Making hydrogen by electrolysis requires a great deal of electricity, about 50 kilowatt-hours per kilogram of hydrogen.[11] A gallon of gasoline contains roughly as much energy (115,000 BTU) as does a kilogram of hydrogen. However to make a gallon of gasoline requires only about 0.27 kilowatt-hours of electricity.[6] This means that making hydrogen by electrolysis uses almost 200 times as much electricity as making the equivalent amount of gasoline.

Most of the electricity in the United States is currently made using coal, which when burned produces tremendous amounts of atmospheric CO_2 emissions. So, it is the combination of a manufacturing process that requires a lot of electricity with an electricity source that produces large quantities of CO_2 that makes electrolysis a poor way to produce hydrogen.

If the country invests in better ways to convert coal into electricity or in more nuclear power plants, then the CO_2 emissions will be smaller than stated above.

Part 4

Hydrogen Cars and Greenhouse Gases

"My plan calls for a hydrogen-based energy economy by 2020. Hydrogen is the most abundant element in the universe—and if we can tap it in the right way we can achieve a revolution for our time as far reaching as any we have ever known—from the invention of the wheel to the coming of steam power and electricity. Tapping into the power of the lightest element, hydrogen-powered cars can go long distances while emitting water vapors instead of exhaust fumes."- Senator John Kerry [12]

In 2003, Americans drove a total of 2,890,893,000,000 miles and consumed 138,608,000,000 gallons of gasoline while doing so.[13] As discussed earlier, both gasoline cars and hydrogen ones generate CO_2, either directly by burning fuel or indirectly during the manufacture and distribution of the fuel. These are the amounts shown in Table 6.

What would have happened if 20 percent of the cars were running on hydrogen fuel and the other 80 percent on gasoline?

Table 9 shows that increasing the number of hydrogen cars has almost no effect on atmospheric CO_2 emissions, assuming the hydrogen comes from Steam Methane Reforming (CO_2 drops from 1.67 to 1.63 billion tons per year). If, however, the hydrogen is manufactured by electrolysis, the CO_2 emissions actually increase as more hydrogen cars are driven (2.13 vs 1.67 billion tons per year).

Table 9: The Effect of Increasing the Number of Hydrogen Cars on CO_2 Emissions

CO_2 (Billion Tons per yr)		
No H_2 cars	20% H_2 cars (SMR)	20% H_2 cars (Electrolysis)
1.67	1.63	2.13

How do these emissions compare with those from all fossil fuel sources in the country? Figure 5 shows this comparison. In 2002, all U.S. fossil fuel sources resulted in six billion tons per year of CO_2 entering the atmosphere. On this scale, the difference in CO_2 emissions between gasoline cars and hydrogen (SMR) ones is not noticeable. However, even on this scale, it is clear that cars using hydrogen from electrolysis produce significantly more CO_2 than do gasoline cars.

Figure 6 shows what happens as we begin to introduce hydrogen cars into our economy. Depending on how the hydrogen gets made, CO_2 emissions either decrease slightly (2^{nd} bar) or increase significantly (3^{rd} bar). Total U.S. CO_2 emissions are shown for scale (1^{st} bar).

Figure 5: Comparison of CO_2 Emissions from Cars with Total U.S. Emissions [14]

