Cornell University

School of Civil and Environmental Engineering

Exploring the Hydrogen Transition:

Investigation of an Alternative Fuel

Fall 2004 – Spring 2005

Executive Summary

The need for a transition to an alternative fuel is clear and continually increasing. 63% of crude oil consumed in America is imported, a quarter of which comes from the Middle East (forbes.com, 2005, eia.doe.gov, 2005). As Americans buy more vehicles and drive them further, energy consumption and oil use increase. As a result, greenhouse gas and particulate emissions will continue to be problematic. Ideally, vehicles would be powered by a clean, efficient, non-polluting fuel. Hydrogen fits all of these characteristics, and as hydrogen fuel becomes more technologically and economically feasible, the transition to hydrogen as a transportation fuel is conceivable.

One of the current innovations in vehicles is the advent of hybrid technology. The results are better fuel economy and dramatically lower emissions. Our group examined whether a transition that uses hybrid technology as a stepping-stone to fuel cell vehicles would be more effective than a direct transition from standard gasoline-powered to hydrogen-powered vehicles. Conclusions on path effectiveness were drawn by analyzing the energy consumption, oil use, and CO_2 production for each path.

Our group also determined the necessity for government involvement in order to facilitate a transition to hydrogen-powered and/or hybrid-electric vehicles (HEVs). Short-term and long-term legislative policies were considered, as well as the level of need for each. In addition, our group investigated current initiatives for hybrid and hydrogen transitions, assessing their effectiveness and feasibility.

Based on our research, our group concludes that HEVs will fully penetrate the light vehicle market between 2030 and 2080. This transition will significantly increase average light vehicle efficiency, leading to decreased energy and oil consumption, and reduced carbon dioxide emissions. Successful hybrid penetration will also delay fuel cell vehicle introduction by at least ten years, as the expected decrease in oil consumption will ease the need to find alternative fuels.

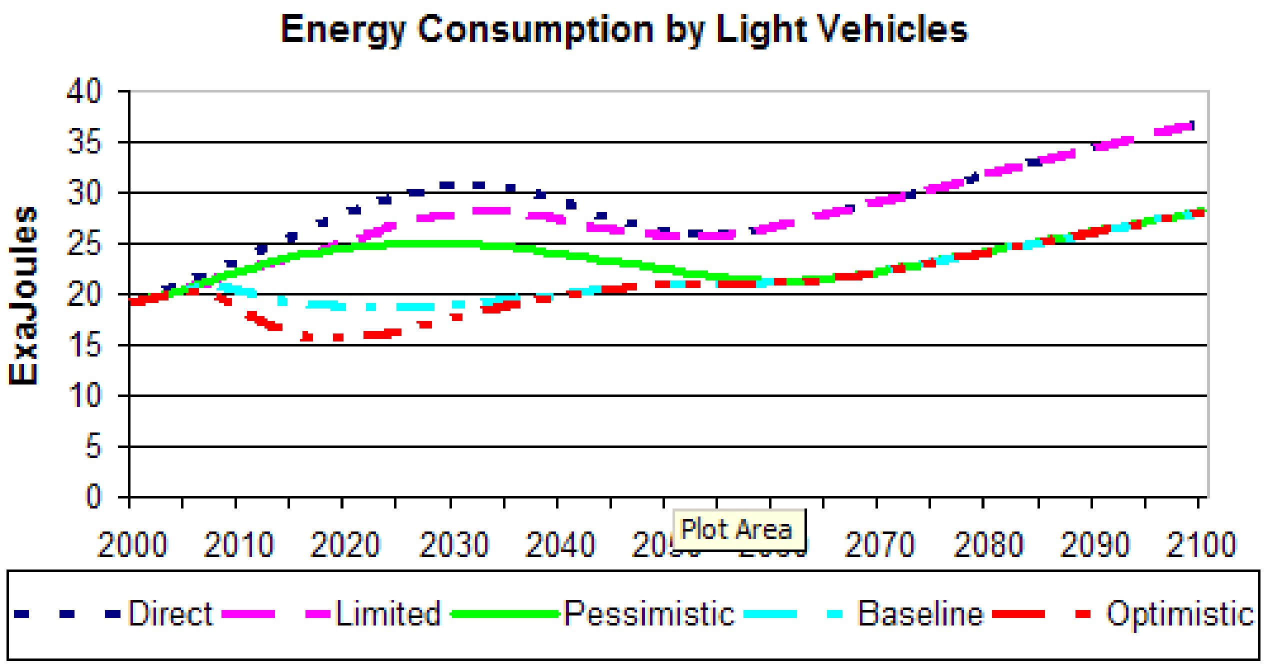

Figure 1: Annual energy consumption by light vehicles for five transition scenarios

The graph is a comparison between the different scenarios for both a direct transition and a hybrid transition. The curves depict different scenarios based on estimates for hybrid penetration. The baseline, pessimistic, and optimistic curves illustrate energy predictions for a hybrid-path transition scenario, while the direct and limited curves illustrate energy predictions for a direct-path transition scenario. Over time, all scenarios for the hybrid path illustrate larger savings in energy consumption as compared with the direct path, which can be expected to lead to further reductions in pollutant emissions and oil use. Considering all aspects of the two transitions, we find that the hybrid path is more desirable than a direct path to fuel cell vehicles. The endpoint technology for the hybrid path is more efficient, and the cumulative savings in energy and CO_2 emissions are greater than those realized by a direct transition to hydrogen-powered vehicles.

Our group also considered the feasibility and impact of transitioning from conventional diesel engines to hydrogen fuel cells in heavy duty vehicles. After determining that hydrogen fuel cells in tractor trailers were impractical due to size, cost, and infrastructure issues, efforts were focused on transit buses. A transition model was created by applying a logistics curve to forecast data for bus demand in order to approximate the shape that the actual transition from diesel buses to hydrogen fuel cells buses would take through 2060. Once the transition model was implemented, various representative scenarios were examined.

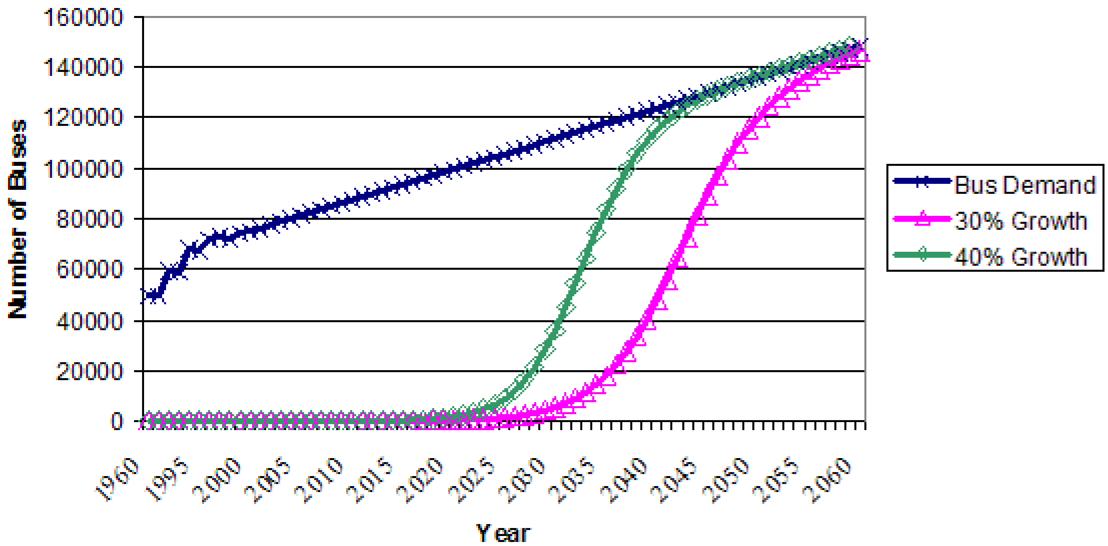

Figure 2: Bus transition model with 30% - 40% growth rate

In addition, our group created an energy model to examine the trends in bus energy use and efficiency and determine the amounts of diesel and hydrogen required to meet future transit buses demands. From this model, it was found that, if no improvement in efficiency existed in changing from diesel engines to fuel cells, roughly a kilogram of hydrogen would be needed for every projected gallon of diesel.

Also, our group investigated the requirements of the transition to hydrogen fuel-cell buses in terms of infrastructure and bus conversion. The physical and financial requirements for infrastructure were examined. Additionally, the fuel cell bus conversion study focused on power systems, fuel storage, and the balance of system.

Transit buses were determined to be an ideal launch platform for the hydrogen transition due to their large size, centralized refueling, location in high pollution areas, high profile, and subsidized funding. Additionally, the impact of various technologies such as H_2 ICE engines, Hythane buses, Hydrogen delivery trucks, and HEV buses on the speed of the direct transition from diesel buses to hydrogen fuel-cell buses was found to be uniformly positive, with the possible exception of the HEV bus. Ongoing pilot programs in Iceland and Europe were also examined, and the transition model was expanded by examining its potential impact on a bus transition in Washington D.C.

One of the problems associated with the introduction of hydrogen fuel cell vehicles is creating the refueling infrastructure to support the vehicles. A fully developed network can rely on market forces to sustain and adjust it to meet vehicle growth, but it is difficult for market forces to begin that growth. Research has shown that a small network of well-placed stations can serve to demonstrate the new technologys viability and allow a demand for hydrogen fuel cell vehicles to grow. Our group designed a plan to build a network for the District of Columbia (DC) and analyze its behavior. It was believed that this city represented a typical American city and also provided a unique opportunity to showcase hydrogen technology in view of lawmakers and, to some extent, the American people.

Research conducted during the growth of diesel fuel passenger vehicles in California in the late 1970s showed that when the diesel fuel was available at 10-15% of gasoline stations, a majority of the public perceived only moderate to little difficulty in refueling their vehicles. Using this basis, our group compiled a list of all gasoline stations in DC and constructed an unbiased algorithm to select a single station from each zip code in DC. These selections were further reduced to a base network of 11 stations in order to meet the 10-15% requirement, as well as to reduce costs. The Shell Hydrogen station that is currently in operation on Benning Road was included as part of this base network.

