A Consumers Guide to the Benefits and Obstacles of Transitioning to the Hydrogen Fuel Cell

By

Gordon M. Boggie

B.S. Mechanical Engineering
Newark College of Engineering, New Jersey Institute of Technology, 1980

and

Elizabeth A. Keys

B.S., Accounting
Wallace E. Carroll School of Management, Boston College, 1991

Submitted to the Alfred P. Sloan School of Management in Partial Fulfillment of the Requirements for the Degree of

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Massachusetts Institute of Technology

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Signature of Author ....
MIT Sloan School of Management
May 6, 2002

Signature of Author ....
MIT Sloan School of Management
May 6, 2002

Certified By ....
John Van Maanen
Erwin H. Schell Professor of Organization Studies
Thesis Supervisor

Accepted By ....
Stephen J. Sacca
Director, Sloan Fellows Program

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ABSTRACT

Hydrogen Fuel Cells are a much talked about technology often represented as promising virtually unlimited amounts of non-polluting power by chemically reacting hydrogen, the most abundant element in the universe, with oxygen without combustion. Our analysis indicates that fuel cells are indeed a promising technology still under development. Our analysis concludes that there are considerable problems to overcome before a widespread transition to hydrogen fuel cells occurs, including cost, infrastructure, performance and most importantly generation of the hydrogen fuel itself. The infrastructure and hydrogen generation hurdles are extremely large, enough to require significant government intervention before renewable hydrogen resources displace fossil fuels. We believe the transition to renewable hydrogen fuel sources, and fuel cells are inevitable given the diminishing, non-renewable fossil fuel reserves. We further believe that we are rapidly approaching the date required to make fundamental energy policy changes to enable a hydrogen economy. Disappointingly, there is little evidence that U.S. government is prepared to make this decision in a timely manner.

Thesis Supervisor: John Van Maanen
Title: Erwin H. Schell Professor of Organization Studies

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Chapter 1: The Reasons for An Alternative Source of Power

1.1 Background

The internal combustion engine has powered vehicles for over 100 years. Central power stations began supplying electricity to commercial establishments in the early 1880s and electricity permeated homes in the 1920s[1]. In the United States, internal combustion engines power 98% of all new vehicles sold and nearly 100% of the population is connected to the electric grid. Moreover, most consumers are quite satisfied with the both the cost and performance characteristics of the internal combustion engine and the electric grid. In a survey conducted by RKS Research and Consulting in 2000, they found that 80% of residential consumers indicated that they were satisfied with the quality of their electricity.[2] So, the first question that needs to be addressed is why should an alternative power source be developed?

One reason an alternative power source is the inefficiency of the current power sources. Thermal electricity plants are approximately 30-35% efficient and there are losses through the transmission and distribution system of about 15%, resulting in a net efficiency of approximately 28-31%.[3] The internal combustion engine, though it continues to improve its fuel economy, is only 19% efficient.[4]

The second reason for an alternative power source is the impact on the environment. Energy use is the largest source of greenhouse gas emissions (CO_2, CH_4, N_2O, etc.), accounting for approximately 86% of total emissions.[5] The United States is the largest source of carbon dioxide (CO_2), which is the most significant greenhouse gas and the one most tied to energy use. With only 5% of the global population, the United States emitted 25% of the global CO_2 emissions, or 1.5 billion metric tons. In 1999, global emissions of CO_2 from fossil fuels was 6.1 billion metric tons (carbon equivalent).

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[1] Friedlander, Ph.D Amy "Power and Light. Electricity in the U.S. Energy Infrastructure 1870-1940". Corporation for National Research Initiatives. Reston, Virginia, 1996, page 3

[2] "Distributed Generation Residential Survey Results", March 2000, page 9. RKS Research & Consulting. Used with permission.

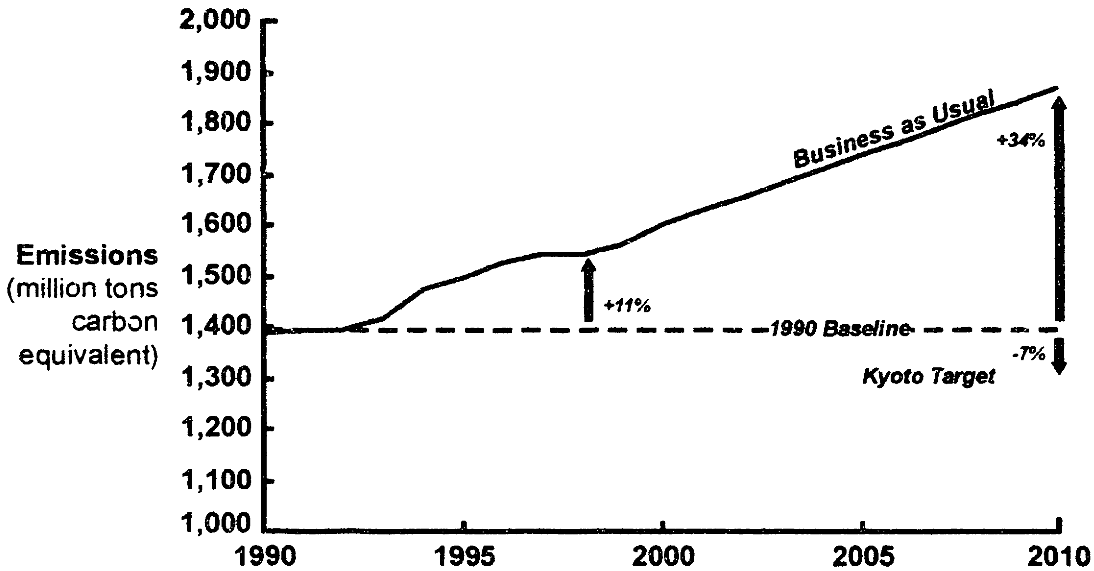
[3] Collaborative Learning Project, January and February 2002.

[4] "Benefits of Fuel Cells in Transportation." Fuel Cells 2000. The Online Fuel Cell Information Center. March 2002.

[5] Fall 2001 Meeting of the SoL Sustainability Consortium, October 2001.

Globally, and in the United States, about one third of the total CO2 emissions come from the combustion of coal; while nearly 45% comes from petroleum use. CO2 emissions in the United States are expected to increase by approximately 2% per year through 2010.[6]

US CO_2 Emissions, 1990 –2010



Source: Fall 2001 Meeting of the SoL Sustainability Consortium

Figure 1-1

These emissions have a significant impact on the health of the world's population. There are over 113 million in the United States and over one billion people worldwide that suffer from severe air pollution.[7] According to the World Bank, over 700,000 deaths result annually. Many of the emissions are thought or known to cause cancer in humans.[8] The Environmental Protection Agency estimates that vehicle emissions pose "the greatest potential threat to public health in the largest number of urban areas." According to the Center for Disease Control and Prevention, the number of asthmatics in the United States has increased from 6.8 million in 1980 to 17.3 million in 1998. This disease affects 5

[6] Fall 2001 Meeting of the SoL Sustainability Consortium, October 2001.
[7] "Benefits of Fuel Cells in Transportation." Fuel Cells 2000, The Online Fuel Cell Information Center, March 2002.
[8] Wang, Michael. "GREET 1.5 – Transportation Fuel-Cycle Model." Argonne National Laboratory, ANL/ESD-39, Argonne, Illinois, 1999.

million children in the United States and caused the death of 200 children under the age of 15 in 1999.[9]

The third reason for development of an alternative power source is the reliance on foreign oil. Though fuel economy has significantly improved, the United States' total demand for foreign oil has increased and its share of imported oil is up from 36% in 1975 to more than 50% today. America's reliance on foreign oil could be cut in half if the U.S. Department of Energy reaches its goal of hydrogen energy providing ten percent of total energy consumption by 2025.[10] The reliance on foreign oil has a significant impact on the U.S. trade deficit. Moreover, reliance on foreign oil also has a detrimental effect on national security. Given the tragic events of September 11, 2001, the availability of domestic energy sources are even more important today.

The fourth reason for the development of an alternative power source is the limit on our planet's resources. Over 380 Quads[11] of energy are used every year.[12] This is the equivalent of approximately 10 barrels of oil for every person on the plant. Thus, with no change in usage, the current supply of oil is estimated to last approximately 100 years. However, it is reasonable to expect an exponential increase in the demand for energy as the total population grows and as developing countries increase their per capita energy demands. Energy use is dominated by the United States and the developed world. The United States uses 97 Quads per year, which is roughly equal to China, Russia, Japan and Germany combined.[13] Thus, it is reasonable to expect that the demand for energy in the developing countries will grow in step with the growth in their economies.

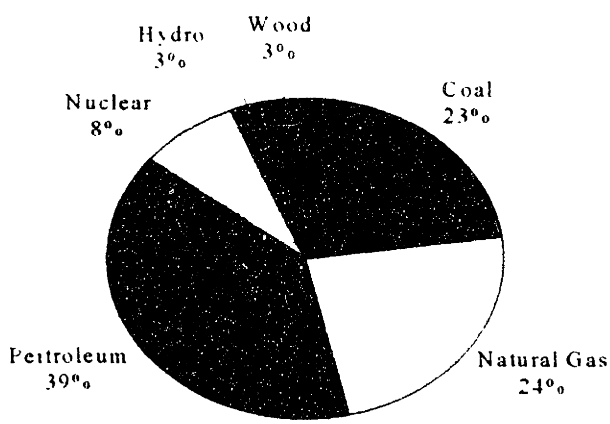
Furthermore, as the world's population rises exponentially, the demand for electricity and automobiles is also expected to rise The world's population today stands at six billion people, an increase of 140 percent over the past fifty years. By 2050, it is expected to top nine billion by 2050. In the United States, electricity demand grows at

[9] Wang, Michael "GREET 1.5 – Transportation Fuel-Cycle Model." Argonne National Laboratory. ANL/ESD-39, Argonne, Illinois, 1999.
[10] "Hydrogen, The Fuel for the Future." National Renewable Energy Laboratory, March 1995.
[11] One Quad is equal to 172 million BBL of oil or 10^15 BTU, the equivalent of the energy required by approximately 10 million homes in the United States.
[12] Fall 2001 Meeting of the SoL Sustainability Consortium, October 2001.
[13] Ibid.

approximately 1-2% per year.[14] In the post World War II years, it grew at approximately 10% and during the 1970s and 1980s it grew at approximately 4%. Today, the global car park – or total number of vehicles in the world – exceeds 750 million vehicles: however, this represents only 12 percent of the people in the world. With no change in vehicle penetration, there would be over 1 billion vehicles on the road by 2050. This number would increase to 2 billion if the penetration of vehicles doubles by 2050. In either case, if we continue to rely on the internal combustion engine, the world's dependence on oil will increase dramatically.

The growth in the demand for energy is of cause for concern due to the reliance on non-sustainable energy sources. In the United States, total electricity production is approximately 3.6 trillion kWh per year, of which 73% comes from fossil fuel sources.

US Sources of Energy



Source: Fall 2001 Meeting of the SoL Sustainability Consortium

Figure 1-2

As noted, the United States accounts for 25% of the global energy use but only 5% of the total population. Consequently, the drain on fossil fuels will increase exponentially as the world's population grows and develops.

[14] Fall 2001 Meeting of the SoL Sustainability Consortium. October 2001.

We recognize that there are counter arguments to each of these issues. Some would argue that all of the problems would be solved if we lived like the Amish without the use of electricity or automobiles. However, these people fail to recognize that energy has a significant effect on our social as well as economic well-being. Energy, and the ability to convert energy into useful work, was the single most important factor enabling our civilization to move from an agrarian to an industrial and now to information-based economy. Energy gives us the basics (heat, light and mobility) and the advanced (cell phones, laptops and the Internet). In fact, the freedom provided by vehicles is equated to the freedom provided by walking:

> "The truth is that our attachment to cars is profoundly rooted – not only in the practical necessities of life but also in our emotions. Research shows that there is a deep psychic connection between freedom and movement. Babies achieve locomotion. Adults re-experience it through the motorcar. Waiting for a bus or a train unleashes hidden, unconscious fears of abandonment in many."[15]

Furthermore, according to a study done by the Department of Energy, the transportation sector accounts for $975 billion in gross domestic product and over 13 million jobs in the United States.[16] In addition, the American Petroleum Institute estimates that the U.S. Oil Industry employs 1.5 million people and the top ninety U.S. energy companies generate $792 billion in revenues.[17] Thus, we believe that we have a better chance at developing a cleaner, more efficient and more sustainable source than we do at abolishing electricity or the automobile.

1.2 Objective

The objective of this thesis is to provide a broad overview of the key issues that must be overcome before the hydrogen fuel cell will become a serious competitor to either the internal combustion engine or the electric grid and natural gas upon which the

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[15] Maxton, Graeme P. and John Wormald. "DRIVING OVER A CLIFF? Business Lessons from the World's Car Industry." The Economist Intelligence Unit, Addison-Wesley Publishing Company, 1995, page 33.
[16] "Benefits of Fuel Cells in Transportation." Fuel Cells 2000, The Online Fuel Cell Information Center, March 2002.
[17] Fall 2001 Meeting of the SoL Sustainability Consortium, October 2001

United States relies to power its vehicles and buildings. The purpose of this thesis is not to analyze what needs to happen to make hydrogen fuel cells work in niche markets or for specialized products but rather what must happen for this technology to be accepted by the mass-market consumer. We believe that in order for hydrogen to become the predominant fuel, the hydrogen fuel cell must equal or exceed the current performance of prevailing technologies at no additional cost. Moreover, the requisite hydrogen-refueling and production infrastructures must be developed. Our research found widely divergent expert views as to when and if hydrogen will ever prevail and how the transition will occur. Though we will not attempt to answer these questions, we will attempt to separate the hype that is prevalent in the media from the reality, to illustrate the complexity of the issues and to identify the key questions that one should consider when thinking about the reality of a hydrogen powered future

1.3 Approach

To meet our objective of providing a broad overview of the key issues associated with the mass commercialization of hydrogen fuel cells, we conducted a series of informal interviews in January and February of 2002 with representatives from U.S. publicly held companies that are investing a significant amount of time and resources in developing and marketing alternative power sources for commercial, residential and automotive applications. We interviewed primarily vice presidents or directors of the groups responsible for business and market development of alternative power sources and corporate strategy We interviewed five representatives from a major automobile manufacturer. Three of the interviewees were part of the company's alternative propulsion group and two of the interviewees were part of the company's corporate strategy group responsible for the hydrogen fuel cell business. We also interviewed four representatives from a hydrogen fuel cell manufacturer, including members of its business and market development groups. All interviews were conducted based on the agreement that the specific quotes would not be attributable to specific companies or individuals.