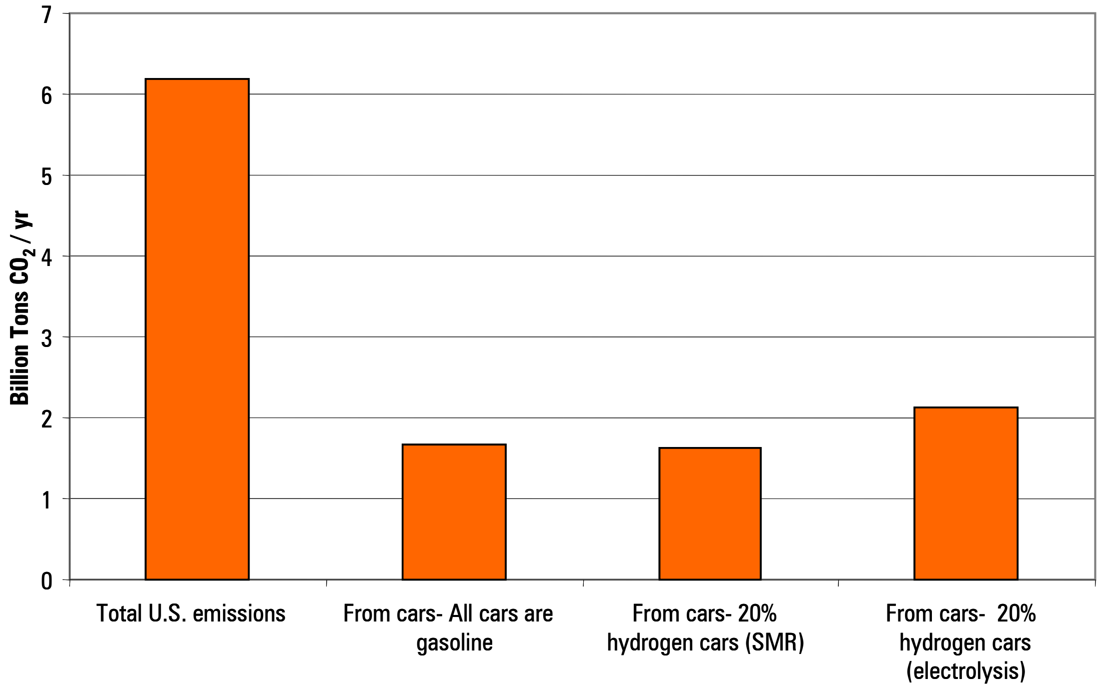
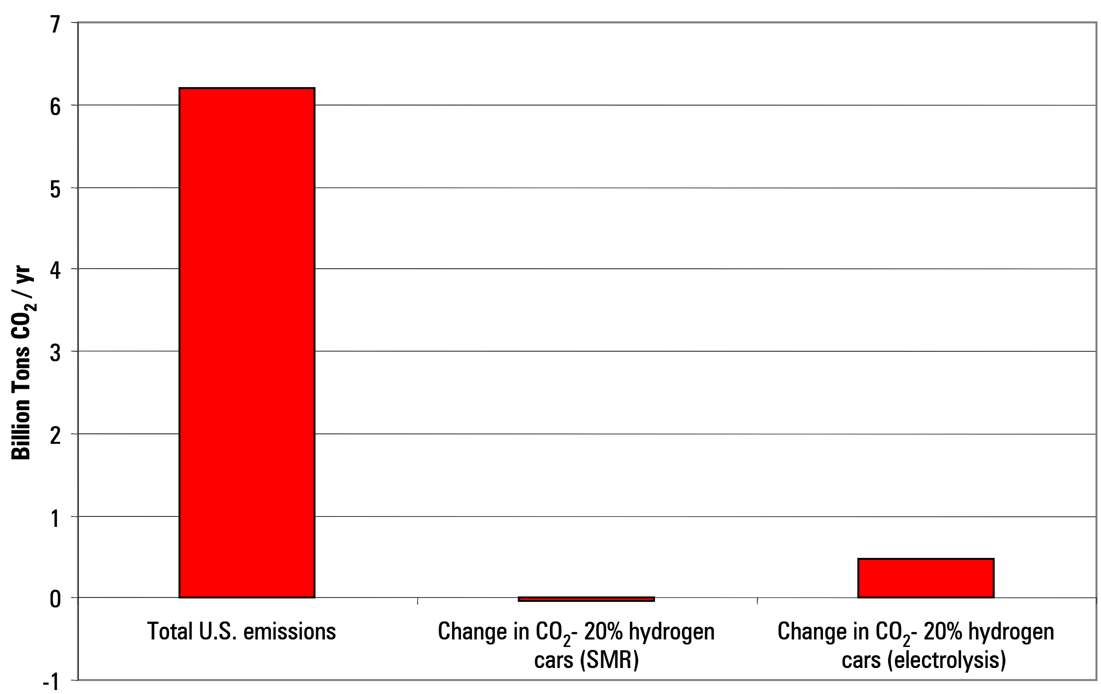


Figure 6: The Effect of Hydrogen Cars on Total CO_2 Emissions



Part 5

How will H_2 Cars Affect America's Oil and Gas Balance?