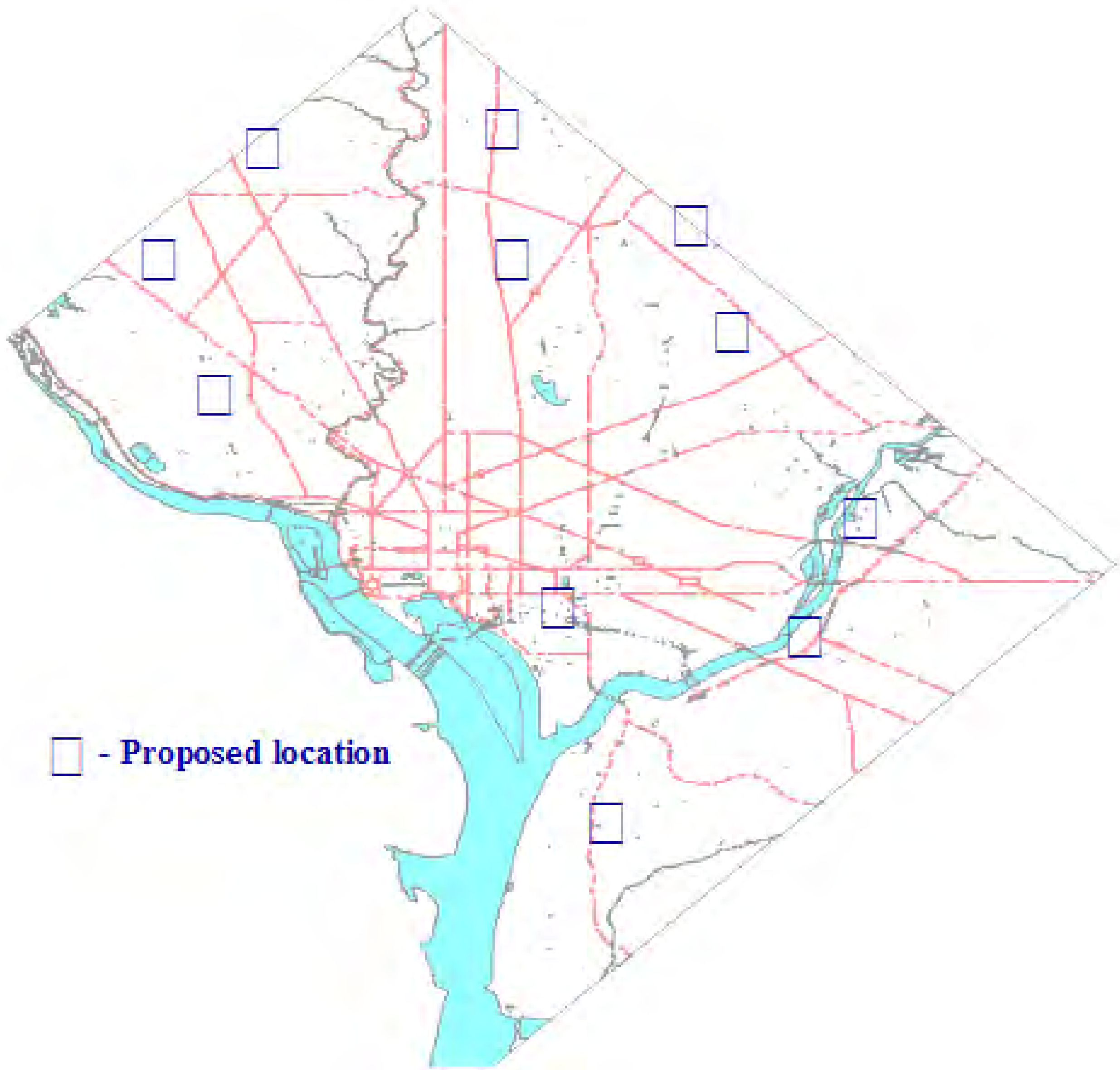

Figure 3: Map of Washington, D.C. with proposed locations for hydrogen refueling stations

Next, a simulation model was created to conduct a thorough analysis on both DC and the surrounding counties to determine how the demand for FCVs might grow over time according to population growth, socioeconomic statistics, and urban sprawl. The model found that the proposed network could adequately serve the growth in both the suburban and urban areas of DC for approximately ten years before more construction would be needed. Furthermore, the model demonstrated that an urban network could encourage suburban FCV ownership, and eventually create a market for suburban stations.

Finally, an economic analysis was performed to demonstrate the feasibility of constructing the

DC hydrogen network. An estimated initial investment of $20 million would be needed to construct these 11 stations, which could be recovered over 15 years by selling hydrogen at $3.44/kg in the first year, and steadily declining the price to $1.68/kg at the end of the analysis period. The research also concludes that the overall feasibility of the project will require the cooperation of many entities including multiple hydrogen providers and energy corporations.

Our group also created Gen H Power Park, which produces hydrogen and electricity for the next generation of energy. As a pilot program to promote the hydrogen economy, Gen H Power Park will begin service in January of 2010 and immediately begin to dispense *H*Max hydrogen fuel and *e*Max electricity. Gen H Power Park will continue operation up to December 2020 and possibly beyond, pending economic success.

With a footprint of 21,000 sq. ft., Gen H Power Park is located at the southernmost tip of Shepherd Parkway S.W., east of I-295 in Washington, D.C.. It is effectively positioned to serve the Washington D.C., Maryland, Virginia, and West Virginia Primary Metropolitan Area while situated only 500 ft. away from its hydrogen source, Blue Plains Advanced Wastewater Treatment Plant (AWTP). Blue Plains AWTP is Gen H's sole provider of biogas, a renewable source of energy. To produce hydrogen, Gen H Power Park utilizes the Steam Methane Reforming process (SMR) with subsequent pressure swing absorption because of its effective cost-saving property. The hydrogen harvested from the process is stored in a cascading storage system for dispensing. Thanks to the simplicity of the design, Gen H Power Park can offer hydrogen at $8.31/kg for vehicle use.

The rest of the biogas acquired from Blue Plains Wastewater Treatment Plant is fed into a Proton Exchange Membrane (PEM) fuel cell for electricity generation to provide power for Gen H Power Park as well as the neighborhood. The commercial viability, low maintenance, and operating costs of the PEM fuel cell help make Gen H Power Park economically competitive over other designs. The cost of electricity that Gen H will charge the public is $0.0865/kWh.

Gen H Power Park's design extends to providing employees and patrons with an accident-free environment. A Failure Modes and Effects Analysis (FMEA) and Fault Tree analysis were used to identity 54 different failure modes and to mitigate the 4 most accident prone ones. Safety measures and controls have been integrated effectively to prevent Gen H Power Park from both catastrophic failures and personal injury.

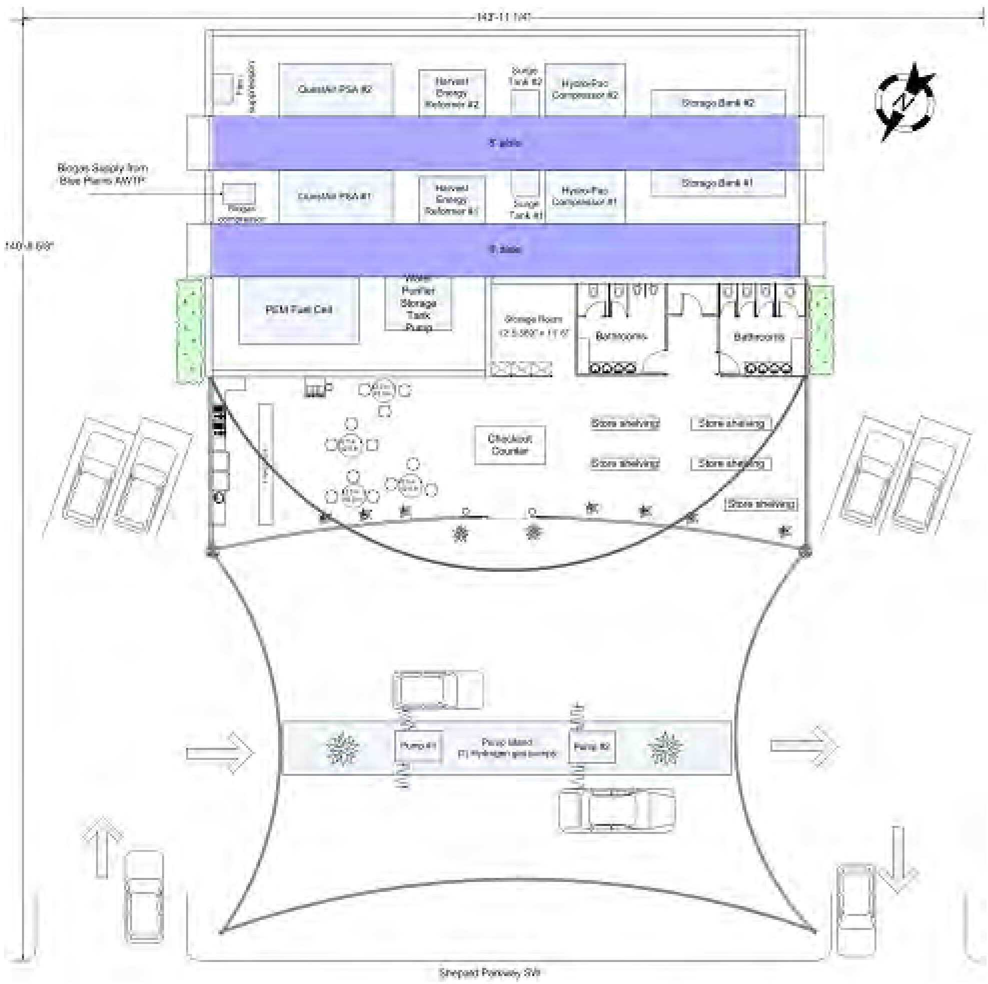

Figure 4: Proposed design for Gen H Power Park

From the community perspective, the design of Gen H Power Park proves to be environmentally friendly. The process is carbon-neutral due to the fact that the input source is biogas. Gen H does not derive its energy from the processing of fossil fuel.

In order to promote the hydrogen economy, Gen H Power Park will employ a broad marketing and education plan. The plan will educate the public about the hydrogen economy and its future, as well as boost sales of HMax and eMax.

Lastly, our group concludes that government involvement is necessary for fuel cell vehicles to successfully enter the market in the next thirty years, due to the technological and economic difficulties surrounding the transition and their associated costs. Implementing business incentives, pilot government fleets, educational programs, and increased CAFE and emissions standards can help make the hydrogen economy a reality.

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Introduction

Due to the rising cost and diminishing supply of oil-based fuels, as well as the growing concerns about pollution and global climate change, there has been a great deal of research on alternative fuel technologies. One of the most promising of these new technologies is hydrogen fuel cells. Fuel cells need only hydrogen, the most abundant element in the universe, and oxygen as fuels. Since fuel cells use a chemical process, not a combustion process, their emissions are much lower than conventional technologies. This makes them a promising solution to the transportation needs of the future. Despite its future potential, hydrogen as a transportation fuel is currently faced with a number of challenges, such as unsolved technical hurdles, the need to develop a large scale infrastructure to supply hydrogen, and the need for substantial cost reduction.

In this report, we examine the requirements needed to manage the transition to using hydrogen as the next generation of transportation fuel. Research in this area was conducted in four specific areas. First, we investigated the transition to using fuel cells in passenger vehicles and the impact that hybrid electric vehicles, a technology familiar to most people, will have on this transition. We then discuss a potential launch pad for the hydrogen transition, heavy duty vehicles (HDVs), paying particular attention to fuel cell transit buses. Next, we describe a specific example of a hydrogen production facility, the Gen H Power Park. Finally, we concentrate on a plan for creating a hydrogen infrastructure in Washington D.C. Each area of research will be discussed in detail below.