In addition to our interviews, we participated in a collaborative learning project through the Society of Organizational Learning (SoL) and a major utility company in January and February of 2002. All of the companies that participated in the study were publicly held corporations and are members of the SoL. The utility company initiated the study to help understand how energy customers think about new energy choices such as distributed generation so that they could better tailor their product and service offerings to meet customer needs. The purpose of the SoL study was to help the utility company identify the problems commercial customers might have if they were to select distributed generation to serve all or part of their electric requirements.

The collaborative learning process was facilitated by simulated sales meetings with companies that represented potential distributed generation customers. The goal of these simulated sales sessions was not to close a sale, but rather to learn about what would make distributed generation an attractive product. To achieve this goal, the simulated sales sessions tried to resemble as closely as possible a typical sales meeting. As such, the meetings focused on the attributes (cost, reliability, environmental performance, etc.) of the product as they pertained to the customer, rather than on the details of the particular technology (fuel cells, gas turbine, etc.). The participants in the simulated sales sessions included the following:

- Utility Company: Sales representative, marketing strategy manager and SoL representative
- Customer: Energy manager, finance representative and SoL representative
- Third Party: Facilitator, researcher

Immediately following the sales presentation, the participants engaged in a dialogue about what happened during the simulated sales process and what was learned. These reflections provided insight as to how commercial customers "think" about sources of power. The focus of the reflection session was on the following:

- Why distributed generation?
    - How do you think about electricity?
    - How do you weigh the different product characteristics (costs, power quality and reliability, environmental benefits?)
    - On the whole, was this proposal attractive? If not, what are the main characteristics that would have prevented adoption?

    - How attractive does the product need to be to overcome the installation hassle?
- The Offer
    - What is the interest in different services & financing packages with the product?
    - What is the impact of positioning this as an energy service rather than a new technology?
- Sales Process
    - What about the way the product was presented that was helpful or not helpful?
    - What information was presented that you didn't need?
    - What information was not presented that you would have like to have seen?
- Customer Decision-Making Process
    - What would happen next if the deal looked good?
    - What are the potential organizational barriers to adopting DG?

The focus of our literature review was fuel cell technology, major infrastructure projects, hydrogen generation, product innovation, distributed electricity generation and sustainability of resources. While conducting the review, we also consulted with the following MIT professors:

- John M. Deutch, Institute Professor at MIT, specializing in technology, energy, international security and public policy issues.
- Eric A. von Hippel, Professor, Management of Innovation, specializing in product development, idea development, new concept development and lead user research.
- Henry D. Jacoby, Professor of Management Economics, Finance, Accounting, specializing in global environmental issues.

We realize that there are an almost infinite number of people to interview and literature to review regarding these issues. However, we believe that this thesis will provide a reader a general understanding of the issue and help him or her to understand the significance of the issues to be resolved and to be able to better distinguish the hype from the reality when considering the likelihood that hydrogen fuel cells will be commercialized.

1.4 Structure of Thesis

This thesis is divided into seven chapters that that each address key barriers that must be overcome before the hydrogen fuel cell will become a serious threat to the internal combustion engine or to the electric grid.

Chapter Two describes the basic hydrogen fuel cell technology, provides a brief development history, outlines its current applications and provides an overview of the alternatives to hydrogen fuel cells. Chapter Two also outlines the benefits of hydrogen fuel cells; the key issues and why we believe that hydrogen is the fuel for the future.

Chapter Three examines the issues associated with the methods of production of hydrogen. Though hydrogen is the most abundant resource in the universe, current methods of production are reliant upon fossil fuels wherein hydrogen is produced either by (1) reforming natural gas or petroleum products; or by (2) electrolysis of water. Both methods are currently reliant on today's energy infrastructure. The reliance on fossil fuels to generate hydrogen is a key issue since it compromises several of the key benefits of transforming to a hydrogen-powered economy.

Chapter Four discusses the issues related to the development of a hydrogen infrastructure. Though hydrogen is used today, there is not an infrastructure in place to support a hydrogen-based economy. There are issues with respect to production capacity, accessibility, distribution and storage as well as safety that must be addressed before the mass commercialization of fuel cells can be realized. This problem is especially challenging with respect to the application of fuel cells to automobiles given the wide-ranging gasoline infrastructure to which the U.S. consumer has grown accustomed. In Chapter Four, we illustrate two different strategies for the development of the requisite infrastructure. The first strategy is a "centralized" strategy that is predicated on an initial roll-out of fuel cells in fleet vehicles. The second is a "decentralized" strategy that is based on the integration of the deployment of hydrogen fuel cells in buildings and vehicles.

Chapter Five examines the relative costs of hydrogen fuel cell technology. The polymer exchange membrane (PEM) hydrogen fuel cell technology has been in existence since 1960s. Its most widely recognized application is the space program. The PEM and other types of fuel cells are currently being used commercially in hundreds of locations, most notably to power the NASDAQ. Given that it is a proven technology, one could reasonably assume that it is a matter of bringing the technology down the cost curve and that the technology could be easily adapted for other applications. Chapter Five analyzes the cost barrier and why the current technology is going to be difficult to replace from a cost perspective unless the cost of the "externalities" are included in a business case analysis. Traditionally, of course, such costs are omitted.

Chapter Six outlines the performance characteristics of three main applications of fuel cells: Industrial size (200kw) distributed generation fuel cells, residential fuel cells, and automotive applications. Importantly, the automotive performance analysis takes into account not just the performance of the fuel cell running on hydrogen, but also the efficiencies in the production of hydrogen itself. This methodology provides a "systems level" approach and forms the baseline for comparison with other energy sources. In addition, comparison of fuel cell powered vehicles is made not only to today's ICE powered vehicles but also to the next generation hybrid vehicles which is perhaps more representative of future technology trends. We believe that comparing the fuel cell vehicle to the next generation hybrids gives a more representative comparison than using the "worst case" ICE analysis. Finally, Chapter Six outlines some technological breakthroughs that are required in the hydrogen fuel cell technology before it will be sufficient to meet the needs of automobile consumers.

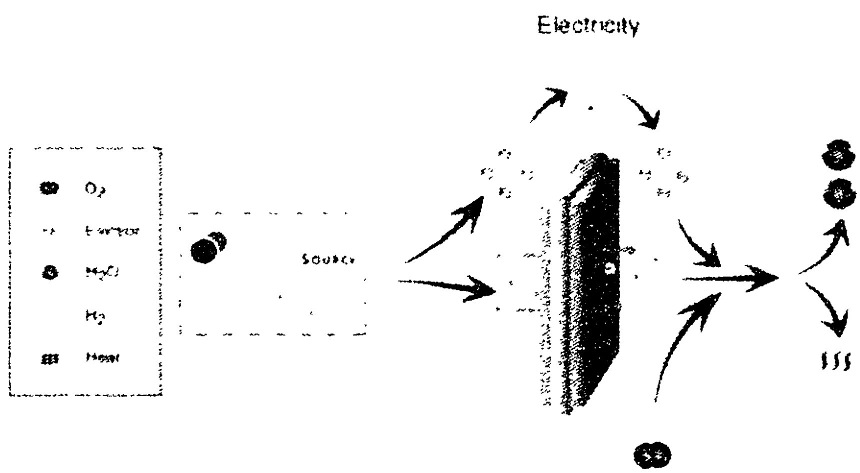
Chapter Seven summarizes the core questions that are being wrestled with in the thesis. Here we suggest what must be considered when making an assessment as to when and if hydrogen will become the fuel of choice. In this final chapter, we also present our view of the likelihood that hydrogen fuel cells will become the choice of the mass market consumer and propose several key actions that, if implemented, could accelerate the adoption of hydrogen fuel cells.

Chapter 2: Pros and Cons of Hydrogen Fuel Cells

2.1 Description and Brief History of Hydrogen Fuel Cells

In fundamental terms, a fuel cell is a device that chemically combines hydrogen and oxygen without combustion to produce electricity (See Figure 2-1). A fuel cell consists of an anode (negative charge) on one side and a cathode (positive charge) on the other with an electrolyte in between which facilitates movement of the charged hydrogen atom from the anode to the cathode.

Physics of Fuel Cell Operation



Source: HydrogenSource website 2002

Figure 2-1

The voltage differential of a single fuel cell is 0.7 volts;[18] several cells are "stacked" together, similar to Nickel Cadmium batteries, to create the desired current flow. Fuel cells have been termed "the ultimate battery" in that they can generate constant electric current continuously given a supply of hydrogen. Fuel cells have the

[18] "How Stuff Works" http://www.howstuffworks.com/index.htm

potential to be the source of electrical power for almost any application - from replacing batteries in cell phones and laptops on the low end to providing power to the national electric grid on the high end.

The recent attention to fuel cells belies the fact that fuel cells have been around for quite a long time. Sir William Grove invented fuel cells in 1839, while he was involved in experimental generation of hydrogen by electrolysis. Electrolysis is the process that separates the hydrogen molecule (H_2) and oxygen molecule (O_2) from water (H_2O) by passing electrical current through submerged electrodes. Grove correctly reasoned that the process could be reversed and electric current generated by reacting H_2 with O_2. Early attempts at further development of fuel cells by Grove and others were attempted but abandoned primarily due to low power output and cost. Interest in fuel cell development resurfaced in the 1930's when Francis Bacon substituted the original platinum catalyst with a lower cost alkali based electrolyte.[19] While some experimental fuel cells were produced in very limited quantities using technology similar to Bacon's this in the 1950's, fuel cells did not receive any serious interest in applications until the 1960's when the U.S. space program searched for a source of electrical power for extended space missions.[20] Conventional batteries did not have the required performance in duration of power generation and had severe weight penalties. Given the on-board supply of pure hydrogen and oxygen used for the primary propulsion system, and relatively high power density, fuel cells were chosen over riskier nuclear power to provide electric current for extended manned missions. As a result, NASA awarded hundreds of contracts for basic research on virtually every detail of fuel cell development. John Appleby, Director of the Center for Electromechanical Systems and Hydrogen Research at Texas A&M University states:

> "The massive U.S. aerospace fuel cell effort has undoubtedly provided the single most important impetus to the development of electrochemical engineering science in respect to energy conversion."[21]

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[19] Hoffman, Peter. "Tomorrow's Energy Hydrogen, Fuel Cells and the prospects for a Cleaner Planet". The MIT Press, Cambridge, MA, 2001, page 147.
[20] Ibid, page 37
[21] Appleby, A.J. and Foulkes, F. R.; "Fuel Cell Handbook"; Krieger Publishing; Malabar, FL. 1989, page 790.

2.2 Current State

Although, as mentioned previously, hydrogen fuel cells have the potential to be the electrical power source for almost any application, this Chapter concentrates on three of the most promising near term applications;

- Stationary power (distributed generation);
- Residential and light industrial;
- Mobile (automotive).

There are several different types of fuel cells characterized primarily by the electrolyte materials in use and operating temperature, see Table 2-1:

Major Categories and Application of Fuel Cells [22]

Electrolyte	Operating Temperature	Thermodynamic Efficiency	Primary Applications
Alkaline	60-90^0 C	50-60%	Aerospace
Phosphoric Acid	160-220^{0}C	~55%	Stationary Power
Proton Exchange Membrane (PEM)	50-80^{0}C	50-60%	Mobile Residential/Light Industrial
Molten Carbonate	620-660^{0}C	60-65%	Stationary Power
Solid Oxide	800-1000^{0}C	55-65%	Mobile Residential

Table 2-1

We concentrate here on two fuel cell types; Phosphoric Acid and Proton Exchange Membrane (PEM). These are the furthest along in development, are consistent with the applications being studied and offer the greatest probability of near-term

[22] Hoffman, Peter. "Tomorrow's Energy Hydrogen, Fuel Cells and the prospects for a Cleaner Planet", The MIT Press, Cambridge, MA, 2001.

commercialization. This is not to suggest that Molten Carbonate and Solid Oxide fuel cells are not commercially viable; only that they are not as far along in development primarily due to the technical issues of significantly higher operating temperatures.

2.3 Alternatives to Hydrogen Fuel Cells

The primary alternatives to hydrogen fuel cells are broken down by application into two distinct categories; Stationary and Mobile power generation.

- Stationary Applications:
  - Large centralized steam electrical generation facilities using coal, oil, natural gas and nuclear as primary fuel sources, (See Figure 1-1 in Chapter 1 for generation mix). Once the electricity is generated, it is transmitted and distributed (T&D) over the national electric grid with losses up to 15%.
  - Distributed generation featuring Internal Combustion Engines (ICE's) and Gas Turbines that generate electricity close to the point of consumption that minimizes T&D losses and also allows for the recovery of waste heat (Combined Cycle) used for building heating and cooling requirements for added efficiency.
- Mobile Applications
  - ICE powered; primarily compressed ignition (diesel) or spark ignition (gasoline), which utilize a range of fuels including gasoline, diesel, compressed natural gas and methanol.
  - Battery powered relying on recharging batteries with electricity produced by the grid requiring the automobile to be stationary.
  - Hybrid powered utilizing an ICE (either gasoline or diesel) and a battery. Depending on the power requirements, the vehicle may run from the battery, ICE or both. The battery is recharged by the ICE, which eliminates the requirement for having to stop the vehicle while recharging.