"Hydrogen fuel cells represent one of the most encouraging, innovative technologies of our era. If you're interested in our environment and if you're interested in doing what's right for the American people, if you're tired of the same old endless struggles that seem to produce nothing but noise and high bills, let us promote hydrogen fuel cells as a way to advance into the 21st century. If we develop hydrogen power to its full potential, we can reduce our demand for oil by over 11 million barrels per day by the year 2040. That would be a fantastic legacy to leave for future generations of Americans."- President George W. Bush[15]

A. The Current U.S. Oil and Natural Gas Balance

The prevailing sentiment of the country is that we are "addicted to Middle East oil." This is a legitimate concern given our current level of involvement in the Middle East and the instability associated with that part of the world. However, the reason that we are "addicted" to this source of energy is that it is cheaper than other sources of energy. Every time we as consumers fill our car's tank with gasoline, we make a deliberate choice to use the most easily available, cheapest energy we can find. After all, there are alternatives to the car, including walking, riding a bicycle or a bus or a train, telecommuting and so on, but most of us choose not to avail ourselves of these alternatives because driving a car is so convenient. In this context, it's interesting to note that although the United States imports huge quantities of goods from abroad (food, pharmaceuticals, electronics, coffee, household items, etc.), we rarely say that we are "addicted" to these items. So while we as a nation are very vocal about our reliance on the Middle East for energy, we must realize that this concern is not unique to oil.

1. How much oil and gas do we use?

The United States is the largest per capita energy user in the world. Much of this energy comes from crude oil and natural gas. In 2003, the United States produced 7.82 million barrels per day of its own crude oil and imported 9.67 million barrels per day (Table 10). Over time, U.S. domestic crude oil production is declining and imports are increasing. This decrease in domestic crude oil production is the reason that the United States is becoming more reliant on the Middle East to supply crude oil.

The United States produces most of its own natural gas, 19,068 billion cubic feet in 2003 (Table 11). It also imports significant quantities of natural gas, primarily from western Canada (Alberta and B.C). In recent years, the the United States has begun to import liquefied natural gas (LNG), largely from the Republic of Trinidad and Tobago. In the United States, annual natural gas production rates have been maintained by drilling more gas wells per year. This is because newer wells are smaller and deplete at higher rates than older ones.[16] While we import about 15 percent of our natural gas from Canada to make up the balance between supply and demand, Canada is also facing its own depletion problems from gas wells, as new wells are generally smaller than old ones.

The general picture for natural gas, then, is one in which the U.S. supplies are holding steady (by drilling an increasing number of smaller wells each succeeding year), and Canadian natural gas imports, while significant, may be reaching their own limit. In this situation, the balance for increased U.S. natural gas demand must therefore be made up by importing natural gas from abroad, most likely in the form of LNG.

If trends continue—and there's little indication that they won't—the U.S. will have to look outside of North America for future sources of natural gas.

Table 10: U.S. Crude Oil Production and Imports (million barrels per day)[17]

	Crude US Domestic	Crude Imports	Product Imports	Total = Domestic +Imports
1999	8.11	8.73	2.12	18.96
2000	8.11	9.07	2.39	19.57
2001	8.05	9.33	2.54	19.93
2002	8.04	9.14	2.39	19.57
2003	7.82	9.67	2.60	20.09

Table 11: U.S. Natural Gas Production and Imports (billion cubic feet per year)[18]

	US Domestic Dry production	Imports Natural gas	Imports Liquefied Natural Gas (LNG)	Total
1999	18,832	3,422	163	22,418
2000	19,182	3,782	226	23,190
2001	19,616	3,977	238	23,831
2002	18,964	4,015	229	23,208
2003	19,068	3,996	507	23,571

B. World Crude Oil and Natural Gas Reserves

The U.S. crude oil and natural gas reserves are shown in Table 12 (NGL refers to Natural Gas Liquids, which is gasoline-like material). Table 13 and 14 show the world crude oil and natural gas reserves for the top 10 countries. For oil, these countries generally include the Middle Eastern nations, which is why we import so much oil from there. For natural gas, Russia holds the largest reserves, followed by the Middle Eastern nations.