HEV

Hybrid technology is the current innovation in motor vehicles. Since their introduction six years ago, hybrid sales have seen remarkable growth with no sign of dissipation. To investigate a future transition to hydrogen power, we will consider different hybrid vehicle penetration scenarios and their effects on total US energy and oil consumption. We will also analyze the effect of developing battery and diesel technologies on the hybrid and hydrogen transitions. We will consider whether a direct path to hydrogen vehicles is more desirable than one using hybrid technology as a stepping-stone. Vehicle emissions and their history in US legislation will be discussed, and an analysis of the effect of the transitions on emissions will be conducted. Finally, we will explore the necessity for government involvement to aid these transitions, and provide recommendations to most effectively ease the hybrid and hydrogen transitions.

HDV

While hydrogen fuel cell technology holds great potential, it is currently plagued by a variety of problems. The size of both the fuel cell and the hydrogen storage tanks are too large to be easily installed into standard passenger vehicles. The range and performance of fuel cells are below the standard set by internal combustion engines. The infrastructure requirements and overall cost of hydrogen fuel cells are well beyond those of conventional diesel engines.

Despite these problems, hydrogen technology could potentially solve a number of problems plaguing transportation, specifically pollution, in the form of greenhouse gas emissions, fuel cost, and availability. The only emission from fuel cells is water vapor, and hydrogen is easily created from readily available resources.

An ideal platform for the hydrogen transition is the transit bus. Transit buses counteract all the weaknesses of hydrogen fuel cells in these early years of the technology's development, while providing a small (less 1% of vehicles on the road), high profile venue to raise public awareness and perception of hydrogen.

Despite this fact, little work has been done to examine the requirements and effects of a hydrogen transition in transit buses. To correct this oversight, we examined all aspects of a possible hydrogen transition in transit buses. We created a model to examine possible scenarios for the physical transition of transit buses to fuel cells. Then, another model was created that examined the effect of these various scenarios on the cost of fuel cell technology. In addition to this, we generated a model to examine the possible effects of the hydrogen transition on energy consumption and vehicle efficiency. Lastly, we examined the physical and financial requirements of creating a hydrogen infrastructure, as well as the actual process of converting transit buses to use fuel cells.

Gen H Power Park Team

We designed Gen H Power Park for hydrogen production and electricity for the distributed generation market. Designed as a proposal for the National Hydrogen Association's annual design contest, the design of Gen H Power Park was designed according to specific requirements. The park must produce and deliver to vehicles 50 kg/d of hydrogen in 2010 and 250 kg/d in 2020. Gen H Power Park must also be capable to handle a peak dispensing hour at 30 kg/hour. In terms of electricity, Gen H Power Park must deliver 100kW to the neighboring grid. The design of Gen H Power Park includes technical design, safety analysis, environmental impact analysis, economic and business plan, as well as marketing and education programs.

Washington D.C.

One of the greatest challenges to the hydrogen transition is the lack of infrastructure in place. Ironically, this is a barrier to the development of both infrastructure and FCVs. If there was an infrastructure in place, then decisions regarding the timing and location of future refueling stations would be fairly straightforward, and easily controlled by market forces. A hydrogen company could look at the network, determine areas of high hydrogen demand, choose a suitable location, and place itself in competition. Without an existing infrastructure, however, it is difficult to determine profitable areas with high hydrogen demand. This makes investing the money to build one station a high-risk venture, let alone the investment of money to build multiple stations.

The barrier to developing FCVs is more obvious. Without a strong infrastructure in place, it is difficult to get the public excited enough to purchase fuel cell cars. This also indirectly affects the research put into developing such vehicles, especially if the vehicle producers are unconvinced of hydrogen's feasibility.

Management, therefore, is a necessity in jumpstarting the transition to a hydrogen-based transportation system. Market forces alone cannot be expected to provide a swift and smooth transition, and perhaps not enough to start the transition at all.

In the following report, we will explain in detail one method for determining a feasible network.

It is unlikely that a single company would undertake this effort alone, but the design assumes that some authority oversees the development of the network and any companies that are involved. This authority may be the government, or simply a consortium of companies that pledge to co-operate. In the first section that follows, we will discuss the background information required to develop a network, including population statistics, driver preferences, the benefits of government involvement, and economic analysis. Next, we will outline a design algorithm, and describe the results of this algorithm in terms of designing a network today. Finally, we will discuss performance measures that could be used to guide the transition past the initial phase.

Part I

Hybrid Electric Vehicles

Chapter 1

Introduction

The need for a transition to an alternative fuel is apparent, and continually growing. US dependence on foreign sources of oil threatens national security and hurts local economies. 63% of crude oil consumed in America is imported, a quarter of which comes from the Middle East (forbes.com, 2005, eia.doe.gov, 2003 [44] [43]). As Americans buy more vehicles and drive them further, energy consumption and oil use increase. As a result, carbon monoxide and smog emissions continue to be problematic, despite rigorous efforts from the Environmental Protection Agency and the California Air Resources Board. In an ideal world, vehicles would be powered by a clean, efficient fuel, where the only byproduct of consumption is water. Such a fuel exists, and as hydrogen fuel becomes more technologically and economically feasible, the promise of a successful hydrogen transition is made more plausible.

The current innovation in vehicles is the advent of hybrid technology, which uses electric power from a battery to aid the driving process, especially during low-speed and stop-and-go situations. The results are better fuel economy and dramatically lower emissions. The popularity of HEVs may hurt the fuel cell transition, since hybrids help decrease oil dependence and emissions levels. To further study this possibility, our team focused on the following question: which transition path is more desirable, a hybrid path that uses hybrid technology as a stepping-stone to fuel cell vehicles, or a direct one that moves from standard gasoline vehicles to hydrogen-powered ones? The criteria for answering this question were the effects of the two paths on energy consumption, oil use, and carbon dioxide production.

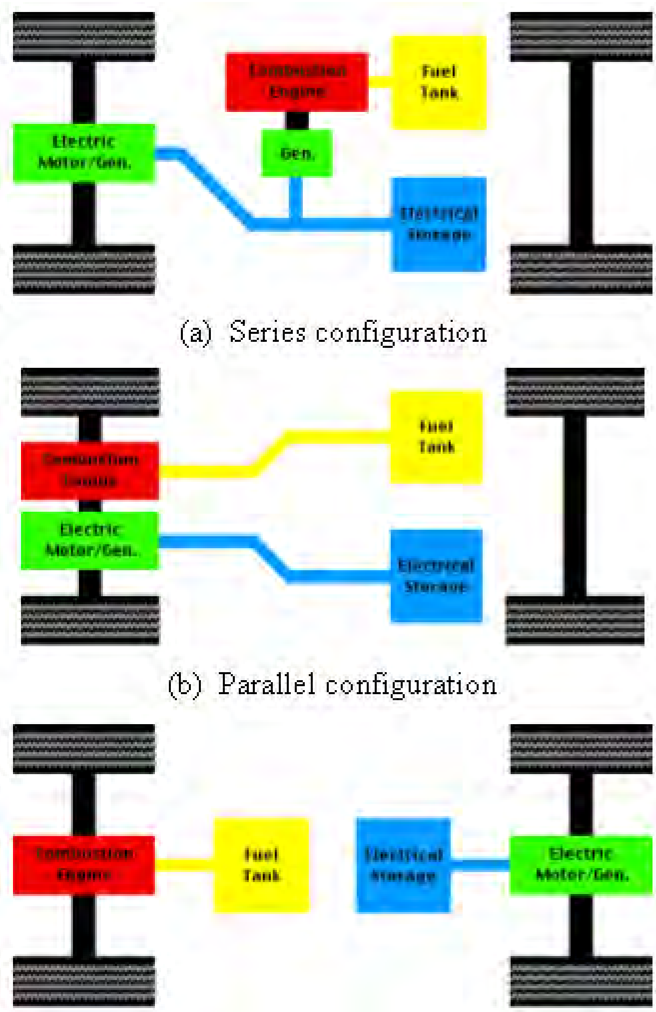
The second major question the directed our research was how necessary is government involvement to make the transition. To answer this question, we considered short term and long term policies, as well as the level of need for each of them. We also investigated current initiatives for hybrid and hydrogen transitions, assessing their effectiveness and feasibility. From our investigation, we hope to show the most effective strategy to launch a successful hydrogen transition in light vehicles.

Chapter 2

The Hybrid Transition

2.1 HEV Technology Summary

Hybrid gasoline-electric vehicles (HEVs) consist of both the internal combustion engine found in typical on-road vehicles and an electrical storage device, such as a battery, flywheel, or ultracapacitor, for energy storage (elecdesign.com, 2003 [4]). The configuration of a hybrid can be either series, parallel, or split. In a series configuration, the engine never directly powers the car. Instead, the engine drives a generator, and the generator can either charge the batteries or power an electric motor that drives the wheels. In a parallel configuration, such as that used by the HEVs sold today, both the engine and the batteries and electric motor connect to the transmission, so both the engine and the electric motor can supply power to the wheels, switching back and forth as driving conditions vary. In a split configuration, such as that used by the Chevrolet Triax concept vehicle, the engine drives one axle and the electric motor drives the other, so there is no physical connection between the engine and the motor (transportation.anl.gov, 2004 [6]).



(a) Series configuration

(b) Parallel configuration

(c) Split configuration

Figure 2.1: Various configurations for a hybrid drivetrain (Altfuels.org [3])

Hybrids can be further subcategorized into mild and strong/full hybrids. Mild HEVs, such as the Honda Insight and the Honda Civic Hybrid, cannot propel the vehicle by battery power alone. The engine flywheel is replaced with an electric starter-generator motor or a belt-driven starter-alternator, which allows the engine to shut off and restart rather than idle and waste fuel. In addition to this automatic start/shutoff feature, a full hybrid, such as the Toyota Prius and the upcoming Ford Escape Hybrid, can also run exclusively on the electric motor during low-speed driving conditions where internal combustion engines are least efficient, further reducing both fuel consumed and emissions. Full hybrids require a larger battery, making the cost of the overall system more than that in a mild hybrid, but the full hybrids are also ten to fifteen percent more efficient (hydrogenforecast.com, 2004 [2]).

Much of the increased fuel efficiency of HEVs can be attributed to the additional battery and electric motor, and to the regenerative braking system that charges the battery. Regenerative braking works by capturing energy normally lost during braking and returning it to the onboard battery. Approximately sixty percent of the total energy consumed in city driving is spent on braking, and theoretically over half of this lost energy can be reclaimed by an HEV upon deceleration (elecdesign.com, 2003 [4]). The electric motor also provides power to assist the engine in accelerating, passing, and hill-climbing, which allows for the use of a smaller, more efficient internal combustion engine (fueleconomy.gov, 2004 [5]).