2.4 Benefits of Hydrogen Fuel Cells

2.4.1 Environment

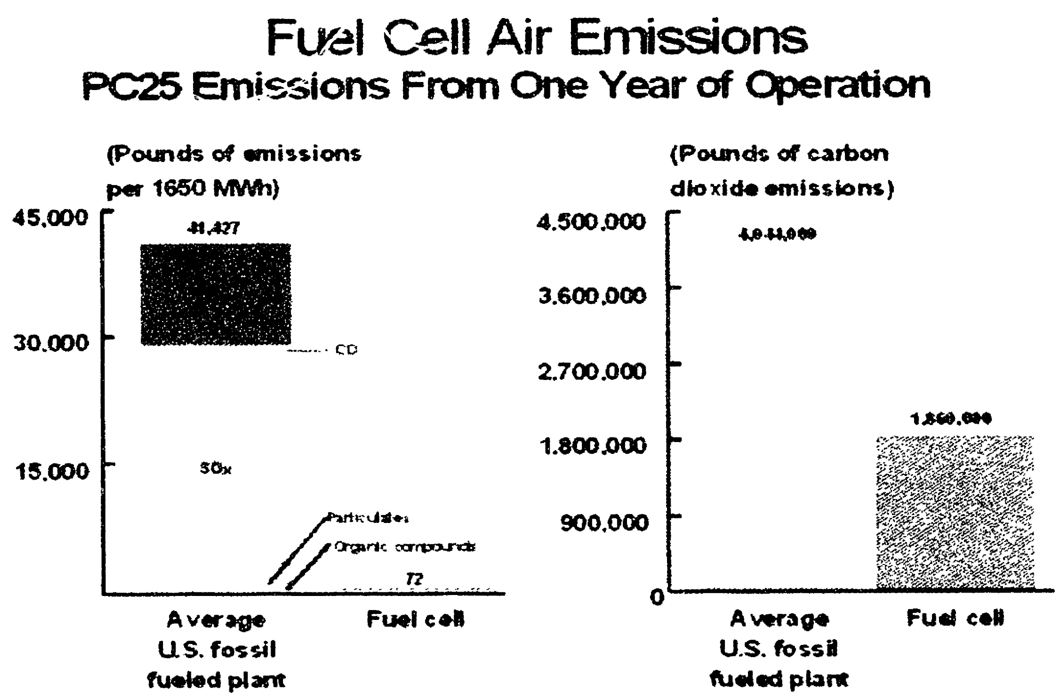
Fuel cells are used to generate electricity, with the waste heat utilized for heat and hot water. Fuel cells produce electricity with high efficiencies with extremely low, if any, emissions. When used with a pure hydrogen source, the only outputs from fuel cells are electricity, water and heat thus eliminating all pollution. When fuel cells are operated with a hydrogen rich fossil fuel (gasoline, natural gas, landfill, methane and other biogases, propane, ethanol, etc.), hydrogen is extracted from these fuels by a reforming process that results in a minor amount of carbon dioxide (CO_2) emissions, (although far less than a combustion process). Since the fuel cells do not use combustion as a means to generate power, there is no opportunity for atmospheric nitrogen (80% of our air) to become part of the process, essentially eliminating production of any of the nitrogen oxides which are key contributors to air pollution. The same is true for sulfur oxides. Even when using natural gas as the hydrogen feedstock, there are substantial reductions in emissions of hydrocarbon (over 99% reduction) and greenhouse gas (over 54% reduction) pollutants (Figure 2-2 presents typical distributed power generation comparisons utilizing natural gas as the hydrogen feedstock)[23]. Chapter 6 has a more detailed discussion of the reduction of pollutant emissions for automotive applications of fuel cells.

2.4.2 Energy Independence and Balance of Trade

As the U.S. economy and our appetite for high energy consuming products grows, our dependence on energy, and hence energy imports, is projected to continue growing. In automotive applications, the greater thermodynamic efficiency of fuel cells, approximately 50% improvement over Internal Combustion Engines (ICE's)[24], will reduce fossil fuel dependence. The use of fuel cells in distributed generation will also decrease dependence on fossil fuels due to the greater efficiencies, (See Figure 2-3).[25] It

[23] United Technologies Fuel Cells website.
[24] "Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis", Argonne National Laboratory; June 2001.
[25] United Technologies Fuel Cells website.

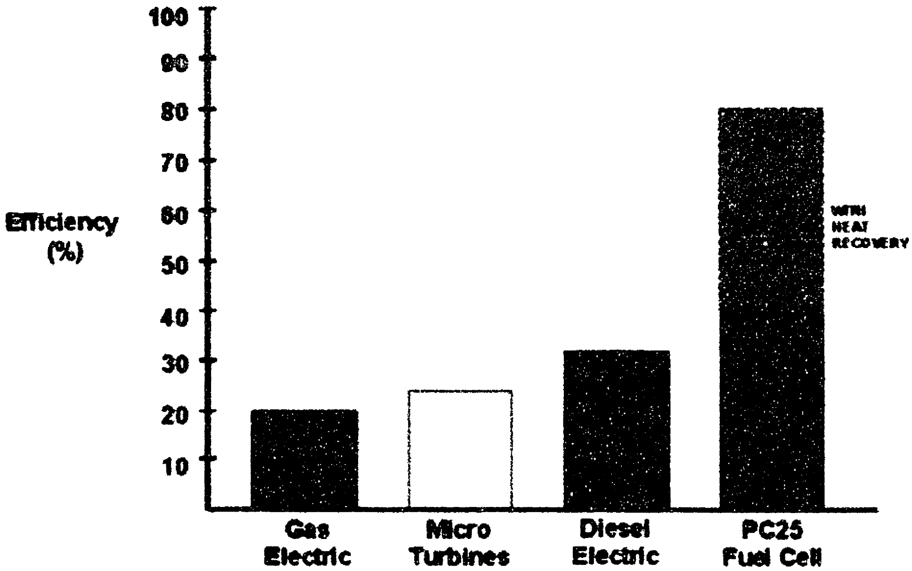
is important to note that since the overall energy demand in the U.S. is growing, and since the primary source of hydrogen available today is from fossil fuels, the U.S. will continue to be dependent on foreign sources for oil and natural gas until the capacity of domestic hydrogen production from a non-fossil fuel source is sufficient to meet demand, even with a transition to fuel cells. Even if nuclear, solar and wind generation methods of producing hydrogen are practical, they are years away from being implemented on the scale that would yield energy independence. Until such a transformational hydrogen generation infrastructure is in place, the U.S. will continue to be dependent on foreign sources of either oil or natural gas as the feedstock for hydrogen generation.



Source: United Technologies Fuel Cells website

Figure 2-2

Efficiency Benefits of Fuel Cells Relative to Other Methods



Source: United Technologies Fuel Cells website

Figure 2-3

2.4.3 Health

It is widely believed that the roots of many of the serious health problems we face today stem from the inefficient and polluting methods we deploy in methods of transportation and electricity production. The U.S. Environmental Protection Agency estimates that two-thirds of pollutants responsible for smog, ground-level ozone, and global warming find their origins from motor vehicles.[26] As mentioned in Section 2.4.1 the byproduct of internal combustion include the poisonous exhaust gases such as carbon monoxide (CO), carbon dioxide (CO_2), a greenhouse gas (GHG), and ozone precursors that consist of oxides of sulfur (SO_x), oxides of nitrogen (NO_x), and hydrocarbons (HC).[27] The U.S. Environmental Protection Agency (EPA) estimates that mobile source emissions represent a "significant risk" to health posing "the greatest potential threat to

[26] Brydges, Jane E. "A Hydrogen Fueling Station in 2005 – Will it Happen? How do we get from Here to There?" Massachusetts Institute of Technology, Cambridge, Massachusetts, June 2000.
[27] Ibid.

public health in the largest number of urban areas." Many of these are either presumed or known human carcinogens.[28]

Ozone (O_3) is a key molecular compound for shielding the Earth's surface from damaging ultraviolet radiation that exists naturally in the high atmosphere. At ground level however, ozone is a significant threat to health. According to the American Lung Association (ALA), "Ozone is capable of destroying organic matter, including human lung and airway tissue. It essentially burns through cell walls, and it is capable of doing this at levels frequently encountered in many U.S. cities".[29] As noted in Chapter 1, the U.S. Center for Disease Control and Prevention (CDC) estimates that the number of U.S. asthmatics has nearly tripled, from 6.8 million in 1980 to 17.3 million in 1998.

All these negative health factors are due to the combustion process of fossil fuels. Combustion produces the chemical reaction of fuel-based carbon and sulfur with the atmospheric-based nitrogen and oxygen that results in the previously listed pollutants and greenhouse gases. By eliminating the combustion process in fuel cells, the harmful combustion by products are eliminated or substantially reduced. It is ironic that in the quest for higher fuel efficiency to meet U.S. CAFĖ standards, automobile manufactures have developed ICE's that operate at higher combustion temperatures which in turn generates higher levels of nitrogen oxides and ozone.

2.5 Summary of Key Issues

2.5.1 Hydrogen Generation

As mentioned previously, the problem of generating hydrogen in sufficient quantities is significant. While the two main methods (reforming of fossils fuels and electrolysis) are well developed, they are not close to being able to provide the capacity of hydrogen required for millions of users. Reliance on the reforming process still leads to the depletion of oil reserves and does not foster energy independence in the U.S. And

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[28] Wang. M. "GREET 1.5 – Transportation Fuel-Cycle Model. Argonne National Laboratory. ANL/ESD-39. Argonne. IL. 1999.

[29] Cahill. E. "Strategies for the Introduction of Advanced Fuel/Vehicle Systems to the Mass Market." Massachusetts Institute of Technology. Cambridge. MA.

the generation of hydrogen by electrolysis given the current generation mix (Figure 1-1 in Chapter One) may actually increase harmful pollutants and green house gases.

2.5.2 Hydrogen Infrastructure

The lack of a countrywide hydrogen infrastructure is a major issue for mobile applications. A long-term vision of utilizing hydrogen "on-board" vehicles instead of "on-board" reforming of liquid fossil fuels requires an infrastructure available for the consumer that is roughly equivalent to the gasoline infrastructure available today. This is a massive undertaking and will be explored in more detail in Chapter Four.

2.5.3 Cost

As with most emerging technologies, a cost-benefit analysis of the hydrogen fuel cells in comparison to the incumbent technologies is not easy or obvious. Chapter Five will cover the cost of fuel cells in greater depth. While for distributed generation applications, phosphoric acid fuel cells are approaching cost equivalence with, and in some cases, bettering cost, of electricity being provided from the grid, the current capital cost of approximately $800K for a 200kw unit[30] our research indicates it does not meet the payback requirement in years imposed by many corporations[31]. For mobile applications, the cost benefit of the incumbent Internal Combustion Engine (ICE) is based on years of production maturity and improvement in an extremely high volume business. The PEM fuel cell being developed for mobile applications has not been able to benefit from scale and a well-established supplier base and is orders of magnitude higher in cost than the ICE. The recurring cost of hydrogen to supply the vehicle is also likely to be a problem given our current generation capability. The Proton Exchange Membrane (PEM) fuel cell for residential use has an estimated initial capital cost of approximately $10,000-$15,000, with additional recurring cost of the fuel source (primarily piped in natural gas or trucked in propane). With approximately 95% of residences the U.S. having access to the electric grid, this large initial capital outlay for purchase does not seem practical, or affordable for most average homeowners. Our

[30] Off Wall Street Consulting Group Inc. website, 2000.
[31] Collaborative learning project, January and February 2002.

research, which included interviews with representatives from a major U.S. manufacturer of fuel cells, indicates the offsetting value proposition for the 5% of the homeowners who are "off-grid" is the cost of putting in utility poles at approximately $25K per mile. At a current projected median price of approximately $12,500 for a residential fuel cell, this results in a capital cost-neutral distance of half a mile away from established power transmission lines for purchase of a residential fuel cell versus installation of utility poles. Significantly, this analysis does not take into account the projected maintenance cost of a residential fuel cell, as there is little available public data concerning projected maintenance costs. Summarily, however, it seems clear that cost is a significant factor effecting hydrogen fuel cell acceptance.

2.5.4 Performance

Chapter Six will cover performance issues in more detail, especially automotive applications. As previously discussed in paragraph 2.4.2, the electrical generation efficiency of stationary fuel cells for distributed generation and residential use is excellent when compared to the electric grid, especially when the available heat energy in a combined cycle operation is considered. While life expectancy of the phosphoric acid industrial fuel cells has been demonstrated to be excellent with over 5,000,000 hours of operation[32], the current demonstrated life of the residential PEM units is not likely to satisfy consumer expectations. The issue of residential fuel cell operating life is discussed in more detail in Chapter Six.

There are two main and related performance problems for PEM fuel cell powered automobiles. Range is currently a significant issue for automobiles that have fuel cells directly fed by hydrogen stored on the vehicle. Current storage technologies of compressed hydrogen (the only cost and energy effective method now available for automotive use) do not provide sufficient range. Current demonstrated ranges for compressed hydrogen fuel cell vehicles are approximately 160 miles, or about half the average of today's vehicles.[33] To solve the current range issue, gasoline or another liquid fuel may be used as a hydrogen feedstock where an on-board reformer is utilized to strip

[32] United Technologies Fuel Cells website.
[33] Research interviews.

the hydrogen from the fuel. The current reformers utilize steam to crack the hydrogen from the fuel source. This requires warm up times of approximately five minutes and is subject to freezing issues in cold climates.

2.6 Summary

Fuel cells have the potential to positively address significant societal issues that range from health problems caused by environmental pollution due to burning fossil fuels to decreasing the U.S. dependence on foreign sources of energy. To capture these potential benefits however, significant problems need to be addressed. These problems are mainly generating and supplying the huge amount of hydrogen required and bringing the cost and performance of fuel cells more competitive with current technologies. Each of these issues are discussed in following chapters.

Chapter 3: Hydrogen Generation

3.1 Issue

Hydrogen, as noted in Chapter One, is by far the most abundant element in the universe and on earth. It is the main component and fuel source for the stars. The earth's oceans are 11% hydrogen by atomic weight. Hydrocarbon fuels, as their name implies, are full of hydrogen. However hydrogen is not is not found naturally in the H_2 molecular form. It is always in a compound with some other elements. Currently, there is greatly insufficient capacity to generate hydrogen in the quantity required to transition to a hydrogen powered economy. We believe that the magnitude of the hydrogen generation issue is not discussed in sufficient detail in most literature relating to fuel cells. We chose to devote a separate Chapter on this issue, separate from infrastructure, to stimulate further thought on this critical enabler.