Table 12: US Proved Reserves *

Crude Oil	Dry Gas	NGL
Million barrels	Billion cubic feet	Million barrels
21,891	189,044	7,459

Table 13: World Proved Crude Oil Reserves

International proved reserves (Oil & Gas Journal, Dec 2003)	Crude Oil
	Million barrels
Saudi Arabia	261,900
Iran	125,800
Iraq	115,000
Kuwait	99,000
Canada [1]	178,893
United Arab Emirates	97,800
Venezuela	77,800
Russia	60,000
Libya	36,000
Nigeria	25,000

[1] Includes Alberta tar sands

Table 14: World Proved Natural Gas Reserves

International proved reserves (Oil & Gas Journal, Dec 2003)	Dry Gas
	Billion cubic feet
Russia	1,680,000
Iran	940,000
Qatar	910,000
Saudi Arabia	231,000
United Arab Emirates	212,000
United States	186,946
Nigeria	169,000
Algeria	160,000
Venezuela	148,000
Iraq	110,000
Canada (rank 19th)	59,069

Part 6

Swapping Oil Imports for Gas Imports

Switching to hydrogen cars will decrease gasoline consumption, which in turn will decrease the country's need to import crude oil from the Middle East. This switch to hydrogen cars would also, however, increase our need to import natural gas from abroad (refer to Equation 1 and Table 5 for the connection between natural gas and hydrogen). Table 15 summarizes the amount of raw materials needed to provide fuel for gasoline cars, assuming they were driven the same number of total miles as in 2003. The gasoline car requires 3,300 million barrels of gasoline and 4,351 billion cubic feet of natural gas.

Table 15: Raw Materials—Base Case: Gasoline Cars Only

CH_4	Coal	Gasoline	Diesel	Resid
Billion standard cubic feet per year	Million tons per year	Million barrels per year	Million barrels per year	Million barrels per year
4,351	26	3,300	40	67

Table 16 summarizes the amount of raw materials required to provide fuel if 20 percent of the nation's cars were to run on hydrogen and 80 percent on gasoline. Less gasoline is required (2,640 vs 3,300 million barrels/yr), but more natural gas is necessary (7,088 vs 4,351 billion cubic feet/yr) as well as almost triple the amount of coal.

Table 16: Raw Materials—20 Percent Hydrogen Cars

CH_4	Coal	Gasoline	Diesel	Resid
Billion standard cubic feet per year	Million tons per year	Million barrels per year	Million barrels per year	Million barrels per year
7,088	66	2,640	34	54

Table 17 shows the incremental raw material requirements, assuming 20 percent of the cars ran on hydrogen (Table 17 = Table 16 - Table 15). Thus the United States would need to produce 660 million barrels less gasoline each year, but would need to import 2,808 billion cubic feet more natural gas each year. By switching to hydrogen cars, the United States would effectively import 660 million barrels less crude, but import 2,808 billion cubic feet more natural gas each year.

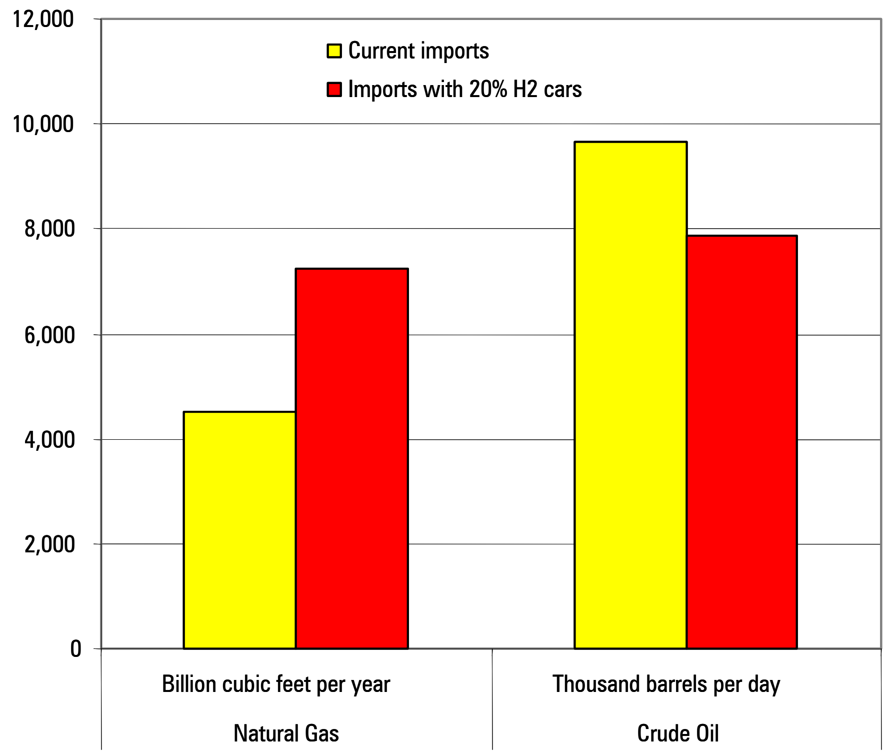
Table 17: The Change in Raw Materials if 20 Percent of Cars Run on Hydrogen				
CH_4	Coal	Gasoline	Diesel	Resid
Billion standard cubic feet per year	Million tons per year	Million barrels per year	Million barrels per year	Million barrels per year
2,808	37	(660)	(5)	(13)