2.2 HEV Penetration Scenarios

2.2.1 Model Formulation

To create scenarios for hybrid vehicle penetration into the auto market, the HEV team gathered data on total annual light vehicle sales in the US from 1980 to the present (TEDB, 2004 [9]). Using the Holts-Winter's Method of forecasting, the data was projected through 2100. We then found historical data on the proportion of light truck sales and passenger vehicle sales within the light vehicle category (TEDB, 2004 [9]). The data showed an increasing proportion of light truck sales, overtaking passenger vehicle sales in 2003. This data was projected, reaching an asymptote of 60% light truck sales. The resultant numbers for sales by vehicle type, shown in Figure 2.2, were then used to begin modeling a hybrid transition.

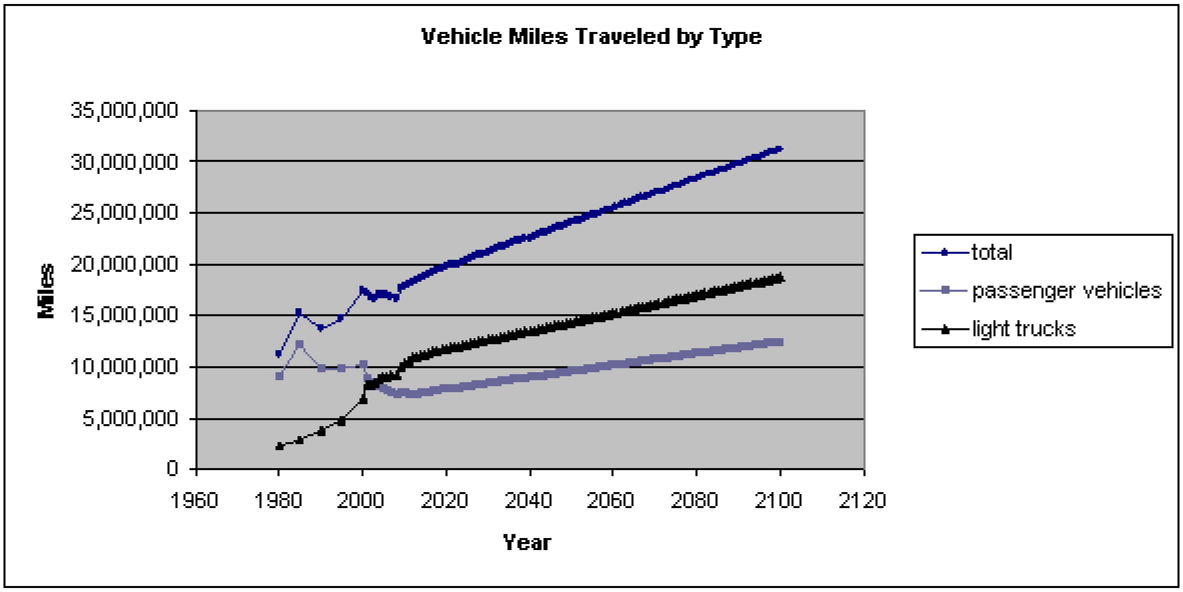


Figure 2.2: Vehicle Miles Traveled Projections

Hybrid cars first entered the U.S. market in 1999 with the Honda Insight, selling 3,788 vehicles. Toyota's introduction of the Prius the following year led to higher sales, totaling 9,350 (bankrate.com, 2004 [15]). Since then, hybrid sales growth has averaged 88.6% annually, reaching over 43,000 units in 2003 (billingsgazette.com, 2004 [14]). Hybrid light trucks are planned to enter the market in 2005 with the Ford Escape Hybrid. To forecast sales for the introduction of hybrid light trucks, we analyzed hybrid passenger vehicle and standard SUV sales. From 1976 to 1979, SUV sales increased from nearly 60,000 units to over 114,000 (TEDB, 2004 [9]). Comparing a regression of this data to hybrid sales from 2000-2003, we see that the rates of increase are nearly identical, as seen in Figure 2.3. From this result, we made the assumption that the first four years of hybrid SUV sales will match this rate.

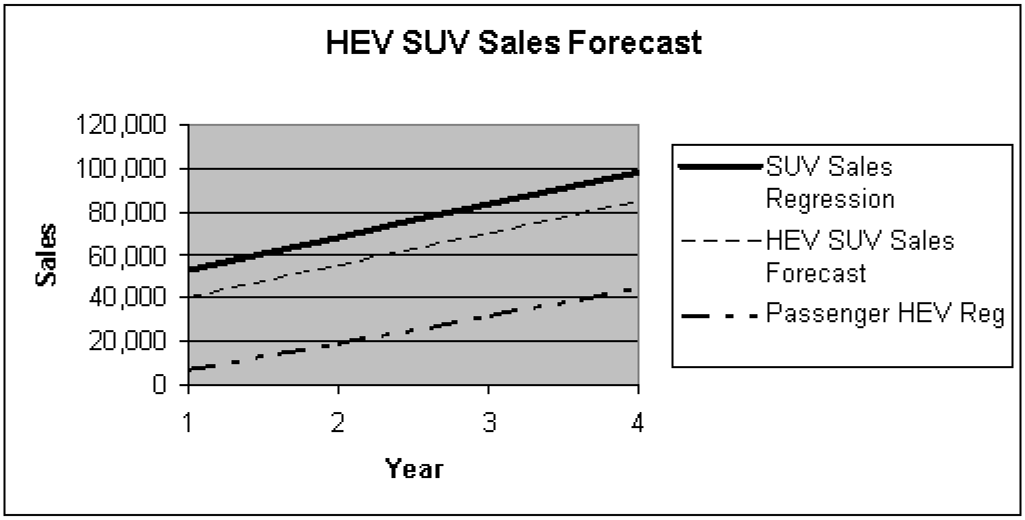


Figure 2.3: Vehicle Miles Traveled Projections

We analyzed three scenarios for hybrid penetration. A pessimistic scenario models the case where the government offers minimal incentive for consumers to buy hybrids, and the auto industry makes little effort to market the vehicles. An unenthusiastic attitude from the auto industry and government may not provide consumers with adequate knowledge about the benefits of hybrid vehicles. These conditions would possibly result in a very slow transition, taking 80 years for full penetration. The baseline scenario is also market-driven, requiring little government incentive. This scenario assumes that the auto industry makes some investment into marketing the technology, resulting in an approximately 40-year transition. The optimistic scenario is a policy-driven one, where the government enacts vehicle standards, on either emissions or CAFE, which would force the auto industry to phase out non-hybrid vehicles. This is analogous to the transition from carburetors to fuel injection technology during the 1970s and 1980s (ca.auto.yahoo.com, 2004 [13]). This transition was a result of an oil shortage in the 1970s, which led to the US government's implementation of emissions controls. The current carburetor technology could not control emissions to meet these new standards, forcing the auto industry to adopt the more expensive fuel injection technology. If history repeats itself, the auto industry will force a transition resulting in full penetration within the next 20 years.

To shape these hybrid market-penetration curves, we used a triangular distribution function (mathworld.wolfram.com, 2004 [17]), using the penetration start and end dates as parameters. The results of this analysis are the following scenarios for the transition to hybrids:

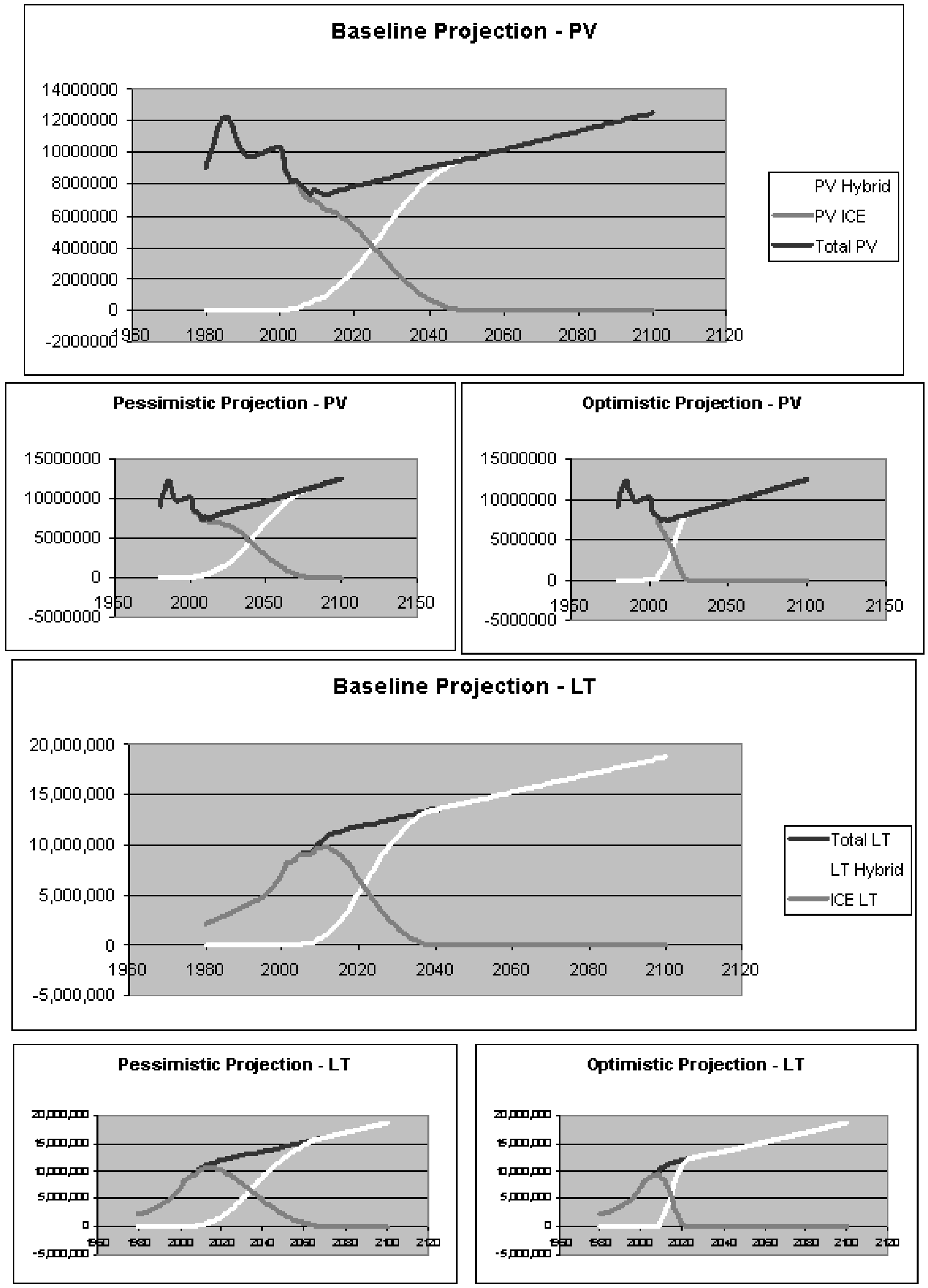


Figure 2.4: Hybrid Sales Projections for Passenger and Light Truck Vehicles

2.2.2 Assumptions

These models assume that the introduction of hybrid vehicles will not affect total annual light vehicle sales. We feel this is a reasonable assumption, because we predict that only a negligible number of consumers will sell a working non-hybrid faster than they would normally to buy a hybrid vehicle. We also assume that hybrid light truck sales will grow more rapidly than passenger vehicle sales. This assumption arises from the fact that SUV buyers are generally less price sensitive than other auto buyers, and that emissions/fuel economy standards affect SUVs the most (maritz.com, 2004 [18]).