Currently there are two well-established methods to generate hydrogen. The first is a reforming process using which essentially extracts the "hydro" from a hydrocarbon source usually a fossil fuel such as petroleum or natural gas. But, hydrogen can also be reformed from biogases, ethanol and other sources. The reforming process typically reacts this hydrogen rich feedstock under pressure steam, stripping the hydrogen and leaving the residual elements, carbon, oxygen, and trace impurities such as sulfur The second method is electrolysis in which water is separated into hydrogen and oxygen molecules by passing an electrical current through electrodes submerged in water The steam reforming process is by far the most widely used today except where extremely pure hydrogen is required. In high purity cases, electrolysis is used.[34]

A few inter-related problems are immediately apparent:

- It takes energy of some sort (electric or heat) to generate hydrogen from either a hydrogen rich feedstock or water.
- This energy has a cost, efficiency and environmental footprint of it's own.

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[34] Hoffman. Peter. "Tomorrow's Energy Hydrogen. Fuel Cells and the prospects for a Cleaner Planet". The MIT Press. Cambridge. MA. 2001.

- Generating hydrogen from a fossil fuel does not yield total energy independence.
- Generating hydrogen from a fossil fuel results in byproducts (various compounds of carbon, oxygen and the trace elements), some harmful but in significantly less quantity than combustion of fossil fuels
- Generating hydrogen from electrolysis generates emissions from the electrical grids generation mix.
- Hydrogen generation on a massive scale requires huge investments in a hydrogen infrastructure.

As described in Chapter Two, fuel cells utilized in the distributed generation application are most likely to use natural gas or other biogases as the hydrogen feed stack. Also as previously shown in Figure 2-2, the emissions (greenhouse gases and deadly oxides of nitrogen and sulfur) from fuel cells utilizing a reformed fossil fuel hydrogen feedstock are greatly reduced. Since the distributed generation application of fuel cells is not primarily dependent on using H_2 as it's source fuel, we will focus the discussion of hydrogen generation for mobile applications that are reliant on H_2 as the primary fuel source.

3.2 Research Findings

In order to answer the "system level" questions concerning the environmental costs and benefits of automobiles powered by advanced fuel technologies, General Motors commissioned Argonne National Laboratory to perform an analysis of different vehicle propulsion system and fuel types (Gasoline, Diesel, Hybrid, Fuel Cell, Electric).[35] The aim of the study was to determine net system level thermodynamic efficiency, environmental footprint and operating cost. The study, dated June 2001, combined a "Well to Tank" (WTT) methodology, which focused on fuel production-to-delivery into the vehicles tank, and a "Tank to Wheel" (TTW) methodology that considered the components on-board the vehicle (propulsion system). The integration of the WTT and

[35] "Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis", Argonne National Laboratory; Volumes I, II & III, June 2001.

TTW analysis became a "Well to Wheel" (WTW) analysis at the system level. We have reviewed this study with faculty in the Chemical Engineering department at the Massachusetts Institute of Technology MIT and discussed the aspects of the study's "independence" from the commissioning company. Our research indicates this study to be independent and is considered to be a thorough system level analysis.

Fifteen vehicle propulsion platforms were studied including:

- Spark Ignition (gasoline)
- Compressed Ignition (diesel)
- Electric (battery)
- Hybrid (both spark and compression ignition)
- Fuel Cell (with and without on board fuel processors)

Thirteen different fuels were analyzed including:

- Gasoline
- Diesel
- Naphtha
- Electricity (Using three generation mixes, U.S., Northeast, California)
- Natural gas
- Hydrogen (gaseous and liquid)
- Ethanol
- Methanol

3.2.1 WTT Energy Efficiency Results

The WTT analysis showed that from the perspective of total energy used to deliver energy to the vehicle. The measure is Btu/mmBTU of fuel delivered to the vehicle. Current petroleum based products were the most efficient at roughly 250,000 BTU/ Btu/mmBTU. (Ref. Figure 3-1) The most energy efficient production of gaseous hydrogen was derived natural gas at roughly 800,000 Btu/mmBTU, roughly 3 times greater than gasoline. Energy consumption using electrolysis was in the range of 2,500,000 Btu/mmBTU or 10 times greater than gasoline. Clearly hydrogen generation does not appear to be nearly as energy efficient as petroleum refining. This clearly illustrates the high amount of energy necessary to generate hydrogen [36]

3.2.2 WTT Greenhouse Gas (GHG) Emissions Result

A similar analysis was done for the GHG emissions generated in delivering fuel to the vehicles tank. The measure is grams/mmBTU of fuel delivered to tank. The petroleum-based fuels were in the 15,000-20,000 grams/mmBTU range (Figure 3-2). The best hydrogen figures (100,000-150,000 grams/mmBTU) were obtained by using a natural gas feedstock. Hydrogen generated by electrolysis was in the 300,000 grams/mmBTU range, reflecting the pollution generated by the mix of fuel sources used in the U.S. electrical generation grid, see Figure 1-2.[37]

3.2.3 Hydrogen Generation

The WTT analysis indicates the energy consumption required to generate hydrogen from both the reforming and electrolysis processes. This consumption of energy is costly and actually increases GHG emissions. To overcome these major WTT negatives, the TTW analysis will have to strongly favor the hydrogen fuel cell by virtue of the fuel cells greater efficiencies and lack of combustion. Chapter Six Fuel Cell Performance, Section 6-3 will cover the TTW and integrated WTW analysis in detail.

3.2.4 Alternative Approaches for Hydrogen Generation by Electrolysis

As the previous section illustrates, relying on the current U.S. grid mix for hydrogen generation by electrolysis uses more energy in total than just relying on petroleum to fuel vehicles. Worse, it increases emissions of GHG and other pollutants into the environment. The options most mentioned to alleviate this problem are to build electrical generation plants that powered by wind, solar or nuclear means Current power densities from solar and wind make the prospect of generating the massive amount of

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[36] "Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis". Argonne National Laboratory; Volumes I, II & III, June 2001.
[37] Ibid.

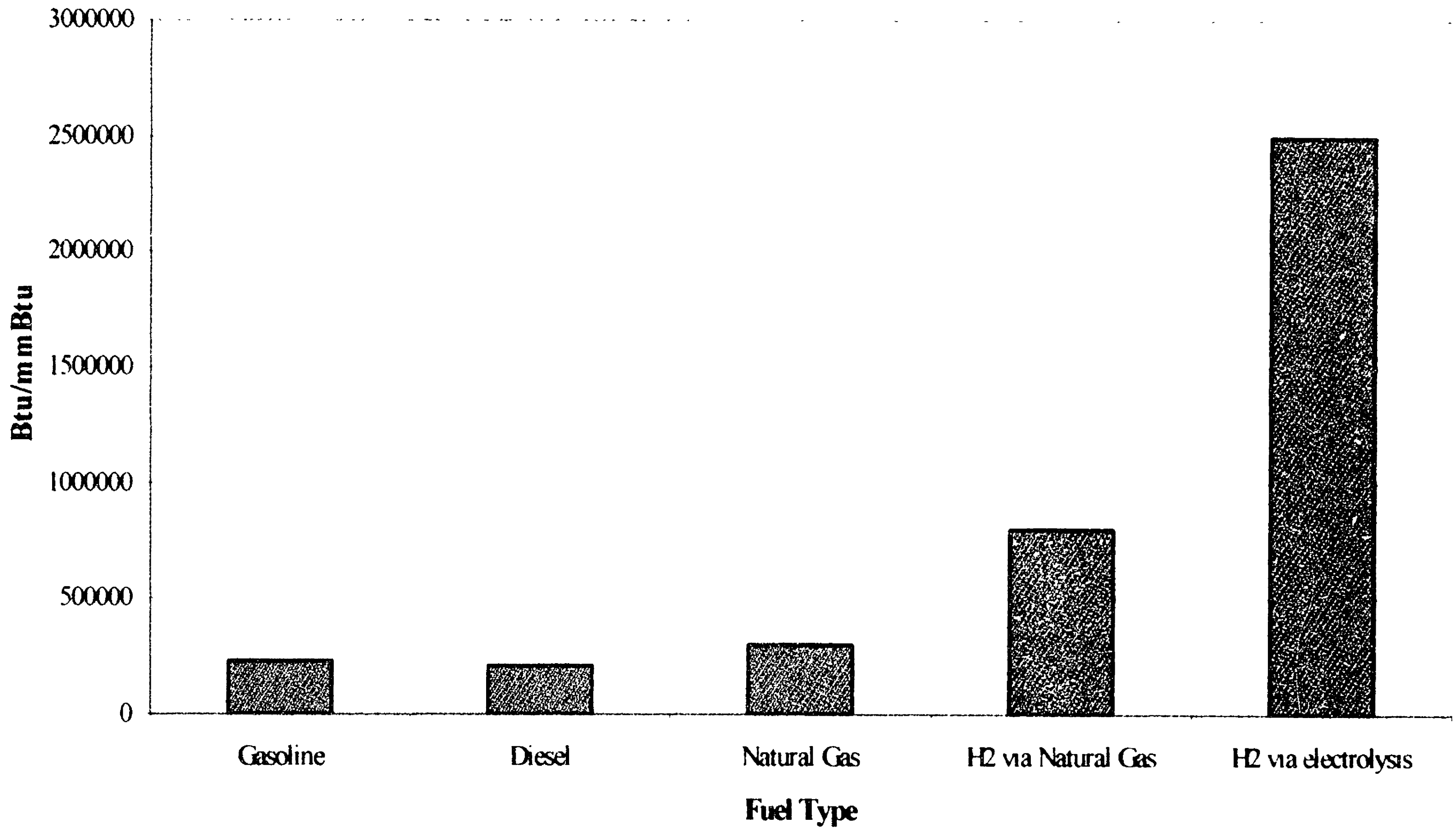
electricity required impractical and costly. Given the current anti-nuclear sentiment building more nuclear plants in the near future also seems impractical. This indicates that large-scale electrolysis is not a near-term option and that hydrogen generation must depend on reforming a hydrogen rich feedstock for the foreseeable future

The production of ethanol, primarily from corn, for use as a feedstock is given much press in the sustainability community. Current ethanol production in the U S. is approximately 1 5 billion gallons per year, equivalent to approximately 1 billion gallons of gasoline due to a lower energy value per gallon of ethanol versus gasoline [38] The U S. Department of Agriculture (USDA) has estimated that ethanol production could double in ten years to 3 billion gallons a year, equivalent to 2 billion gallons of gasoline Given that current U S consumption of gasoline is over 100 billion gallons per year, it is not likely that corn-based ethanol could ever be considered for high volume transportation applications.[39]

Given this current outlook on hydrogen generation (and until alternate methods of generating hydrogen are realized), it appears likely that hydrogen generation will have to rely on fossil fuel sources as a reformer feedstock. Yet, as described in Chapters Three and Six, there is only marginal improvement in our energy independence from foreign sources due to the increased efficiency of the fuel cell. And this increased efficiency is mostly offset by the consumption of energy used in hydrogen generation. This result does not however diminish the significant environmental benefits that can still be realized from fuel cells, even when using a fossil fuel as the hydrogen feed stock.

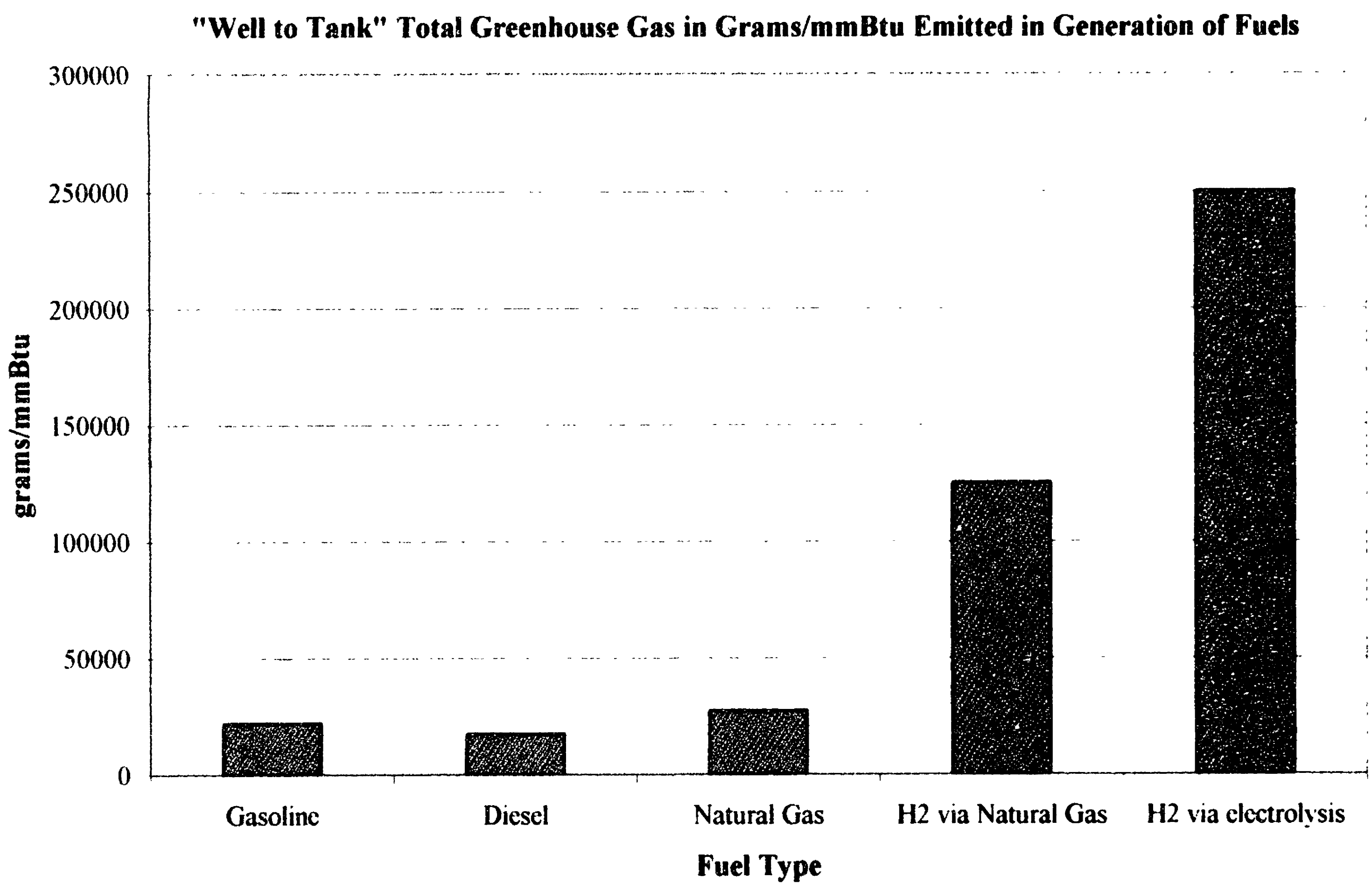
[38] "Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis". Argonne National Laboratory; Volumes I, II, & III. June 2001.
[39] ibid.