Impact on National Import Requirements

Crude oil: 660 million barrels per year is about 1.9 million barrels per day, which according to Table 10 is 20 percent of our total crude oil imports. Natural gas: 2,808 billion cubic feet of gas per year is 60 percent of our total natural gas imports (Table 11).

The move away from gasoline-powered to hydrogen-powered cars in effect would require the United States to swap less imported crude oil (20 percent of our imports) for more imported natural gas (60 percent of our imports). Figure 7 illustrates this tradeoff.

Figure 7: Relative Changes in Natural Gas and Crude Oil Imports for 20 Percent Hydrogen Cars [10]



Part 7

Replacing Imported Oil with Imported Natural Gas

"Increased marginal supplies [of natural gas] from abroad… would expose us to possibly insecure sources of foreign supply, as it has for oil."- Alan Greenspan [19]

Even if the United States were to decrease crude oil imports by 660 million barrels per year (largely from the Middle East), we would still need to import almost eight million barrels per day of crude oil from other countries.

Our natural gas supplies would also re-balance. The natural gas question is harder to answer, however. Because Canada's supply is not large by world standards (Table 14), and because its exports are showing signs of leveling off, the United States would likely need to import from elsewhere. But from where? Because the natural gas would need to get here by ship, it would need to be compressed into LNG. The country's largest supplier of LNG is the Republic of Trinidad and Tobago. However reserves there are small at 34,000 BCF[20] less than Canada's.

So if the United States cannot get much additional natural gas from Canada or the Republic of Trinidad and Tobago, then it would come from other countries holding large reserves. And which are these? The list of countries with the largest natural gas reserves is given in Table 14. With the exception of Russia these are the Middle Eastern countries.

By switching to hydrogen cars, we would simply be substituting Middle Eastern crude oil imports for natural gas imports from the Middle East or Russia. Clearly such a switch does not make the United States any more energy independent.

Part 8

Energy Infrastructure

From the preceding analysis, it should be clear that introducing hydrogen-powered cars to our country will do little to reduce atmospheric emissions of CO_2, and in fact may increase them. Further, hydrogen cars by themselves do nothing to lessen our dependence on foreign sources of hydrocarbon-based energy. In essence, focusing on hydrogen cars in isolation is a distraction from many larger, more important issues currently facing the United States.

In order to properly frame these issues, we must first define which problem it is that we are trying to solve. For example, if we state the problem only as "We must find ways to reduce atmospheric CO_2 emissions," the solution is very simple: we must either stop burning as much fuel as we do, or find ways, like carbon sequestration, to remove CO_2 emissions from the air. However, to follow such a simple course of action would be unworkable, because the United States would be forced to give up on something else, including possibly cheap energy or even the freedom to drive the automobile of our choosing.

When we talk about hydrogen cars, what we are really talking about—or should be talking about—is what kind of energy infrastructure our country needs. What should we do?

A. Define the Problem

The discussion surrounding hydrogen cars serves as a surrogate for the broader issues related to how we make electricity, how efficiently we run our industries, and how we transport ourselves. Taken together, these are the real generators of atmospheric CO_2 and the real reason we rely so heavily on imported oil.

Seen in this light, what we need from our leaders in Congress is a clear definition of the energy tradeoffs facing our country and an open debate regarding the best way forward. These tradeoffs are not simple. For example, should we have:

- Cheaper gasoline or less reliance on the Middle East for oil?
- Increased CO_2 emissions or more nuclear power?
- More solar power or cheaper electricity?
- More wind power or pristine countryside?
- Increased use of domestic coal (more CO_2 emissions) or increased natural gas imports from Russia or the Middle East?