2.2.3 Results

As illustrated in Figure 2.4, our models produce various scenarios for hybrid penetration into the passenger vehicle and light truck market. The pessimistic scenario for passenger vehicles has a crossover point, where hybrids outsell standard ICE vehicles, near 2040. The crossover point exists for the baseline scenario in 2025, and for the optimistic scenario in 2015. Total passenger vehicle sales grow at a constant rate. 90% penetration into the passenger vehicle market will be reached by 2063 in the pessimistic scenario, and by 2039 in the baseline scenario. Optimistically, we can expect 90% penetration by 2021.

Following the assumptions stated previously, the market share of hybrid light trucks will grow more rapidly than will the market share of passenger car hybrids. The pessimistic model has a crossover and 90% penetration point of 2035 and 2054, respectively. The baseline models crossover and 90% penetration points are 2021 and 2032. Optimistically, we can expect a crossover in light truck sales at 2014 and 90% penetration by 2020. Table 2.1 shows sales projections for hybrids for the near-future under the baseline scenarios.

Year	Hybrid PV Sales	Hybrid PV%	Hybrid LT Sales	Hybrid LT%	Total Hybrid Sales
2005	166,000	2.07%	40,000	0.44%	206,000
2006	326,049	4.18%	80,000	0.87%	406,049
2007	371,199	4.92%	120,000	1.30%	491,199
2008	450,236	6.12%	160,000	1.70%	610,236
2009	568,025	7.48%	437,647	4.34%	1,005,672
2010	674,921	9.00%	627,766	6.06%	1,302,687
2011	790,365	10.68%	868,685	8.15%	1,659,050
2012	913,688	12.52%	1,164,003	10.63%	2,077,691

Table 2.1: Baseline Hybrid Sales Projections

2.2.4 Milestones

Current hybrid sales are increasing at an impressive rate, nearly 90% annually (billingsgazette.com, 2004 [14]). According to our models, however, this rate will increase dramatically in the next few years. For this to happen, several milestones are probable. In October, 2004, Gov. Schwarzenegger of California passed a bill to reduce emissions from all vehicles by 25% (seattlepi.nwsource.com, 2004 [19]). California gave the auto industry until 2009 to develop new emissions controls and until 2016 to introduce vehicles with the new technology, aggravating automakers. The industry trade group, Alliance of Automobile Manufacturers, has stated that such implementation would be "almost as complicated as developing the first automobile," and estimated an average price increase of $3000 (seattlepi.nwsource.com, 2004 [19]). California stands as a unique state to challenge the industry. Representing ten percent of the auto market, California is the only state allowed to create its own emissions legislation, since the state government began controlling emissions before the federal government. Other states have the option of adopting Californias emissions standards over the federal governments, something that seven states, over twenty-five percent of the vehicle market, have done (knowledge.fhwa.dot.gov, 2003 [21]). In December 2004, the Alliance of Automobile Manufacturers sued the California government in an effort to block the new standards (philly.com, 2004 [20]). If this attempt fails, the industry will be forced to introduce vehicles with lower emissions. Hybrids, which cut smog-forming pollutants by 90% and CO2 emissions in half, are the best option for the industry to meet this requirement quickly (deq.state.id.us, 2004 [22]).

Along with increased emissions controls, rising gas prices will continue to influence consumer's buying habits, leading them towards more fuel efficient cars. The shift has already begun; vehicle requests in the second quarter of 2004 have dramatically sided in favor of smaller, efficient cars (autobytel.com, 2004 [23]). In fact, requests for Toyotas hybrid, the Prius, have increased by 41%. If these trends in gas prices continue, consumer habit trends will follow, placing a demand on the auto industry for hybrids.

As hybrid technology becomes more established, costs will invariably fall. With falling costs and increased competition with other hybrid manufacturers, the price premium for hybrid cars will decrease. This price reduction will result in further demand for hybrids. One can also speculate that as hybrids enter the mainstream and become commonplace, cultural stigmas against non-hybrids may arise. If better economy and lower emissions can be purchased with minimal effect on performance, people may question why some consumers continue to purchase non-hybrids. Whether this stigma occurs or not, there is enough evidence today that suggests a large increase in demand for hybrids in the near future. As our models show, different magnitudes of this demand will result in different penetration curves. These scenarios have different effects on total energy use and oil consumption, as we will illustrate in later chapters.

2.3 Battery Technology Overview / Projections

2.3.1 Introduction

The battery for a hybrid electric vehicle, used in conjunction with an electric motor, serves mainly as a secondary power source to the drivetrain. Imperfection in the current battery technology, however, poses a major barrier in producing both high performance and cost-effective HEVs that could fully compete with conventional automobiles. In this section we will first investigate the current battery technology in terms of cost and performance then project how the technology would evolve over time.

2.3.2 Battery Types

There are over twenty unique types of batteries on the market with hundreds of variations. In particular there are three types of batteries that are closely related to this research: lead-acid batteries, nickel-metal hydride battery, and lithium-ion battery.

Lead-Acid Battery

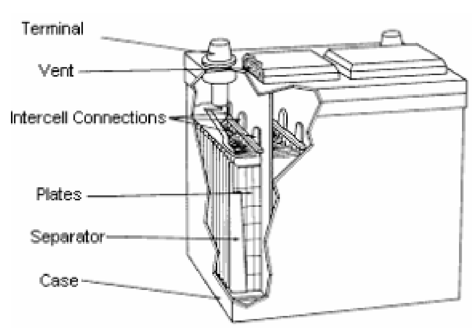


Figure 2.5: Lead-Acid Battery (Radio Shack Corporation, 2005 [58])

Lead Acid battery cells consist of a lead (Pb) electrode and a lead oxide (PbO_2) electrode immersed in a solution of water and sulfuric acid (H_2SO4). When the battery is connected to a load, the lead combines with the sulfuric acid to create lead sulfate (Pb_2SO4), and the lead oxide combines with hydrogen and sulfuric acid to create lead sulfate and water (H_2O). As the battery discharges, the lead sulfate builds up on the electrodes, and the water builds up in the sulfuric acid solution. When the battery is charged, the process reverses, with the lead sulfate combining with water to build up lead and lead oxide on the electrodes (Radio Shack Corporation, 2005 [58]).

Lead-acid batteries can be found in most of today's conventional internal combustion engine vehicles in which battery power is critical only during engine startups. During engine startup, lead-acid batteries are designed to provide strong current for a jump start. After a car is started, its generator takes over from the battery to provide electricity for the entire electrical system.

Nickel-Metal Hydride Battery

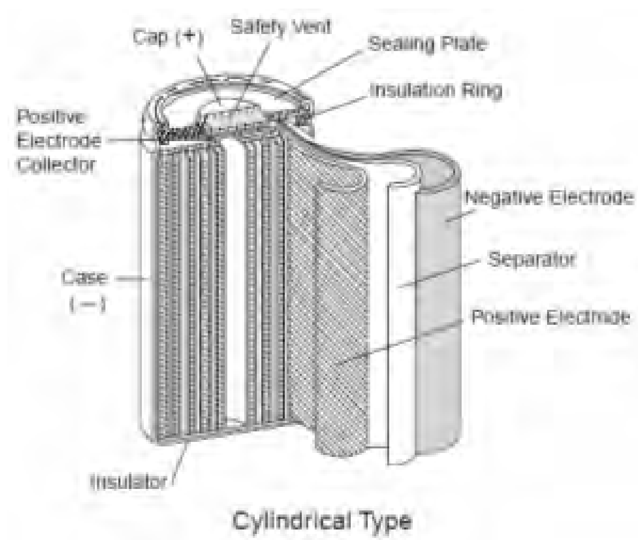


Figure 2.6: Ni-MH Battery (Panasonic, 1999 [56])

Nickel-metal hydride batteries consist of a positive plate containing nickel hydroxide as its principal active material, a negative plate mainly composed of hydrogen-absorbing alloys, a separator made of fine fibers, an alkaline electrolyte, a metal case and a sealing plate provided with a self-resealing safety vent. Hydrogen moves from the positive to negative electrode during charge and reverse during discharge (Panasonic, 1999 [56]).

Most of the current HEVs are powered by Nickel-Metal Hydride batteries that offer far better battery performance than lead acid batteries. The majority of conventional lead acid batteries offer approximately 30Wh/kg and 150W/kg (Department of Energy, 2005 [61]). Nickel-Metal

Hydride batteries, on the other hand, offer over 45 Wh/kg and 1000W/kg (Panasonic EV Energy Corporation, 2005 [57]). These batteries are designed to handle frequent charge/discharges and provide high energy output to power the supplemental electrical engines. While their performance is acceptable, the production cost of the Ni-MH batteries is still too high for HEVs to become price competitive.

Lithium-Ion Battery

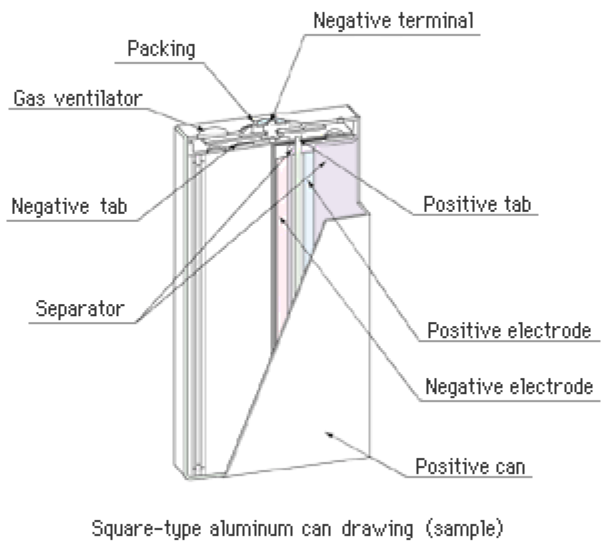


Figure 2.7: Lithium-Ion Battery (NEC TOKIN Corporation, 2005 [54])

Lithium-Ion (Li-ion) batteries have a three-layer structure consisting of an insulative porous separator sandwiched between sheet-like cathode and anode materials. When the battery is charged, the lithium ions in the cathode migrate via the separator to the anode. When the battery is discharged, the lithium ions in the anode migrate via the separator to the cathode (NEC TOKIN Corporation, 2005 [54]).