"Well to Tank" Total Energy in BTU's/mmBtu Consumed in Generation of Fuels



Source: Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems -- North American Analysis", Argonne National Laboratory; Volumes I, II, & III, June 2001

Figure 3-1



Source: Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems -- North American Analysis", Argonne National Laboratory; Volumes I, II, & III, June 2001.

Figure 3-2

Chapter 4: Hydrogen Infrastructure

4.1 Issue

> "In the 21st century we see the dawning of a new era – toward a clean hydrogen economy that will be based on renewable energy resources."[40]

Such is the vision of the Hydrogen Technical Advisory Panel and of the United States Department of Energy Hydrogen Program Achieving this vision requires building a safe and efficient infrastructure capable of delivering hydrogen to homes, business and vehicles across the country Though hydrogen is already being used in modest amounts in the United States, the existing hydrogen infrastructure is not, as we have said, sufficient to support the vision of a hydrogen economy or the Department of Energy's goal of using hydrogen to supply ten percent of the United States' energy demand by 2025.[41] Though there are no technical issues that would prevent building a hydrogen fuel infrastructure in the near-term, there are both engineering developmental needs and other institutional issues that must first be overcome.[42]

4.2 Assumptions

The following analysis is based on the assumption that hydrogen powered vehicles will not carry on-board reformers. The on-board reformer strategy is based on the premise that the current design of the vehicle will remain unchanged and the on-board reformer and fuel cell will be retrofitted into existing designs. This is essentially the strategy of the current hybrid vehicles on the market today. Though several automotive companies are pursuing on-board reforming strategies, we do not believe that this is most efficient strategy in the long-term from either a cost perspective or an environmental perspective. Nor do we believe that the hybrid vehicles will inspire the mass market consumer to purchase a hybrid vehicle since there is no substantive change in the "value

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[40] "Realizing A Hydrogen Future. Hydrogen Technical Advisory Panel Recommendations", National Renewable Energy Laboratory, August 1999.
41 Hammel, Carol J. and Russ Hewett. "U.S. Department of Energy Hydrogen Program Infrastructure Activities – Proceedings of the 2001 DOE Hydrogen Program Review", National Renewable Energy Laboratory, Golden, Colorado, 2001.
[42] Ohi, J. "Blueprint for Hydrogen Fuel Infrastructure Development", National Renewable Energy Laboratory, January 2000.

proposition" (i.e. there is no substantive change in vehicle features, design or functionality that will benefit consumers other than improved fuel efficiency and favorable environmental impact). Current market research indicates that the total market for "green" vehicles is about 3 to 5% of the total vehicle market.[43] This is simply not sufficient to enable the mass commercialization of hydrogen fuel cell vehicles

Rather, we believe that vehicles redesigned around a new hydrogen fuel cell power source offer the best opportunity. An example of this is the AUTOnomy concept car that was unveiled by General Motors in January 2002. The AUTOmony is the first vehicle designed around a fuel cell propulsion system and the first to combine fuel cells with x-by-wire technology, which allows steering, braking and other vehicle systems to be controlled electronically rather than mechanically.[44] In addition, the AUTOmony changes the "value proposition" to the consumer. Larry Burns, GM's Vice President of Research and Development states.

> "AUTOnomy's breakthroughs in vehicle design, versatility and features will inspire our customers to want to buy fuel cell vehicles because they are so exciting and offer more for the money than today's conventional vehicles. This new concept can help us realize important societal benefits, such as renewable energy and minimal emissions, while allowing customers to buy the kinds of vehicles they want with no compromises."[45]

Though the AUTOnomy is yet a concept, it illustrates an understanding that vehicle consumers will want to buy a hydrogen fuel cell powered vehicle for more than fuel efficiency alone.

Based on the assumption that hydrogen fuel cell powered vehicles (and eventually, buildings) will require a direct supply of hydrogen, the following problems associated with the technology must be addressed.

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[43] Meetings with Representatives from Major Automotive Manufacturer, January 2002 and February 2002 and Meeting of the SoL Sustainability Consortium.
[44] General Motors Press Release, January 7, 2002.
[45] Ibid.

4.3 Production Capacity

The current capacity of hydrogen production in the United States is not sufficient to meet expected future demand. Total production is currently about nine million tons of hydrogen per year.[46] However, it is estimated that by 2015, the demand for hydrogen will be at least 20 million tons per year for mobile applications alone.[47] If the total hydrogen powered light-duty vehicles increases to 80 million, then the demand for hydrogen would increase to nearly 90 million tons per year, or ten times our current capacity.

Hydrogen can be produced in many different ways. Many of these methods rely on domestic sources. However, today nearly all of the hydrogen produced is made from steam reforming of natural gas at oil refineries. Natural gas is a fossil fuel source with carbon emissions. Thus, using natural gas to produce hydrogen does not completely solve the pollution problems. Yet, it is the most economic method of production and will likely remain the dominant method until technical and economic barriers of producing hydrogen from renewable resources are overcome. For further discussion of the issues regarding the methods of production, please refer to Chapter Three.

4.4 Accessibility

In addition to capacity issues, an accessibility problem also hinders the transition to a hydrogen economy. Hydrogen is not readily available at nearly every street corner as is gasoline. Nor is it piped into buildings like natural gas and electricity. Although this problem impacts both the stationary and mobile applications, it is especially important when considering the mobile application. Currently, there are approximately 500,000 gas stations in the United States.[48] It is estimated that consumers would require at least 25% of the current number of gas stations in urban areas and 50% of the current number in rural areas if a conversion to hydrogen fuel cells were to occur.[49] A 1992 A.D. Little

[46] 2001 Chemical Economics Handbook – SRI International.
[47] UBS Warburg Global Equity Research, Ballard June 2000, Hart, D., "Hydrogen Supply for SPFC Vehicles", Imperial College, United Kingdom, 2000. Based on 130,000 transit buses and 17 million light duty vehicles in service
[48] Meetings with Representatives from Major Automotive Manufacturer, January 2002.
[49] Ibid.

study estimated that a hydrogen supply infrastructure sufficient for 25 million cars would require a $95 billion investment, or $3,800 per car.[50] Furthermore, this estimate does not include the undepreciated cost of the infrastructure that is currently in use (e.g. natural gas pipelines, gasoline stations, gasoline refineries, etc.) that might not be utilized and therefore, have limited value.

4.5 Distribution and Storage

To be used as a fuel for automobiles or power generation, hydrogen must be cost-effectively distributed and stored. Hydrogen can be stored in liquid form, compressed form, or by chemical bonding. Storage, however, was described by one of the industry experts as. "... probably the single largest challenge we have. It's much larger than the fuel cell itself." Storing hydrogen as a liquid is a difficult process in that is must be cooled to –423 degrees Fahrenheit (-253 degrees Celsius). This requires special handling and materials and requires a significant use of energy for refrigeration.[51] Storage as a gas is also problematic for use in vehicles because the pressured metal tanks used for storing hydrogen are large and heavy. Research is currently being conducted to find a method of storing hydrogen in hydrides.[52] Hydrides, however, are not currently efficient as they store very little energy per unit weight.

Hydrogen can also be piped to fixed locations. But, since there are only about 500 miles of pipeline in Texas, Louisiana, California and Indiana,[53] most hydrogen is transported by bulk shipments in liquified form in large tanks. There are over 10,000 bulk shipments of liquid hydrogen per year in the United States to over 300 locations.

For stationary applications, the increased demand for hydrogen could be supported by either increasing the number of bulk shipments or by adapting many of the existing natural gas pipelines that are currently in place. Pipelines that were initially put in place to transport "town gas, the hydrogen-rich synthetic predecessor of natural gas"

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[50] Lovins. Amory B. and Brett D. Williams. "A Strategy for the Hydrogen Transition." Rocky Mountain Institute. A Report for the 10th Annual U.S. Hydrogen Association. Vienna. Virginia. April 7 – 9. 1999.
[51] "Hydrogen Fuel". Consumer Energy Information: EREC Reference Briefs. March 2002.
[52] Hydrides are chemical compounds of hydrogen and other materials.
[53] Katsaros. Arthur. "U.S Industrial Hydrogen Infrastructure." November 2001.

are capable of transporting hydrogen.[54] Later pipelines that lack the proper seals and metallurgy could be retrofitted with composite liners. Though the distribution and storage is not a critical issue for stationery applications, it is critical for the mobile applications since current storage methods for the liquid and compressed forms are too large and heavy to fit into light-duty vehicles and chemical bonding storage is not considered feasible due to the cost and complexity. Current tanks can hold up to 5,000 psi; however, this would only enable a vehicle to travel 100 miles.[55] Thus, a significant technological breakthrough in hydrogen storage methods is required if hydrogen fuel cell vehicles are going to become a reality.

4.6 Safety

Although no fuel is risk-free, the common notion that hydrogen is more dangerous than gasoline is misplaced. Although hydrogen will ignite, ignition requires a four times greater concentration in air than gasoline. Furthermore, although the flame is invisible, to cause a burn, one must practically be inside the flame whereas burning gasoline can cause serious burns from a distance. In addition due to the greater efficiency of a hydrogen powered fuel cell, a hydrogen fuel cell vehicle would carry 60% less total energy than a fossil fuel vehicle and hydrogen will dissipate much quicker than gasoline in the event of a storage tank failure due to its dramatically higher buoyancy.[56] Cleary, new standards must be developed and consumers will need to be educated on the related hazards and trained on proper refueling procedures. However, the procedures need not be any more complicated than those in existence today.

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[54] Lovins, Amory B. and Brett D. Williams. "A Strategy for the Hydrogen Transition." Rocky Mountain Institute. A Report for the 10th Annual U.S. Hydrogen Association. Vienna, Virginia. April 7 – 9, 1999.
[55] Meetings with Representatives from Major Automotive Manufacturer, January 2002.
[56] Lovins, Amory B. and Brett D. Williams. "A Strategy for the Hydrogen Transition." Rocky Mountain Institute. A Report for the 10th Annual U.S. Hydrogen Association. Vienna, Virginia. April 7 – 9, 1999.

4.7 Implementation Strategies

Given the complexity of the issues associated with the development of a hydrogen infrastructure, it is widely assumed that such a transition will be slow and costly. Donald Huberts, Chief Executive Officer of Shell Hydrogen states

> "If you want to make a fundamental transition on a worldwide basis, you would be talking about hundreds of billions of dollars. But the investments won't be made overnight, and they won't be out of line with investments done in the past and that we continue to make to build and maintain the exiting infrastructure. We can only afford to make such an infrastructure transition once. We have to make sure that what we're going to do is feasible, that it will deliver not only environmental and supply security, but that customers want it. And we have to phase it in a way that's affordable . Between now and 2008, we'll see expanding fleet trials of buses and cars in select communities in Europe and in the United States, and there will also be rails on a smaller scale in Japan Depending on the feasibility demonstrated in those trials and what we learn, the fleet use will be scaled up toward the end of this decade, to perhaps thousands of vehicles. But not until 2012 or so will we see these vehicles in the showroom. This is not a sprint, it's a marathon."[57]

The widely accepted theory is that hydrogen fuel cell vehicles will be initially adopted by fleet users for which a central refueling station could be cost effectively built and maintained. However, this theory is based on the premise that a large infrastructure must be built before hydrogen fuel cells could be deployed in buildings and vehicles and fails to take advantage of a less recognized advantage of hydrogen fuel cells – the hydrogen fuel cells used in buildings is also a source of hydrogen for fuel cell vehicles.

An alternative strategy, which is recognized by some large energy and automobile companies, is dependent upon the integration of hydrogen fuel cells in buildings and vehicles.[58] Hydrogen fuel cells would initially be deployed in buildings. These fuel cells could provide on-site production of electricity as well as thermal energy for hot water, heating and industrial processes. In fact, nearly 50% of the energy from the hydrogen would be converted into high-quality, reliable electricity, while the remainder would be

[57] Excerpts from a conversation between Donald Huberts, CEO of Shell Hydrogen, a Royal Dutch/Shell subsidiary established in 1999 to explore development of the fuel-cell car industry, and BusinessWeek Reporter Christine Tierney, January 25, 2002.

[58] Lovins, Amory B. and Brett D. Williams. "A Strategy for the Hydrogen Transition." Rocky Mountain Institute. A Report for the 10th Annual U.S. Hydrogen Association, Vienna, Virginia, April 7 – 9, 1999

converted into water. The savings from the on-site generation of electricity and thermal energy could be used to offset the cost of the natural gas or electricity and reformer required to produce the hydrogen for the fuel cell.

The use of hydrogen fuel cells in buildings, though not widespread, is not unprecedented. For example, UTC Fuel Cells, the world leader in fuel cell production and development for commercial, transportation, residential and space applications, has delivered more than 245 hydrogen powered fuel cells to customers in 19 different countries and 5 continents since 1991. Customers include Verizon's call routing center on Long Island, New York, the New York City police station, Ford Motor Company's North American Premier Automotive Group headquarters in Irvine, California, a motor postal facility in Alaska, a utility's computer center in Brazil and two breweries in Japan.[59] This fleet of fuel cells has accumulated nearly 5 million hours of operational experience.

The advantage of initially using "the existing natural gas pipeline system or the ubiquitous electrical power grid as the backbone of the hydrogen infrastructure system is that hydrogen is produced where and when it is needed, in quantities that match the incremental growth of fuel-cell sales, minimizing the need for multi-billion dollar investments prior to the introduction of sufficient numbers of fuel cells to provide adequate return on investment."[60] Furthermore, the hydrogen produced on-site costs less than centrally produced hydrogen requiring new pipelines or other distribution means.[61] The early-adopters of fuel-cell vehicles would then have a location to "refuel" their vehicles. While at the office, the excess hydrogen produced by the fuel cell powering the building could be "piped" to the vehicles via a refueling line.

Another benefit of this incremental strategy to developing a hydrogen infrastructure is that it would enable a transition period for the impacted parties. Oil companies and gas station owners would still be able to sell petroleum while developing the capability to produce and distribute hydrogen. They would not need to write-off the

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[59] UTC Press Release, March 20, 2002.