- Increased use of biodiesel or lower freight costs?
- A free market-based energy infrastructure or one based on legislation?

Obviously policymakers cannot make all of these various options top priority; something must give. Until now, we have chosen our sources of energy based largely on market demands. However, we seem to have reached a point in our history where various lobby groups have deflected the discussion into secondary areas like hydrogen cars. As a country we seem to be ignoring the "elephant in the room" (the tradeoffs listed above) by not openly debating them in a crisp way. The consequence has been a continuation of the status quo, with our ever-increasing reliance for energy on unstable regions of the world.

What are our options, then, for producing the clean primary energy needed to power our country?

B. Nuclear Power

There is a growing recognition that nuclear power may provide our country with a way out of our many energy-related problems. In a recent poll, almost two thirds of Americans agreed that nuclear power is safe. [21] In Washington, Congress has passed the Energy Policy Act of 2005 (H.R. 6). This act incorporates a wide range of measures that support today's operating nuclear plants and provides important incentives for building new nuclear plants. (It's unfortunate, however, that this congressional act promotes nuclear technology though tax incentives and other forms of government intervention). Reactor designs have progressed significantly in recent years, with a movement toward "intrinsically safe" designs. In the United States, the federal Department of Energy (DOE) and the commercial nuclear industry in the 1990s developed four advanced reactor types.[22] At least one of these new reactors exceeded Nuclear Regulatory Commission (NRC) safety goals by several orders of magnitude.

Having access to relatively inexpensive nuclear power begins to make a hydrogen-based infrastructure feasible, because in this case, the hydrogen fuel can be cheaply made from water via electrolysis. More importantly, cost effective nuclear power makes it possible to displace hydrocarbon-based power from natural gas and coal plants, resulting in direct significant savings in atmospheric CO_2 emissions and reduced reliance on foreign sources of hydrocarbons.

A nuclear power renaissance, therefore, holds great promise for providing our energy needs.

C. Clean Coal Power

The United States Department of Energy estimates that we have more than 200 years of coal reserves at current usage rates. This enormous inventory can provide clean energy as long as it is used in a way that minimizes its environmental impact.

“Clean Coal” refers to a set of emerging related technologies for producing electricity via the combustion of coal. The reason that these technologies are considered “clean” is that the generation facilities include equipment designed to remove sulfur compounds and ash from the flue gas, and the plants are slightly more heat-efficient than older, coal-fired ones. Depending on the design, clean coal plants have a thermal efficiency of between 34 percent, which is about the same as existing “non-clean coal” plants, and 40 percent for higher-efficiency designs.[23] In general, clean coal plants will still produce very large quantities of atmospheric CO_2 emissions, unless they are of a particularly efficient design. So, while clean coal gets rid of some pollutants, it will have limited impact on CO_2 emissions.

D. Renewable Energy Sources

“Renewable” energy generally refers to a type of energy that is self-replenishing. One example of renewable energy is biodiesel—an automotive fuel made from vegetable oil or animal fat. Biodiesel is ill-suited as a raw material for hydrogen production because it contains a very high carbon to hydrogen ratio (roughly 2/1 C/H), which means that large quantities of CO_2 will be released when the hydrogen is made from vegetable-oil-based fuel. However, when considered as a replacement for petroleum-based diesel, biodiesel has the potential to reduce both our dependence on foreign crude oil and CO_2 emissions (CO_2 made during combustion ends up as new soybean plants, one raw material used in manufacturing biodiesel). The tradeoffs associated with biodiesel include devoting large tracts of land to farming sources of vegetable oil, and the accompanying large irrigation and fertilizer requirements. The cost to make biodiesel is not well known at this point.

Other types of renewable energy include wind and solar power. These make it possible to both harness electricity to make hydrogen for cars with very little CO_2 emissions, and to reduce dependence on foreign hydrocarbons. The main issues related to wind and solar currently relate to the cost to produce the power, and to the potential for each source to meet our country’s power needs. Currently wind power costs between 30 percent and 40 percent more than power from a conventional gas turbine, and solar power costs nearly 10 times more (Table 18). It is estimated that wind can supply 20 percent of the U.S. electricity needs[24], and solar power has the potential to supply American energy requirements 3.5 times over.[25] These claims, however, must be tempered by the fact that both wind and solar power rely on special geography (windy, sunny areas), many of which will be subject to environmental constraints in the same manner that oil drilling and exploration currently are.