Li-ion batteries are considered ideal for use in HEVs. They do not suffer from the memory effect and offer much more specific power and energy that could greatly boost HEVs' performance while reducing the overall volume and weight of the batteries.

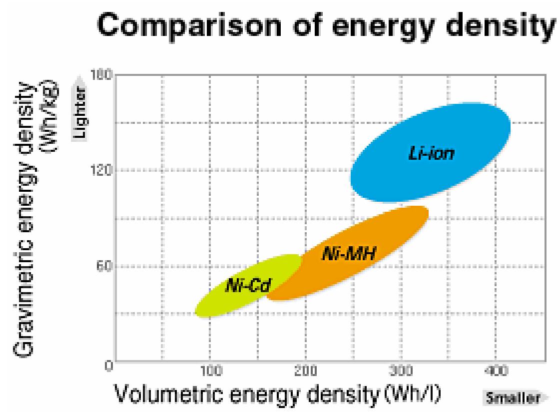


Figure 2.8: Energy Density Comparison (NEC TOKIN Corp, 2005 [54])

Together with lithium-polymer batteries, lithium batteries will lead the development of the future HEV batteries. This report, however, will focus mostly on the current Ni-MH technology since the lithium batteries are still early in its development stage for use in HEVs.

2.3.3 Battery Performance Overview and Projection

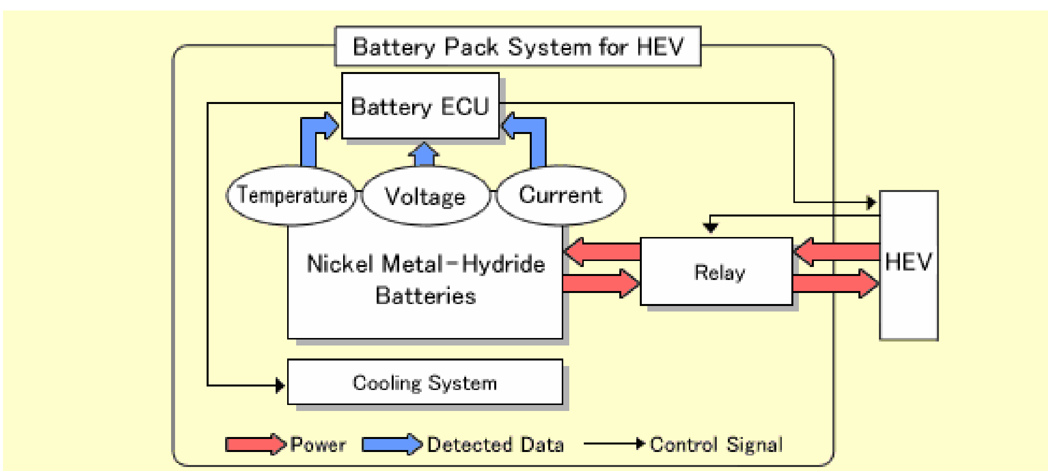


Figure 2.9: Example of Ni-MH Battery System for HEVs (Panasonic EV Energy Corporation, 2005 [57])

Unlike electric vehicles, HEVs do not rely on batteries as their primary energy source, thus require much smaller batteries to run efficiently. HEV manufacturers have put most of their attention on the specific power of their batteries so they could implement more powerful electric engines. The

Model	New Prismatic Module	Current Prismatic Module
Nominal Voltage	7.2V	7.2V
Nominal Capacity	6.5Ah	6.5Ah
Specific Power	1300W/kg	1000W/kg
Specific Energy	46Wh/kg	46Wh/kg
Weight	1040g	1050g
Dimension	19.6(W) X 106(H) X 285(L)	19.6(W) X 106(H) X 275(L)

Table 2.2: Principal Specifications (Panasonic EV Energy Corporation, 2005 [57])

recent development of the Toyota Prius battery has confirmed this trend:

The new battery used in 2004 Toyota Prius is 30% more powerful than its predecessor while offering the same specific energy. Because of this improvement, Toyota was able to boost the output of the Prius electric engine from 44 hp to 67 hp and increase the cars 0 60 mph performance from 12.8 seconds to just 10 seconds (Vasilash, 2003 [68]).

The current pace of HEV battery improvement translates to about 30% power increase every 3 years and 6% increase per year. A 10 year projection on HEV batteries' specific power performance under three scenarios (pessimistic, baseline, and optimistic) is depicted in Figure 2.10, below.

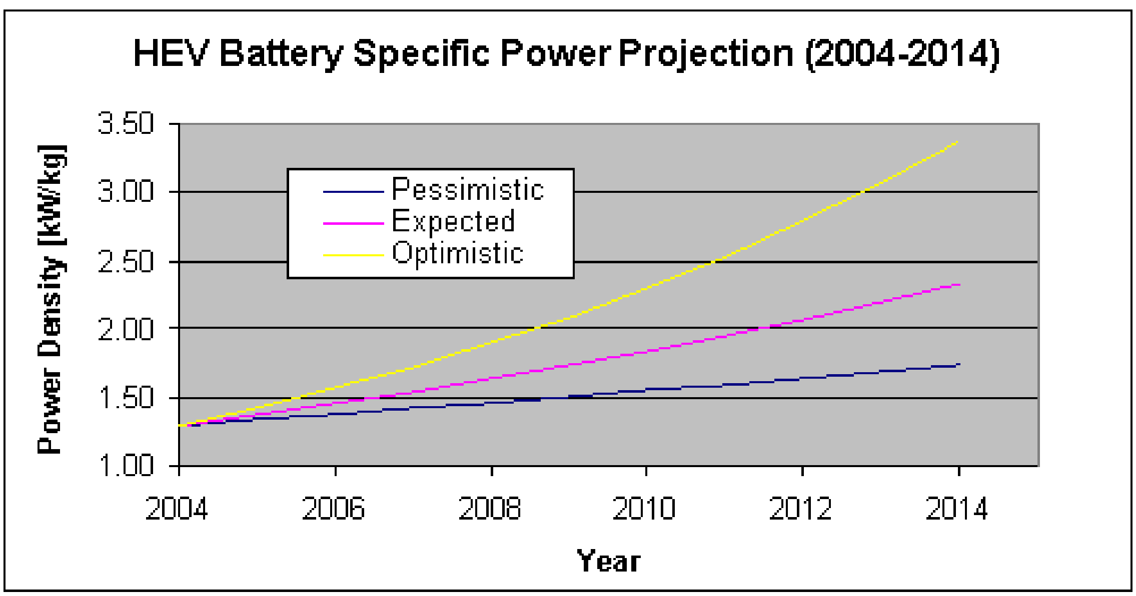


Figure 2.10: Battery Performance Projection

The pessimistic scenario assumes a 3% annual increase, the baseline scenario assumes a 6% annual increase and the optimistic scenario assumes a 10% annual increase. Lithium batteries will slowly replace Ni-MH batteries in HEVs but the projection should provide a good estimate for the industry's battery advancement in the next 10 years.

2.3.4 Battery Cost Overview and Projection

High battery cost continues to be one of the key barriers to making HEVs affordable to average consumers. The Ni-MH battery was barely affordable to automakers upon HEV's market introduction. A steep \$3,000/unit production cost counted as over half of the HEV price premium. The cost went down to around \$1,100 in 2004 and is expected to drop again in the coming years (Terashi, S, 2003 [59]).

The current rate of battery cost reduction, with the above data, accumulates to about 63% every 7 years and 15% per year. A 10 year projection on the expected HEV battery cost is shown in Figure 2.11.

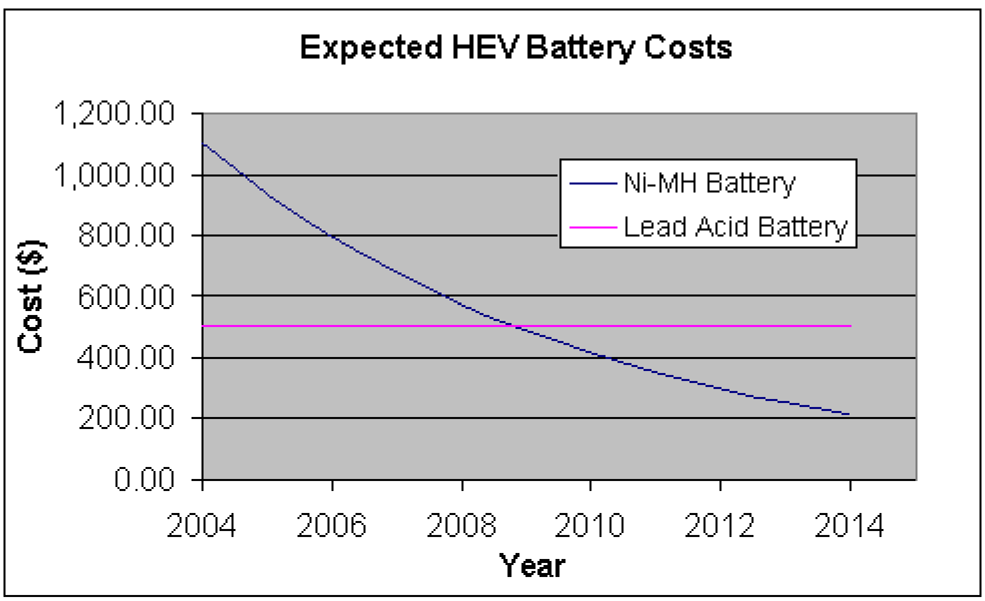


Figure 2.11: Battery Cost Projection

With the today's lead acid battery averaging at 130 W/kg we could power an HEV with an equivalent lead acid battery set for only \$500, far less than the cost of Ni-MH batteries. With the current expected rate of cost reduction, however, the cost of Ni-MH batteries should drop below the cost of lead acid batteries between 2008 and 2009. Low battery cost will not only assure faster HEV market penetration but also help in financing further HEV research and development.

2.4 Diesel Technology and Its Impact on HEVs

2.4.1 Introduction

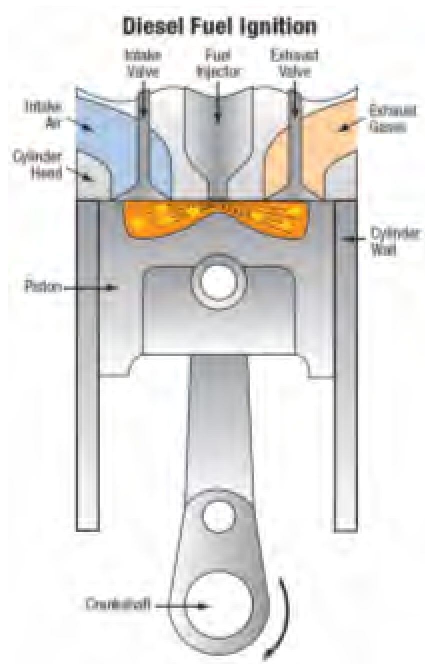


Figure 2.12: Diesel Fuel Injection Engine (US Department of Energy, 2003 [61])

Invented by German engineer Rudolf Diesel in 1892, diesel engines are an internal combustion engines that convert chemical energy in fuel to mechanical energy that moves pistons up and down inside enclosed spaces called cylinders. Diesels differ from gasoline engines primarily in the way the explosions occur. Gasoline engines start the explosions with sparks from spark plugs, whereas in diesel engines, fuel ignites on its own by compressing fuel/air mixture to extremely high temperatures. On average diesel engines are 50% more efficient than gasoline engines and have the potential for another 25% improvement (US Department of Energy, 2003 [61]).