[60] Thomas, C., Brian James, Franklin Lomax, and Ira Kuhn. "Fuel Options for the Fuel Cell Vehicle: Hydrogen, Methanol or Gasoline?," Fuel Cell Reformer Conference, Diamond Bar CA, South Coast Air Quality Management District, November 20, 1998.

[61] Ibid.

capital invested in the current infrastructure overnight. Rather, they would be able to divert funds from the development and implementation of new technologies related to the production and distribution of petroleum to the production and distribution of hydrogen. Donald Huberts from Shell Hydrogen states:

> "We're trying to make hydrogen as cheaply and in as compact a form as possible in a joint venture with UTC Fuels Cells called Hydrogen Source. We're doing that using natural gas and gasoline now, because we thing we have to find a practical, affordable solution first, and then in the longer term, we can make hydrogen from renewable fuels... We're working on metal hydride storage tanks in a joint venture called Hera with Hydro-Quebec of Canada and GFE of Germany. We're also working on projects demonstrating how hydrogen can be supplied. We're building a hydrogen station in Iceland and one in Amsterdam. We've built a liquid hydrogen station for the California Fuel-Cell Partnership, and we'll be building more."[62]

Energy companies would gradually be able to transform their business models from that of simply generating the electricity for the grid or refining and distributing petroleum to providing "total solutions" for their customers energy needs.

One of the problems with this theory is that consumers would be limited to refueling their vehicle while at the office and thus, would not be able to use that vehicle for long-range travel. However, this would be quickly remedied as the number of fuel cell vehicles increased, as entrepreneurs would open "refueling" stations using the same fuel cell that powered the buildings and the existing natural gas or electricity to power the fuel cell. Thus, refueling stations would be built as needed, requiring only an incremental investment to support the incremental demand. Once the fuel cell market reaches a critical level, the energy industry will be able to develop a business case to supply hydrogen that has adequate financial returns.

Another problem with this strategy is that it does not immediately resolve the environmental issues, since it is dependent upon both the electricity grid and natural gas. However, the use of hydrogen fuel cells is environmentally friendly when the user takes

[62] Excerpts from a conversation between Donald Huberts, CEO of Shell Hydrogen, a Royal Dutch/Shell subsidiary established in 1999 to explore development of the fuel-cell car industry, and BusinessWeek Reporter Christine Tierney, January 25, 2002.

advantage of the thermal energy that is generated for heating purposes. One of the potential customers of distributed generation we interviewed as part of the Collaborative Learning Project stated:

> Combined heat and power from gas is green...Distributed generation in and of itself is not going to save the planet, but it will help put a dent in the global warming issues and I think that there is enough [evidence] out there to support that.[63]

Although the use of hydrogen fuel cells for distributed generation will not solve all of the environmental problems, it is clearly a step in the right direction. Furthermore, accepting an interim strategy that is initially reliant upon natural gas and the electric grid will enable a rapid commercialization and mass use of fuel cells. This, in turn will provide a catalyst and a business case for developing sustainable methods of producing hydrogen. Lastly, more rapid commercialization of automotive fuel would enable automakers to avoid further investments in vehicles powered by the internal combustion engine and the related liquid refueling infrastructure, an estimated $1 trillion savings.[64]

[63] Excerpt from the Collaborative Learning Project. January and February 2002. We would like to remind the reader that names of both individuals and companies have been withheld as per agreement with the interviewees.

[64] The estimate as calculated by multiplying the per-vehicle costs in Thomas et. al. 1998 by the world's fleet of 500 million light vehicles, which is growing by about 5% per year.

Chapter 5: Are Customers Willing to Pay More and Can the Cost of Today's Technologies be Matched?

5.1 Issue

The central issues surrounding hydrogen fuel cells is whether customers are willing to pay more for environmentally friendly products and whether the hydrogen fuel cell can match the cost effectiveness of the technologies in use today. In most analyses of the cost of a hydrogen fuel cell, the cost of the fuel cell itself as well as the cost of the fuel and related maintenance costs is included. Consumers will also often include positive impacts such as a reduction in the amount of equipment downtime; however, through during the simulated sales sessions as part of the SoL, we did not come across a consumer that included the benefits to human health and the environment that new technologies bring to the table. Nor, did we find a consumer that included the cost of the negative externalities that result from the use of existing technologies.

5.2 Distributed Generation Application

The net cost / benefit of implementing a hydrogen fuel cell is a complex calculation that will have varied results depending on the assumptions made regarding power needs, sources of fuel and type of manufacturing process. At a simple level, the cost effectiveness of distributed generation can be easily calculated by comparing the cost of electricity from the grid to the amount of capital invested in the hydrogen fuel cell and the cost of operating the fuel cell, including the cost of the fuel required to make the hydrogen. However, this is too simplified, since it does not include the added benefits or costs to the consumer. Examples of added benefits from distributed generation are as follows:

- Reduced costs of thermal energy loads by properly using the steam or hot water from the manufacturing process for heating and cooling requirements
- Reduced exposure to volatility in the price of electricity
- Improved power reliability and quality
- Reduction in environmental contaminants
- New revenue stream

Examples of added costs are as follows:

- Standby charges for having access to the grid
- Exit fees for leaving the grid
- Additional incremental costs for interconnection to the grid

This list is not all-inclusive and the benefits and costs will depend on the power needs, alternative power sources and utilities of each individual consumer. As the costs and benefits will vary significantly by customer, we do not believe it is meaningful to provide a detailed cost analysis.

What is important, however, is that we believe that research generally indicates that customers are not willing to pay more for "environmentally friendly" sources of power. When we discussed the approval process for energy projects, the Director of Environmental Management at one of the companies involved in the SoL collaborative learning project stated:

> "If it is a capital project who's return exceeds the cost of capital, it is pretty much a no brainer. If it doesn't exceed the cost of capital, in these tough economic times, the sustainability benefits would have to be significant... If the project doesn't return the cost of capital, it is the magnitude of our ability to advance our sustainability goals that is the deciding factor."

This is a company with publicly stated sustainability goals. Yet, even they will not approve projects solely on the basis of a positive impact on the environment. This message is consistent with the other companies with whom we met and with research conducted by RKS Research & Consulting that found that 86% of organizations rarely adopt new energy technologies unless they can show a cost savings.[65] They are willing to consider projects that improve the environmental picture, but these projects must also return their cost of capital. These findings are not surprising given that we spoke to publicly held companies that face increasing pressures from shareholders to generate adequate returns.

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[65] "Distributed Generation 2000/2001 Business Customer Awareness & Interest", page 9, RKS Research & Consulting. Used with permission.

5.3 Automotive Application

The cost issue with respect to an automotive application is far more challenging. In fact, a financial representative from one of the automotive companies we interviewed stated:

> "I don't think it is a forgone conclusion that fuel cells will prevail [given] where we are today versus where we need to be."

The cost effectiveness of the internal combustion engine has increased significantly since 1986. It has reduced from nearly 16% of the total cost of an entry–level passenger vehicle to 8% of the total cost of the vehicle, without considering the improvements in technology.[66] "The cost is lower in real terms as well, even though the 2001 engine is made from more expensive materials (aluminum) and features many more sophisticated components."[67]

A vehicle requires approximately 100 kilowatts of power. Therefore, if a vehicle costs $20,000, the fuel cell must not exceed $1,600, or $16 per kilowatt, if no other changes were made to the design of the vehicle. This estimate, however, is too simplistic, as the hydrogen fuel cell vehicle would have a different cost structure than the existing internal combustion cars. For example, parts such as the catalytic converter would no longer be required. Industry experts believe that a fuel cell can be economically competitive if the cost per kilowatt could be reduced to approximately $50 per kilowatt. However, today the cost of a kilowatt from a hydrogen fuel cell is at least 10 times this amount assuming volume production and 1000 times more assuming only the production of prototypes. Prototype production is of course the current state.

The widely assumed answer to reducing costs is further technological innovation and increased production volume. But, as yet, no one has answered the question as to how to generate the volume. Some industry experts look to the stationary application as one source; however, the cost of a kilowatt would need to be approximately $1,000 to

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[66] Ealey, Lance. "Emissionary Positions: The battle for the next automotive power plant", McKinsey Quarterly Article, February 15, 2002.
[67] Ibid.

$1,500 per kilowatt before the hydrogen fuel cell will become widely adopted in the stationary market.

The question as to whether or not consumers are willing to pay more for an economically friendly vehicle is widely debated. In interviews with the automobiles executives, they report that focus groups responded to the fuel cell vehicle by saying the following:

> "It's clean, green...and that's all wonderful. And yes, you [automobile company] should do that. But I am not going to sacrifice safety or reliability.... Is it going to be cheaper? It should be cheaper, shouldn't it?"

Although consumers like the idea of an environmentally friendly, fuel-efficient vehicle, the mass market is apparently not willing at the moment to make any substantial trade off in performance, safety or cost. If fact, estimates indicate that less than 5% of the U.S. automobile market buys a vehicle based on environmental impact and that fuel economy is low on the list of priorities when shopping for a vehicle. The apparently small number of consumers (estimated at 5%) willing to pay an increased cost for environmentally friendly products is substantiated through market research on other consumer products ranging from household detergents, appliances and clothing where the range of the percentage of committed "green" consumers is 3-5%.[68] While a substantial majority of consumers surveyed say they would spend more for environmentally friendly products, when the purchase decision is made this is not the case.

A book titled "Green Marketing" Jacquelyn Ottman suggests that marketing products as "green" may even have negative impacts.[69] Consumers often equate "green" products with inferior performance at a higher price. In other cases, consumers just expect environmental performance to be built into the products they are buying and don't see "green" as a product discriminator. Ottman suggests significantly downplaying environmental performance, even with products that are significantly better than the competition, to avoid the perception of inferior performance and higher cost. In short,

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[68] Winter SoL and Rocky Mountain Institute Collaborative Innovation for Sustainability Workshop. February 3-6, 2002.

[69] Ottman, Jacquelyn A. "Green Marketing". NTC Business Books. Chicago. 1993.

alienating 93-97% of the consumer base for the 3-7% of the committed "green" consumers is not a money making strategy.[70]

However, a recent Autobytel survey of online car shoppers indicated that 67% of women and 55% of men would either "definitely buy" or "strongly consider" a hybrid if a model comparable to an ICE vehicle was available. Furthermore, the respondents to the survey clearly indicated that additional cost is not necessarily a barrier to purchasing a hybrid vehicle. In fact, 45% of consumers indicated they would be willing to pay $1,000 to $2,000 or more for a hybrid version of a vehicle that had the same functionality but better fuel economy.[71] We suspect that the sample population of online shoppers is not representative of the larger mass-market automobile consumer, as the online shopper is clearly an early adopter of technology and thus differs from the "average" consumer. Moreover, the online automobile shopper is probably no different than other consumers who say they are interested in buying "green" but when it comes to the purchasing decision, they do not. Knowledgeable marketing practitioners suggest that although customers like to say that they will pay more for a product, when the time comes to make the purchase, only a small portion actually choose the more expensive product.[72]

5.4 Are Hybrids the Answer?

The most common hybrid technology in use today is known as parallel hybrid, in which either the internal combustion engine or the battery can power the vehicle independently depending on the situation. This dual technology requires the integration of two separate technologies. This is a complex and costly technological solution. Furthermore, as the internal combustion engine is the dominant power source, the environmental benefits are not maximized.

The Toyota Prius and Honda Insight are examples of parallel hybrid vehicles that are on the market today. At first glance, they seem to overcome the cost issue since they are selling for approximately $20,000 However, what many consumers do not realize is

[70] Winter SoL and Rocky Mountain Institute Collaborative Innovation for Sustainability Workshop. February 3-6, 2002.
[71] Autobytel Inc. Press Release, March 21, 2002.
[72] Winter 2002 SoL and Rocky Mountain Institute Collaborative Innovation for Sustainability Workshop. February 3-6, 2002.

that these vehicles are being heavily subsidized by the automakers. Furthermore, the benefits are quite costly when you consider the cost of the replacement batteries. The automakers are further subsidizing the cost of the vehicle as they have issued up to 8-year warranties on the batteries in their hybrids. The batteries must be replaced at regular intervals and cost from $1,200 to $1,500 per battery. This ongoing replacement requirement will probably have a negative impact on the residual values of the vehicles, making the vehicles more costly in the long run. Though we were unable to obtain confirmation from the automakers themselves, the support for such a statement is that they have apparently limited their production of the vehicles. Why would any automaker limit production of a vehicle that is profitable?

Arguably, there is significant progress being made in the areas of reduction in the cost, weight and size of hybrid components. Yet, the battery life and dual technology requirements remain problematic. As the hybrid provides the only real solution to the California Air Resources Board's 2003 mandate for Zero Emissions Vehicles, it will likely gain momentum until the more streamlined hydrogen fuel cell automobiles become available. Industry estimates of hybrid vehicle penetration range as high as 10% of global automotive production by 2010.[73] This said, we do not believe the hybrid technology will prevail in the long run as the hydrogen fuel cell is a far less complex technology. It would not be the first time in history that a new technology has replaced a hybrid technology.

5.5 Alternative Analysis

The economic analysis for both the distributed generation and automotive applications of hydrogen fuel cells fails to capture the cost of the negative externalities on human health and the environment that are known or thought to be caused by the generation of electricity and the internal combustion engine. The driver of an automobile does not pay for the health care cost of the asthma sufferer Nor do they recognize the cost of the use of non-renewable resources. The cost of gasoline does not include a

[73] Ealey, Lance. "Emissionary Positions: The battle for the next automotive power plant", McKinsey Quarterly Article, February 15, 2002.

charge for the depletion of a limited supply of petroleum. Consumers are not charged for the polluting effects of their vehicles or for depleting a non-renewable resource. There is, at present, no financial incentive for consumers to demand a vehicle that is environmentally friendly.

One way to stimulate demand for environmentally friendly productions is to increase the cost of existing technologies through a usage-based tax. These funds could then be used to subsidize the cost of more environmentally friendly sources of power. Simultaneously, increasing the cost of existing technologies and lowering the cost of hydrogen fuel cells could substantially mitigate the cost issue and increase the likelihood that fuel cells could compete against the incumbent technologies.