Taken together, solar and wind power have the potential to meet more of our country’s electricity needs. However, in order for this to become a reality, we will either need to pay significantly more for electricity (currently a factor of up to 10 for solar) or wait until technological advances bring the prices down.

Table 18: Relative Costs for Electric Power by Source [26]	
Source	**Cents per kilowatt hour**
Combined cycle gas turbine	3-5
Wind	4-7
Solar PV central station	20-30
Solar PV distributed	20-50

E. Cutting Out the Hydrogen Middle Man

Eventually we will figure out how to provide ourselves with plentiful, clean and inexpensive electricity, whether from wind, solar, nuclear, or other sources like coal liquefaction and cleaner use of oil. When this happens we'll finally be able to efficiently generate hydrogen to power cars, thus reducing both our reliance on foreign sources of hydrocarbons and the atmospheric emissions of CO_2. Of course, with plentiful, clean electricity available the question arises: "Why do we need hydrogen to power cars?" After all, it would be more direct to simply use the clean electricity to power electric cars. Other factors must be weighed such as the vehicle range and how to dispose of batteries, but in this situation, it is not obvious that hydrogen itself adds any value.

It is interesting to note that hydrogen can now be purchased for use in vehicles. A spot check at a hydrogen refueling station in Los Angeles shows that hydrogen costs $13/kg to buy. Based on the efficiencies used in this study, at this price, it is three to four times more expensive to drive a hydrogen-powered car than a gasoline one. It is likely that hydrogen prices will decrease with time, but they will need to come down by a factor of four to make them competitive with gasoline. So, even with the availability of clean electricity, market considerations may limit the use of hydrogen cars due to high fuel costs.

One additional, problematic consideration is that hydrogen is a very explosive material. Hydrogen is a very explosive material. As a new hydrogen economy picks up steam, the amount of the gas being transported would dramatically increase, raising concerns relative to public safety and even homeland security. Both of these concerns have become real obstacles to California's recent interest in building an LNG terminal off the coast of Ventura.

F. Summary

The discussion regarding hydrogen cars is essentially a surrogate for a broader, more important discussion on what kind of energy infrastructure our country needs. By itself, hydrogen does not solve any of our great energy problems. Discussions about hydrogen cars and a hydrogen-based economy do, however, serve to highlight the issues and tradeoffs that we as a country need to make in order to achieve an environmentally sound, secure, and inexpensive energy infrastructure.

Part 9

Conclusions and Recommendations

In the broader scheme, there are many things the country can do to start addressing its future energy needs with respect to reduced emission of pollutants and increased security. These include:

- Energy conservation can buy time until we can solve our deeper problems, and market pricing of energy will incentivize conservation as oil does become more scarce. Keep in mind that such efficiency gains often come at the expense of factors like vehicle size, which impact passenger safety.

- Allow hydrogen cars to emerge when the technology and the market are ready, such as when clean electricity becomes sufficiently available.

- Revisit nuclear power. Build new safe reactors and deal effectively with safety issues concerning waste re-storage, terrorism and accidents. Note however that nuclear power should best emerge not through government subsidies or tax credits, that distort the market, but by competitive and private industry that seeks to deliver safe nuclear power efficiently.

- Solar power technology will likely have a role, but will have to increase in efficiency by a factor of 10 to make it competitive with other sources of electricity.

- Use technology to increase our industrial efficiency in terms of energy use and use of raw materials. Real-time mathematical models running in industrial plants are very effective in reducing emissions, saving energy and raw materials.

Hydrogen-powered cars are not a panacea. This analysis has clearly shown that producing and transporting hydrogen to fuel these cars emits about as much CO_2 as gasoline cars and significantly more when hydrogen is made via electrolysis. Rather than reducing our use of Middle Eastern oil, hydrogen cars would simply cause us to switch our use from Middle Eastern crude oil to Middle Eastern or Russian natural gas. Given these facts, then what are the merits of hydrogen cars? The answer is that there don't appear to be any. This will continue to be the case until there is a large-scale switch to new, primary, non-polluting energy sources, including nuclear power.