2.4.2 Diesel technology as a competitor to the HEVs

As HEVs gained momentum in the recent years due to surging energy needs and environmental concerns so did diesel powered passenger vehicles. More than 34,000 Jetta TDIs were sold in 2004 compared to 47,000 Toyota Prius (Kitman, J. 2004 [49]). To many consumers diesel powered vehicles have been nice alternatives to HEVs because of their closely matched price, performance and gas efficiency.

	2005 Toyota Prius	2005 VW Jetta TDI
MSRP ($)	20,875	21,815
Horse Power	110	100
Torque (ft-lbs)	82	117
City EPG	60	32
Highway EPG	51	43
0-60 mph (s)	10.7	11.7

Table 2.3: Prius vs. Jetta TDI (Edmund, 2005 [46])

As we can see from the table the newest generation of Toyota Prius holds a clear performance advantage over Jetta TDI at a comparable price level. On top of its lack of efficiency, the Jetta TDI emits roughly twenty times more nitrous oxide, almost three times more hydrocarbons, and twice as much carbon monoxide, even though it is clean by historic diesel standards (Kitman, J. 2004 [49]). As HEVs becomes more and more efficient and environmental friendly, the future of the diesel passenger vehicles as alternatives to the HEVs holds uncertain.

2.4.3 Diesel technology as a compliment to the HEVs

Even though cars that rely solely on diesel engines may never be as efficient as the hybrids the diesel technology could bring fresh improvement to HEVs because of the diesel engine's higher efficiency compared to gasoline engines. Toyota, for example, has been considering the use of diesel engines in its new line of hybrid SUVs that could further improve gas efficiency and reduce emissions by approximately 17 percent (Hofmann, 2004 [47]).

The main long term benefit of using diesel powered HEVs lies in biodiesel fuel. Biodiesel is a clean burning alternative fuel, produced from domestic, renewable resources. Biodiesel contains no petroleum, but it can be blended at any level with petroleum diesel to create a biodiesel blend. It is simple to use, biodegradable, nontoxic, and essentially free of sulfur and aromatics (National Biodiesel Board, 2005 [53]).

Diesel technology is more likely to be used as a compliment, rather than an alternative to the hybrids, and the use of Biodiesel fuel could be the most effective way of reducing oil consumption in the very near future.

Chapter 3

FC Transition and Effects on Energy Use

3.1 Assumptions

3.1.1 FC Transition Timeframe

To model the fuel cell transition, we used the introduction and full penetration dates determined by the 2003-2004 Cornell Engineering Management Hydrogen Team. From their analysis, they expect a 40-year transition, beginning as early as 2020 (Managing Hydrogen, 2004 [24]). President Bush's Hydrogen Initiative plans for a transition launch date of 2020, nearing complete transition around 2040 (Hydrogen Energy Transition, 2004 [25]). One of our team's overriding directives was to decide whether a direct path to fuel cell vehicles was more desirable than a path using hybrids as a transition technology. To address this question, we needed fuel cell transition scenarios for both paths. Many sources view the President's scenario as overly optimistic (Hydrogen Energy Transition, 2004 [25]). More realistically, a fuel cell transition beginning in 2020 will take 40 years to complete. We decided to use this scenario to map our direct path transition, as seen in Figure 3.1.

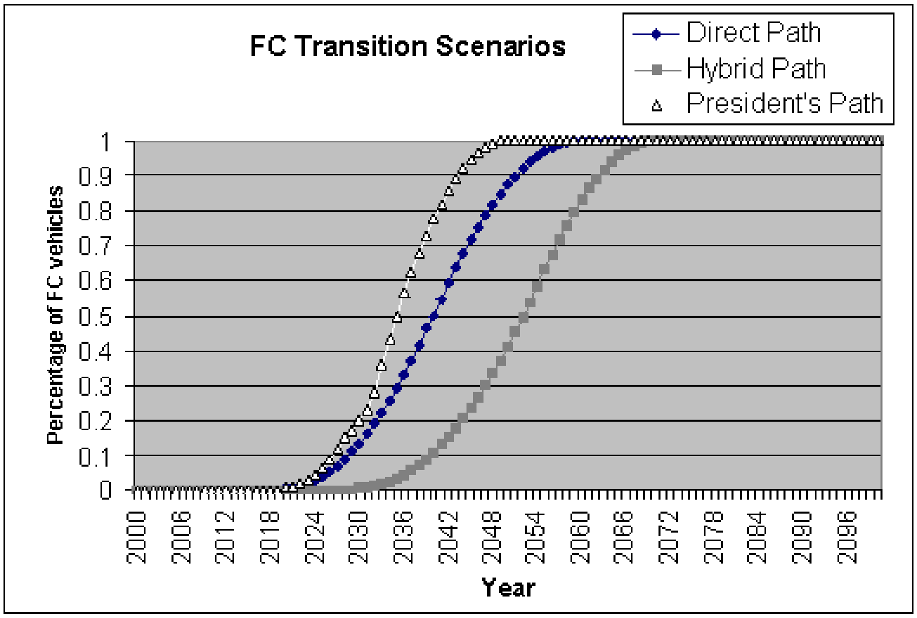


Figure 3.1: FC Transition Scenarios

The hybrid path assumes that hybrid vehicles will successfully penetrate the auto market. If this occurs, the US will begin experiencing significant savings in oil use as soon as 2007. Demand for a fuel cell transition would diminish, delaying the launch date. The model estimates a 10 year delay for the hybrid path, moving the start date to 2030, as seen in Figure 3.1.

3.1.2 Model Formulation

To create penetration models for the fuel cell transition, a technique similar to the hybrid penetration was used. Beginning with a total vehicle miles traveled data for light vehicles, the data was forecasted through 2100. A triangular distribution was then used to shape the transition, following the year parameters for each path (mathworld.wolfram.com, 2004 [17]). This gave us yearly estimates for vehicle miles traveled by fuel cell vehicles, which will be important to analyze energy use and oil consumption.

The model assumes that the hydrogen fuel is generated from natural gas steam reformation. Realistically, the transition will require a switch to more plentiful resources to generate the hydrogen fuel. Options include biomass, coal, and electrolysis, as outlined in Part 3. A renewable resource would be preferable for sustainability.

3.2 FCV vs FCHV Comparison

3.2.1 Drivetrain Comparison

Fuel Cell vehicles (FCVs) mix hydrogen fuel with oxygen from an air compressor to create electricity, water, and some heat (magnet.fsu.edu, 2001 [26]). This occurs in the fuel cell stack, producing between 50 and 90 kW or more (hut.fi, 2002 [27]). This electricity is sent to a power converter that sends the power to a motor, which turns the axle and moves the vehicle (hut.fi, 2002 [27]). The only byproducts of this process are water and heat, achieving an efficiency rate more than twice that of a standard internal combustion engine (Hydrogen Energy Transition, 2004 [25]). Figure 3.2 illustrates this process.

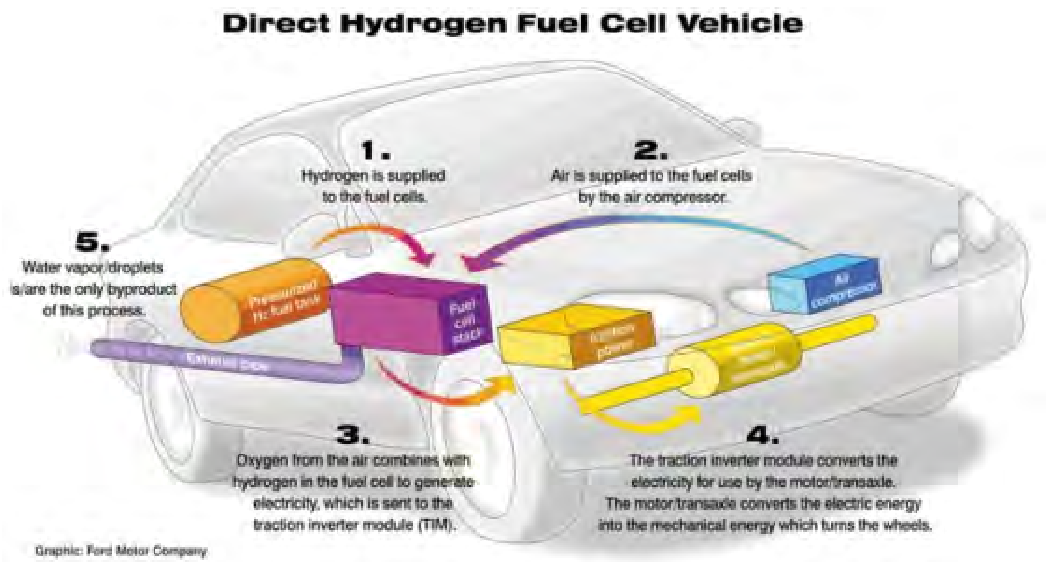


Figure 3.2: FCV Diagram

Fuel cell hybrid vehicles (FCHVs) are FCVs with a secondary battery to provide primary energy during idling and low speeds, and extra energy for acceleration (Hydrogen Energy Transition, 2004 [25]). Power from the fuel cell stack, 90 kW in Toyota's FCHV-4, and the secondary battery, 21 kW in the FCHV-4, are combined at the power control unit, which optimizes efficiency through a sophisticated energy management system (toyota.co.jp, 2004 [28]). The electricity is then sent from the power control unit to the motor to move the vehicle, as shown in Figure 3.3. This drive train is the same used in gasoline hybrid vehicles. In fact, Toyota uses the exact Prius drivetrain for their FCHV, replacing the gasoline motor with a fuel cell stack (Hydrogen Energy Transition, 2004 [25]). Since fuel cell stacks generate DC electricity, the Prius drivetrain is more efficient in the FCHV than with gasoline engines.