In short, we do not believe that consumers are currently willing to pay significantly more for environmentally friendly sources of power. Nor, do we believe that hydrogen fuel cells can compete on a broad scale unless the true cost of the existing technologies is used in the analysis. We now move to take up the performance questions surrounding hydrogen fuel cells.

Chapter 6: The Performance Issue

6.1 Distributed Generation - Phosphoric Acid

As previously documented in Table 2-1, the electrical generation performance of Phosphoric Acid fuel cells is excellent at approximately 55% efficiency. When waste heat is recovered in combined cycle use, the thermodynamic efficiency moves toward 80%. This high efficiency, coupled with virtually no Transmission and Distribution (T&D) losses that are part of the centralized power generation and grid construct, are key components in the value proposition of distributed generation. . During our field research with DTE Energy, we found that the technical performance (cost, efficiency, etc) of distributed generation was well understood by candidate users, typically plant and facility managers, and not an obstacle for adoption. The operating life of phosphoric acid fuel cells has been demonstrated in excess of 8 years of operation and is not considered a significant issue for industrial use The major obstacles for adaptation uncovered in our field study were.

- Financial, cost and payback of the units (covered in Chapter 5)
- Development of a knowledgeable workforce skilled workforce to maintain system
- Issues regarding environmental permits and transferring emission licensing from utilities to customers facility.
- Questioning if generating electric power was a "core competency" of business
- Reaction of electric utility and concern of either being taken off-grid or facing a major increase in price to be served as "back-up" customer.

6.2 Residential – Proton Exchange Membrane (PEM)

Similar to the industrial distributed generation application, the electrical generation and over thermodynamic efficiency of the residential PEM fuel cell are excellent The financial considerations as well as customer familiarity with the fuel cell system are also similar to the industrial applications. Our interviews indicated that experts believe once consumers passed the financial hurdle, they tended to think of the fuel cell as very similar to a central air conditioning unit, "call in a professional when service is required", and were comfortable adapting to home power generation.

Unlike the industrial distributed generation application, the residential PEM fuel cell currently has a significant performance drawbacks concerning customer acceptance. Consumers expect the operating life of a residential fuel cell to be in-line with other major appliances they own such as refrigerators, central air conditioning units and dishwashers, etc. The expected life of these appliances, roughly speaking, is 10 years of operation with only minor maintenance. Life expectancy of the PEM fuel Cell operating in a residential generation mode is much less. The expectation gap centers on the customers thinking of the fuel cell as another appliance. The residential customer generally fails to understand the dramatically different operating duty cycle between a "normal" appliance and that of the residential fuel cell.

Electricity, and therefore electricity generation, is demanded in the home 24-hour a day 365 days per year. This amounts to over 8,700 hours of operation a year for a residential fuel cell. Applying the 10-year life expectancy of the consumer would result in a required fuel cell operation life of 87,000 hours. The current operating life of PEM fuel cell development for residential use is on the order of 15,000 hours, clearly not in the same range as consumer expectations. To put this in perspective, the average household dishwasher would operate over 40 years and the average household refrigerator would operate over 170 years yield if were possible for them to achieve the currently demonstrated 15,000 operating life of a PEM residential fuel cell.

Manufactures of fuel cells have explored alternatives such as providing maintenance contracts and leasing to overcome the current operating life limitations. But, to date, these have not been warmly embraced by potential consumers. Another approach would be to have redundant fuel cells similar to industrial installations, but this would put even higher price pressure on the consumer

6.3 Automotive – Proton Exchange Membrane (PEM)

As mentioned in Chapter Four, one of the major issues with automotive fuel cell performance is not with the fuel cell itself but with the ability to store hydrogen on-board the vehicle Since liquid hydrogen can be ruled out economically due to the very high costs associated with refrigeration, the methods achieved to date for gaseous hydrogen storage have only yielded a vehicle range on the order of 160 miles. Until better storage solutions are invented, the only fuel cell vehicles with equivalent range to today's vehicle are of the gasoline with on-board reformer configurations.

Currently there are two main performance issues with the gasoline and on-board reformer configurations. The first is a warm-up time of approximately 5 minutes until the reformer generates enough hydrogen for vehicle propulsion. The second issue is freezing of distilled water inside of the reformer in cold weather. Neither of these issues has a near term solution that would make it performance neutral to today's vehicles.

The final performance element of fuel cell vehicle performance is connected to the Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) conclusions of the Argonne National Laboratory Analysis as referenced in Chapter 3. Figure 6.1 illustrates the TTW efficiency of several vehicle platforms. This is the technical area where fuel cell vehicle outperforms other alternatives by a wide margin, and makes up the efficiency loses due to hydrogen generation detailed in Chapter 3. In the referenced study conducted by Argonne National Laboratory, a current platform for a full size pickup truck was modeled. The conventional gasoline engine in the pickup truck demonstrated an efficiency of approximately 17% or 20 miles per gallon. Gasoline and diesel hybrid vehicles demonstrated 21 and 25 % efficiency or 24.4 and 29.4 miles per gallon respectively. The efficiency of a fuel cell vehicle running on hydrogen is approximately 36% for an equivalent miles per gallon of 43.2 and fuel cell hybrid vehicles have an efficiency of 41%, equivalent to 48.1 miles per gallon.[74] The, roughly speaking, 100% improvement in efficiency of the fuel cell powered vehicle versus the Internal Combustion Engine (ICE) powered vehicle is the often quoted factor of two benefit of fuel cell vehicles. However, this is still not the complete system level analysis required.

Integrating the "Well-to-Tank" (WTT) analysis in Chapter 3 and the above "Tank-to-Wheel" (TTW) analysis yields the "Well-to-Wheel" (WTW) analysis. This is the best way to measure relative performance of the different propulsion configurations from a total system level perspective.

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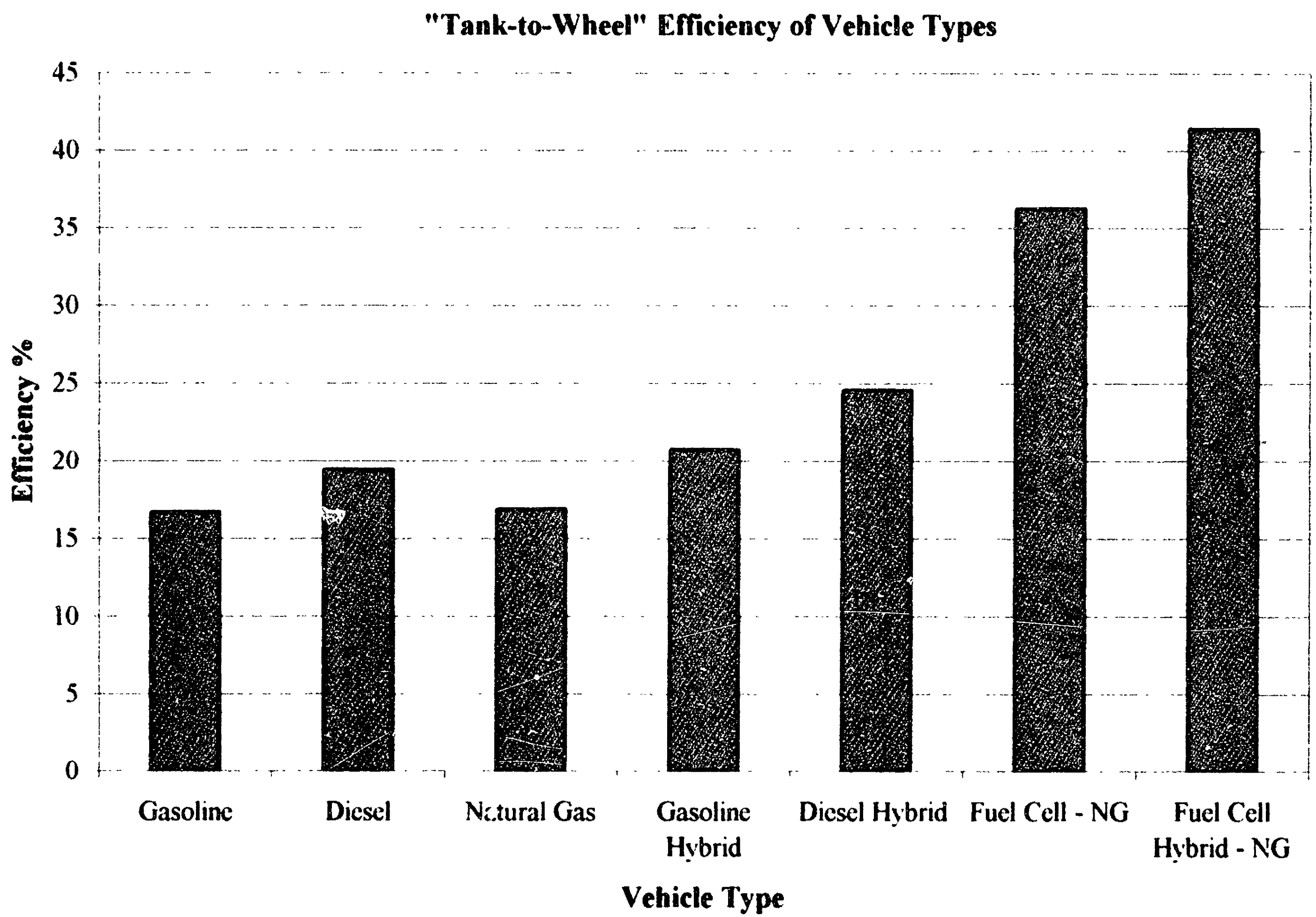
[74] "Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis", Argonne National Laboratory; Volumes I, II, & III, June 2001.

Figure 6-2 illustrates that a Fuel Cell Hybrid vehicle using hydrogen generated from a natural gas feedstock indeed provides the best specific energy consumption per mile at approximately 4,300 Btu's/mile. Close behind however is the Diesel hybrid at 4,800 Btu's/mile, followed by the non-hybrid fuel cell at 5100 Btu's/mile. As expected due to the current grid generation mix, the fuel cell vehicles powered by hydrogen generated by electrolysis are not competitive and are actually worse than the current gasoline spark ignition engine vehicle. The relatively good performance of the diesel hybrid should not go unnoticed as potentially the most formidable competitor to fuel cell powered vehicles on a energy consumption basis.

Figure 6-3 illustrates the Green House Gas (GHG) emissions of the studied vehicle platforms. As expected, the fuel cell hybrid vehicle, with hydrogen generated from natural gas feedstock, has significantly better performance than other systems at approximately 290 grams/mile than the diesel hybrid at 390 grams/mile. Essentially all of the GHG associated with the fuel cell vehicle is attributable to the initial generation of hydrogen from the natural gas feedstock at the production facility, with virtual no emissions due to operating the vehicle.

6.4 Summary

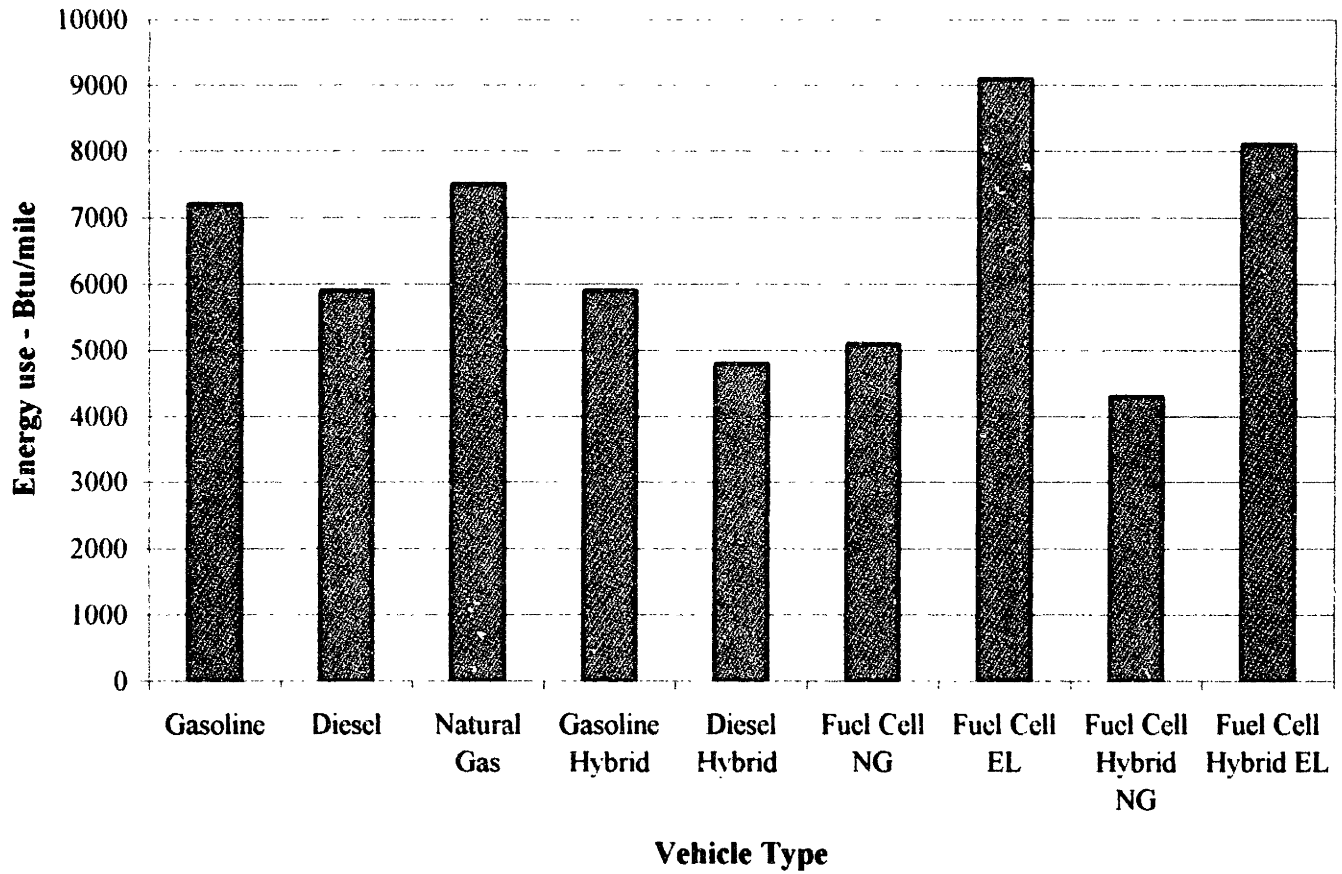
Fuel cells have significant performance advantages in nearly all applications in terms of environmental emission benefits when compared to today's dominant technologies. However, as discussed, it is imperative to take into account the complete system level analysis when comparing competing technologies, especially in the automotive application, where the energy consumed and environmental emissions released during production of hydrogen are significant. To obtain a more accurate picture, it is also imperative to compare the advantages of fuel cells not only to today's dominant propulsion technologies, but also to emerging technologies, such as diesel hybrid propulsion, where the advantages with fuel cells are not as significant. We now move to the final chapter to review our findings and assess the degree to which fuel cells are likely to emerge as an energy source in the near and distant future.