If reducing greenhouse gases and our dependence on foreign oil are our immediate goals, then the solutions do not lie with hydrogen cars. Rather, we should be looking at ways to remove barriers to increasing the efficiency of our existing fleet of cars as well as that of our industrial infrastructure. Policies that drive up the cost of new cars slow down turnover to new cars. Similarly, policies that drive up the cost of manufacturing slow down the adoption of newer, more efficient, manufacturing plants. This latter has a far larger impact on both greenhouse gas emissions and energy independence than just changing the kinds of cars we drive.

In order to become energy-independent, we will need truly new sources of energy, such as solar power, wind power and safe nuclear power, all of which are currently problematic, either commercially, politically or psychologically. Given the facts presented here, we are better off as a country investing in genuinely clean sources of power than we are in a hydrogen economy.

In the final analysis, we will continue to burn gasoline and refined products until the cost—either economically or politically—of doing so is greater than the costs of the alternatives.

About the Author

William Korchinski is a chemical engineer who has spent his career working worldwide in the oil refining and chemical industries. His primary focuses include the development and deployment of rigorous process simulation technology, the design and installation of real-time multivariable controls, and economic studies related to the process industries. Mr. Korchinski, who has an extensive background in statistical analysis and mathematical solution techniques, has worked for a number of corporations and consulting firms. He has worked at over 50 industrial sites throughout the world and has developed a dozen commercial technologies. Currently he runs his own business, Advanced Industrial Modeling, Inc., in Santa Barbara, California.

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Appendix Terminology Used

Term	Definition
BBL	Barrel (used to measure oil flows)
BTU	British Thermal Unit- energy required to raise 1 lb of water 1 °F
Electrolysis	Hydrogen generation via electrolysis
FC- H_2	Hydrogen fuel cell vehicle
Gas cogen	Gas-fired Combined Cycle Turbine Electric Generator
Gas single	Gas-fired Single stage Turbine Electric Generator
Hydro	Hydroelectric electricity generator
ICE	Internal Combustion Engine
LNG	Liquefied Natural Gas
Resid	Heavy fuel oil
SCF	Standard cubic feet (used to measure gas flows)
SMR	Steam methane hydrogen reformer
SMR- CH_4	Hydrogen reformer- CH_4 feed

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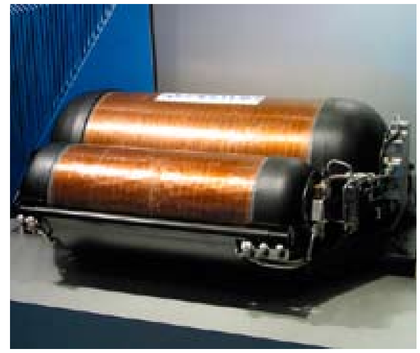
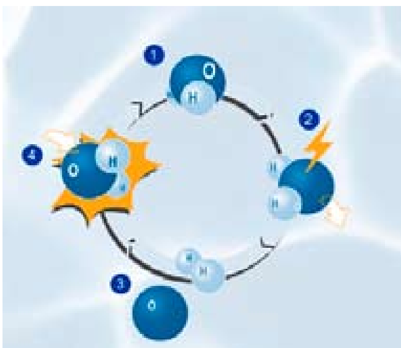


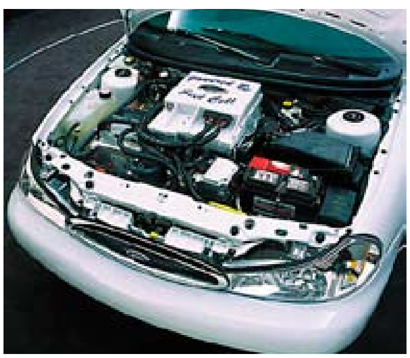
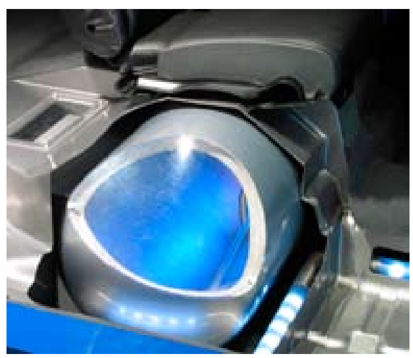


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