Source: "Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis". Argonne National Laboratory; Volumes I, II, & III, June 2001.

Figure 6-1

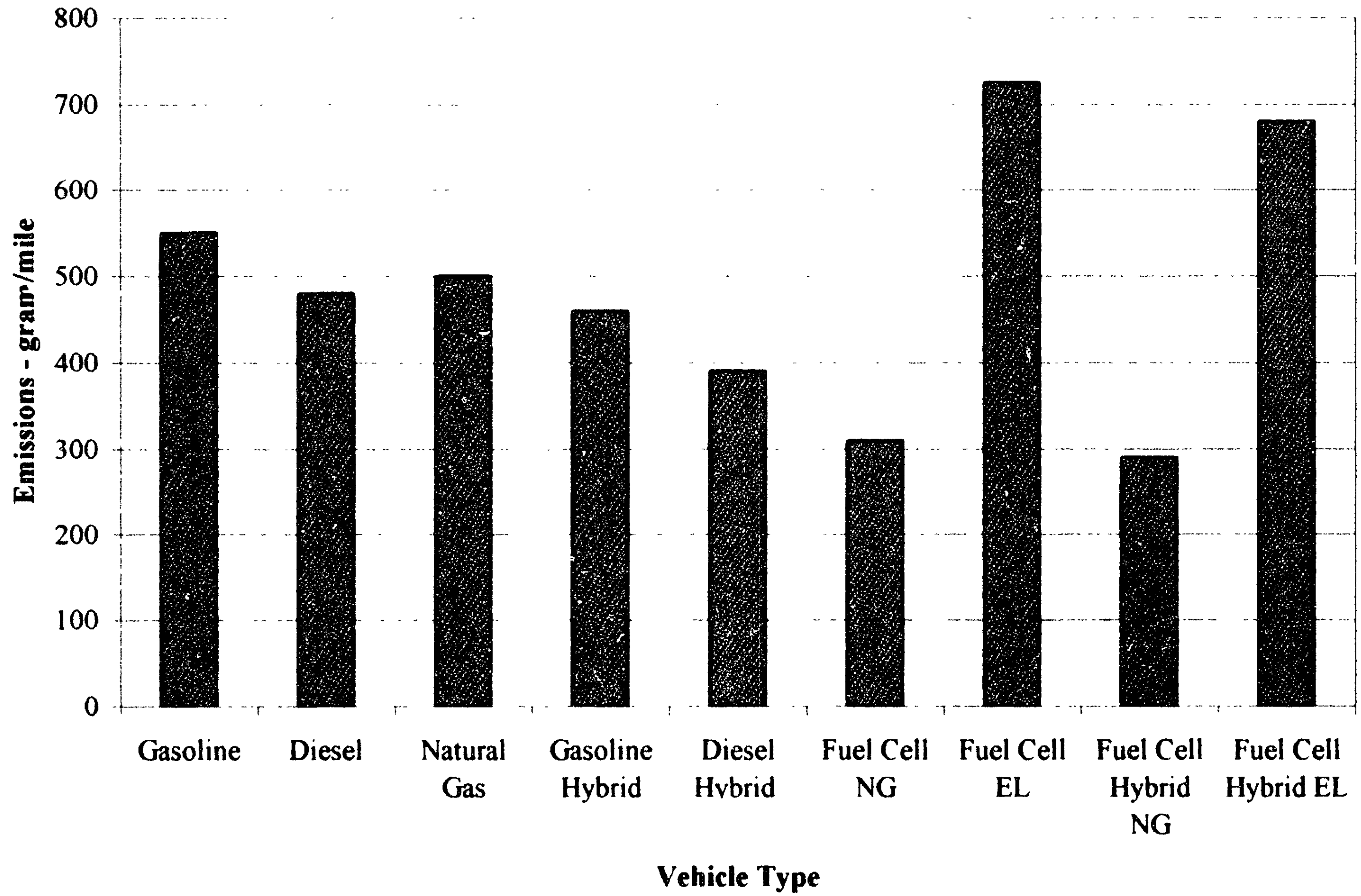
"Well-to-Wheel" Efficiency of Vehicle Types



Source: "Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis", Argonne National Laboratory; Volumes I, II, & III, June 2001.

Figure 6-2

"Well-to-Wheel" Greenhouse Gas Emissions of Vehicle Types



Source: "Well to Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis", Argonne National Laboratory; Volumes I, II, & III, June 2001.

Figure 6-3

Chapter 7: Conclusion

7.1 Hype Versus Reality

Our research uncovered widely divergent expert opinions on whether or not we will the hydrogen fuel cell will become the dominant source of power. By reading today's press, one could easily be led to believe that the U.S. is well on its way to becoming a hydrogen fuel cell powered economy. For example, on April 18, 2002 Dow Jones published the following headline:

"Gov Engler Reveals Plan To Make Michigan Fuel-Cell Leader"[75]

The story reports on Michigan Governor John Engler's announcement of an economic development plan to make Michigan the leader of fuel-cell research, development and manufacturing. Engler said it is important for Michigan to be the home for fuel-cell development because the state relies heavily on the automotive industry for jobs and resources. Engler plans to begin construction in 6 months and expects that the market for fuel-cell products to grow to an estimated $95 billion by 2010. It is only at the bottom of the story does the author mention any of the problems that must be overcome before such a market could reach the estimate levels:

> "However, fuel-cell vehicles are expensive to make and it will cost billions of dollars to build a vast network of hydrogen stations..."[75]

Yet we would not conclude that the press has simply got it wrong. Progress has been made in large part due to sizeable investments by the private sector. There are hydrogen fuel cell buses in operation today, fully functioning prototype light-duty hydrogen fuel cell powered vehicles as well as several hundred stationary applications are also in operation. In fact, we spoke with some industry experts that firmly believe that a cost effective and efficient hydrogen fuel cell vehicle will be ready for mass production within the next decade.

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[75] Parker, Jocelyn. "Gov Engler Reveal Plan To Make Michigan Fuel-Cell Leader." Dow Jones Newswires, April 18, 2002.

Some critics; however, say that the entire idea of a hydrogen fuel cell vehicle is the way the oil and automobile companies are deterring the U.S. government (and the public in general) from implementing more difficult fuel economy and emissions standards. Others say that the technical limitations and hydrogen generation issues are so great that the hydrogen fuel cell will never be able to outperform an ICE hybrid. One industry expert stated. "This industry is full of lies and liars." By this he means that the competitive nature of the industry and the battle for funding is driving the industry players to overstate their technical capabilities.

Our research; however, does not support the critics who claim hydrogen fuel cells will never flourish, nor does it support the belief that the transition to a hydrogen fuel cell power source is a foregone conclusion. Rather, our research leads us to conclude that the transition to a hydrogen fuel cell power source is far more difficult than it appears on the surface (especially for automotive applications) and that numerous "barriers to entry" remain in place The barriers of cost, performance, infrastructure and hydrogen generation are significant, and in many cases. have no easy solution. Our assessment of the degree of difficulty to overcome each problem is summarized in Table 7-1 below.

LIKELIHOOD OF PROBLEM RESOLUTION			
PROBLEM	DEGREE OF DIFFICULTY		
	Commercial	Residential	Automotive
Cost	Low	Medium	High
Performance	Low	Medium	High
Infrastructure	Low[1]	Low[1]	High
Hydrogen Generation	Low[76]	Low[1]	High

Table 7-1

As indicated, difficulty levels range from low t high across three application areas. However, we believe that the reasons for developing alternative power sources -- including the inefficiency of today's power sources, their negative impact on human health and the environment, the need for energy independence and the reliance on non-renewable resources -- are important enough to warrant further development of hydrogen fuel cells. Although the problems to mass commercialization of hydrogen fuel cells are significant, we believe that there are several key actions that could be initiated and/or further developed to overcome some of these problems. Some of the ways to enable this transition are indicated in the remainder of this concluding chapter.

7.2 Enablers

7.2.1 Fees for the Usage of "Dirty" Sources of Power

One of the primary reasons that the current technologies are so cost efficient is that consumers are not charged the cost of the negative externalities, (e.g. environmental impact, health impact, etc.). If the government were to levy fees for the use of polluting technologies and for the use of non-renewable resources so that the price charged to the

[76] Assumes an initial reliance upon the current natural gas pipeline system or other existing source of fuel to generate hydrogen on-site.

consumer reflected the "true" cost to society, "greener" technologies would immediately become more cost competitive. Moreover, if the government were, in turn, to use the fees generated by such taxation to subsidize the cost of "greener" technologies and the development of the requisite infrastructure, the problem of cost competitiveness could be substantially mitigated. In theory, as relative costs decrease, demand will increase and fixed cost per unit will decrease. Moreover, as usage increases, so to will the profitable infrastructure business models. As the infrastructure becomes more widespread, so to will the use of hydrogen fuel cells.

7.2.2 Increase Consumer Awareness

Though the negative impact of today's sources of power has been widely studied and disseminated, it does not seem to have permeated the minds of the mass consumer. This is similar to when it first became known that smoking is dangerous or that seatbelts save lives. It was not until major consumer awareness campaigns were rolled out did consumer behavior change. If the U.S. government and fuel cell manufacturers are serious about developing a market for hydrogen fuel cells, then they should look to the smoking and seatbelt campaigns as guides for developing a national campaign for the use of "greener" sources of power. An increase in consumer awareness will increase consumer demand for "greener" sources of power, which in turn will lead to the positive feedback loop described in 7.2.1.

7.2.3 Develop "Cleaner" Nuclear Power

The use of nuclear power to produce hydrogen could have significant positive impact on the efficiency and cost of hydrogen production. However, as previously discussed, any suggestions to increase the use of nuclear power given today's technology would be hotly contested. However, if a cleaner, safer method of nuclear power were developed, the issue of hydrogen production would be largely mitigated. Without a substantial increase in domestic electric energy production, we will be dependent on foreign sources of fossil fuel as a feedstock for hydrogen. Without this new electrical generation being "clean", the increased generation for production of hydrogen will cause serious negative environmental impacts due to our current electricity generation mix. Solar and windmill generation are not practical at the scales required to provide a national hydrogen infrastructure, neither is generation of hydrogen from ethanol (corn) or other biomass.

7.2.4 Increase Corporate Social Responsibility

Corporate social responsibility is a relatively new issue for many corporate leaders. Are corporations responsible solely to their shareholders or do they have a responsibility to the societies in which they operate? Although there are widely divergent views on this matter, several large multi-national companies are adopting a broader definition of their role in society. Nike, Ford, Shell and BP are examples of multinational corporations that have changed their traditional view and are moving toward the position that they have a responsibility to more than just their shareholders. These companies, although they are still profit focused, have come to realize that they can make contributions to a more sustainable society and still make a profit. Shell states in its 2001 Annual Report to Shareholders:

> "The objectives of the Royal Dutch/Shell Group of Companies are to engage efficiently, responsibly and profitably in the oil, gas, chemicals and other selected businesses and participate in the research and development of other sources of energy. Shell companies are committed to contribute to sustainable development."

This change in thinking has spurred the development of cleaner methods of exploration and production and investment in cleaner fuels and alternative sources of energy, including hydrogen, while, at the same time, the company has been delivering adequate company profits.

7.2.5 Heightened Need for Energy Independence

As this thesis is being written, the conflict between Israel and the Palestinians is escalating, causing further unrest in an already volatile area in the world. In addition, Iraq is threatening to cut off supplies of oil to the U.S. as the U.S. continues to wage the war against terrorism. Though the U.S. has significant oil in reserve as well as in the ground, the cost at which it could be drilled is substantially higher than the current world market price. If the U.S. were forced to resort to drilling, oil prices would rise significantly, which would not be beneficial to the U.S. economy. Using the price at which the U.S. could drill its sovereign oil as a comparison to the cost of a hydrogen fuel cell would improve the business case for the fuel cell.

7.3 Summary

Although a new source of power is inevitable, we do not believe that a transition to hydrogen fuel cells as the dominant source of power will happen in the near term without the implementation of one or more of the enablers described above. Despite the many benefits that would result, the issues of cost, performance and hydrogen infrastructure and production are too great given the current status of the existing technologies for the transition to occur without a change in the way we think about the cost of our current energy supply. Petroleum and natural gas are likely to remain the dominant energy sources in the near term due to their relatively low costs of production and use (or, at least as long as externality effects are not built into the price). Finding ways to attach such costs to energy prices is, in the end, one of the most pressing problems we now face.

This conclusion is not the one we had hoped to reach when we commenced our research. In fact, we are quite disappointed that not more is being done by public sector to coordinate, facilitate and further the efforts of the private sector to speed the develop of hydrogen fuel cells and the related storage technologies, production methods and infrastructure or to better educate consumers on the true cost of the existing sources of power. No single company or industry has the financial or human capital or the technology to make this transition alone. Visionary leadership, not unlike that of Dwight D. Eisenhower and the Federal Aid-Highway Act of 1956, which authorized the interstate highway system, is needed to drive the transformation to a hydrogen-powered economy. With the right leadership, we hope that no one will need to rewrite this thesis in ten years.

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8.2 Meetings

Fall 2001 Meeting of the SoL Sustainability Consortium, October 2001.

Meetings with Representatives from Major Automotive Manufacturer, January 2002.

Meetings with Representative from Major Fuel Cell Manufacturer, February 2002.

Participation in the collaborative learning project through the Society of Organizational Learning and a major U.S. utility company in January and February of 2002.

Winter 2002 SoL and Rocky Mountain Institute Collaborative Innovation for Sustainability Workshop, February 3-6, 2002.

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