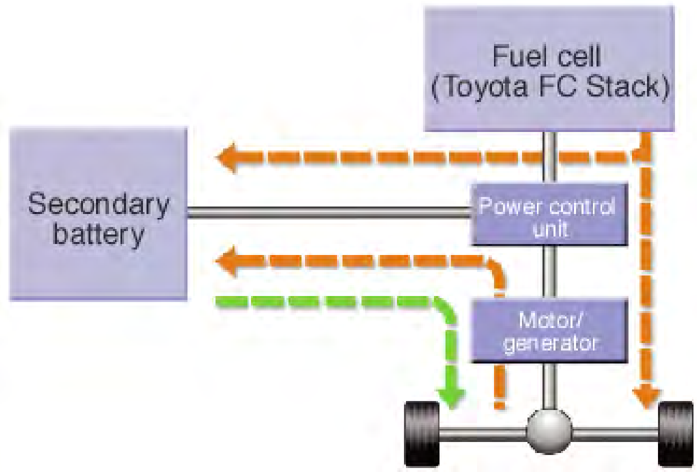


Figure 3.3: FCHV Diagram (toyota.co.jp, 2004 [25])

A major advantage to the hybrid drivetrain is its ability to generate power from braking resistance and use the generated electricity to recharge the secondary battery, as shown in Figure 3.3. Regenerative braking eliminates the need to charge the battery manually from an external power source. A detailed diagram showing the configuration of a FCHV is displayed in Figure 3.4.

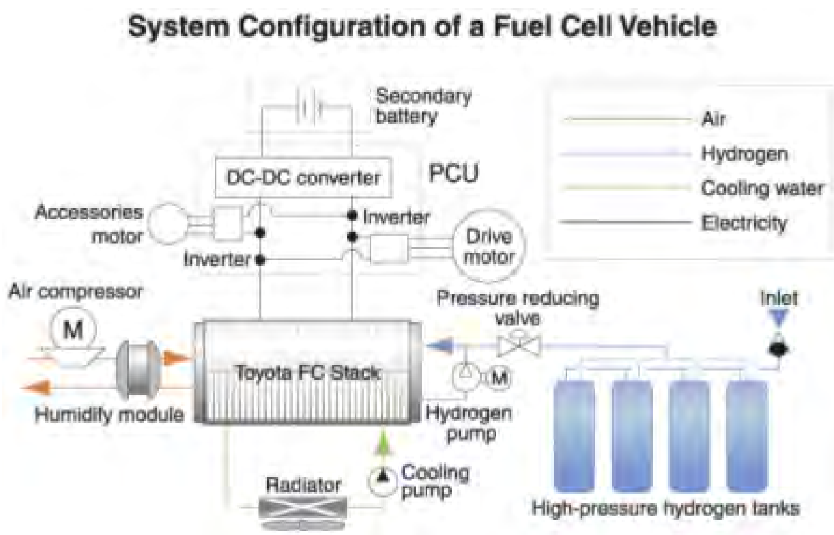


Figure 3.4: FCHV System Configuration (toyota.co.jp, 2004 [28])

3.2.2 Efficiency Comparison

Conventionally, efficiency is measured by the amount of distance traveled in a unit of distance such as "miles per gallon." This measure of efficiency discounts the energy loss during the production/generation of the fuel. A more comprehensive measure is well-to-wheel efficiency. Well-to-wheel measures the percentage of energy retained from the raw materials used to produce the fuel to the motion of the vehicle (Hydrogen Energy Transition, 2004 [25]). Well-to-wheel efficiency is the combination of the efficiency of fuel production (well-to-tank), and the efficiency of the vehicle (tank-to-wheel). By measuring efficiency with well-to-wheel, one can determine the effects on energy consumption and carbon dioxide emissions from the entire fuel technology infrastructure.

The refining process to convert crude oil to gasoline is very efficient, measuring 88%. This well-to-tank efficiency is significantly more efficient than any hydrogen production method. For example, hydrogen produced from natural gas is one of the most common and efficient sources for hydrogen fuel (uregina.ca, 2003 [29]). The current well-to-tank efficiency for hydrogen produced this way is 58% (Hydrogen Energy Transition, 2004 [25]).

While the well-to-tank efficiency for gasoline is very high, the tank-to-wheel efficiency of standard internal combustion engines is quite low, measuring 16%. HEVs, though, achieve approximately 35% efficiency. The resultant total well-to-wheel efficiencies for the two gasoline powered technologies are 14% for ICEs, and 30% for HEV (Hydrogen Energy Transition, 2004 [25]).

Non-hybrid FCVs receive 38% tank-to-wheel efficiency. With the benefits of a secondary battery, FCHVs can achieve 30% more efficiency, measuring 50%. The resultant well-to-wheel efficiencies for FCVs and FCHVs are 22% and 29%, respectively (Hydrogen Energy Transition, 2004 [25]). These numbers have been condensed in Figure 3.5.

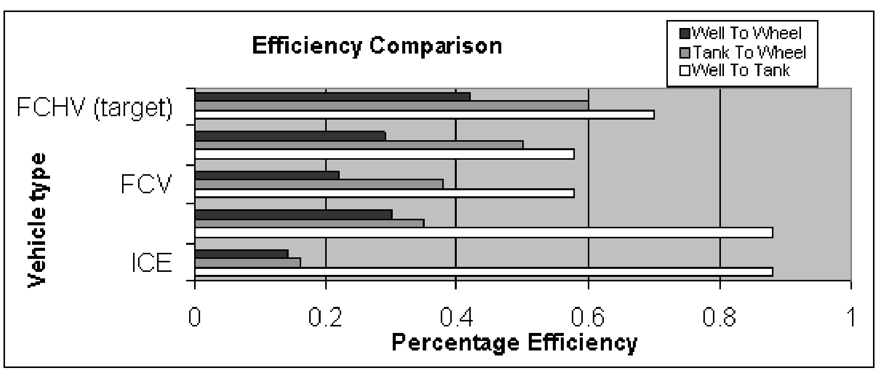


Figure 3.5: Fuel Efficiency Comparison by Vehicle Type

Currently, HEV well-to-wheel efficiency is slightly better than FCHV efficiency. FCHV technology must become more efficient for the technology to be marketable. For this reason, Toyota MC has set target efficiencies for its FCHV. By the time fuel cell technology is ready for mass production, well-to-tank efficiency for hydrogen production should be 70%, and tank-to-wheel vehicle efficiency should be 60%. This would give a total well-to-wheel efficiency of 42%, as shown in Figure 3.5.

3.2.3 Conclusion

FCV is the endpoint technology for the direct path scenario for a fuel cell transition, while FCHV is the endpoint for the hybrid path. To help determine which path is the most viable, we must compare their endpoints.

FCVs are simpler, requiring relatively less sophisticated components. FCVs do not need the complex power control units that FCHVs do. They require no expensive secondary battery, and if hydrogen production efficiency reaches Toyotas target of 70%, then FCVs will have nearly 30% efficiency. One should be careful to note that the technological difference between FCVs and FCHVs is not large, when kept in the larger perspective of the transition, but significant enough to mention.

FCHVs may require more expensive components, but as battery technology progresses, the costs are sure to decline. Furthermore, the benefits to efficiency, which translate to savings in energy consumption and carbon dioxide emissions, add value to FCHVs. FCHV technology can also have lower transition costs, since FCHVs share a drivetrain with HEVs. Toyota uses the eFCV is the endpoint technology for the direct path scenario for a fuel cell transition, while FCHV is the endpoint for the hybrid path. To help determine which path is the most viable, we must compare their endpoints.

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Because of the efficiency, manufacturing transition costs, and steadily declining battery costs, FCHV technology is generally better than FCVs. This means that the endpoint for the hybrid path is more desirable than the endpoint of the direct path. The contest between the two paths is far from over though, as the relative energy consumption and emissions savings have yet to be determined. xact Prius drivetrain in their FCHVs. This lowers the cost to modify manufacturing plants to build fuel cell cars.

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3.3 CAFE Standards and Projections

The inefficiencies of U.S. automobiles were brought into sharp focus by the Arab oil embargo of 1973-1974, and the resulting tripling in the price of crude oil. The fuel economy of new cars had declined from 14.8 mpg in model year 1967 to 12.9 mpg in 1974. To reduce dependence on imported oil, the Energy Policy and Conservation Act of 1975 (EPCA) established corporate average fuel economy (CAFE) standards for passenger cars. Beginning with a standard of 18 mpg in model year 1978, the CAFE standards rose to 27.5 mpg in 1985, essentially doubling the fuel economy for the new car fleet. The EPCA also established fuel economy standards for light-duty trucks, beginning at 17.2 mpg in model year 1979 and rising to 20.7 mpg in 1996 (TEDB, ed. 24 [9]).

Compliance with the CAFE standards is measured by calculating a sales-weighted mean of the fuel economies of a given manufacturer's product line, with domestically produced and imported vehicles measured separately. As originally enacted, the penalty for non-compliance was $5 for every 0.1 mpg below the standard, multiplied by the number of cars in the manufacturers new car fleet for that year (policyalmanac.org, 2004 [8]).

Annually, sales-weighted fuel economies are also estimated for all of the automobiles sold in the U.S., with some manufacuters exceeding the standard, and some falling short of the standard and paying heavy fines. Although these CAFE estimates have generally exceeded the CAFE standards slightly, the actual average on-road fuel economy for passenger cars (measured by dividing the total passenger vehicle miles traveled by the total gallons of gasoline consumed) is much lower. The same has been true for light trucks. As shown in Figures 3.6 and 3.7, the measured on-road fuel economy for both passenger cars and light trucks has never exceeded 85% of the standard. Given that the standards for passenger cars have been constant for twenty years, longer than the average car lifespan, the difference between the CAFE standard and the on-road fuel economy is most likely due to the inaccuracies in the measurement of actual on-road driving conditions. Fuel economy is estimated through tests performed by the EPA and the Department of Energy. These tests, which have been in use since 1985, continue to assume a national speed limit of 55 mph and dont take into account increasing congestion in cities.

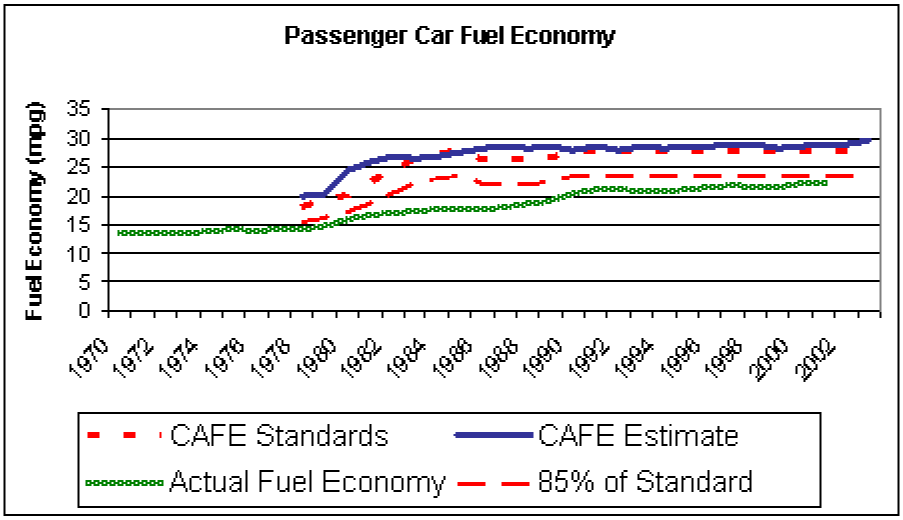


Figure 3.6: Historic data on the fuel economy of passenger cars

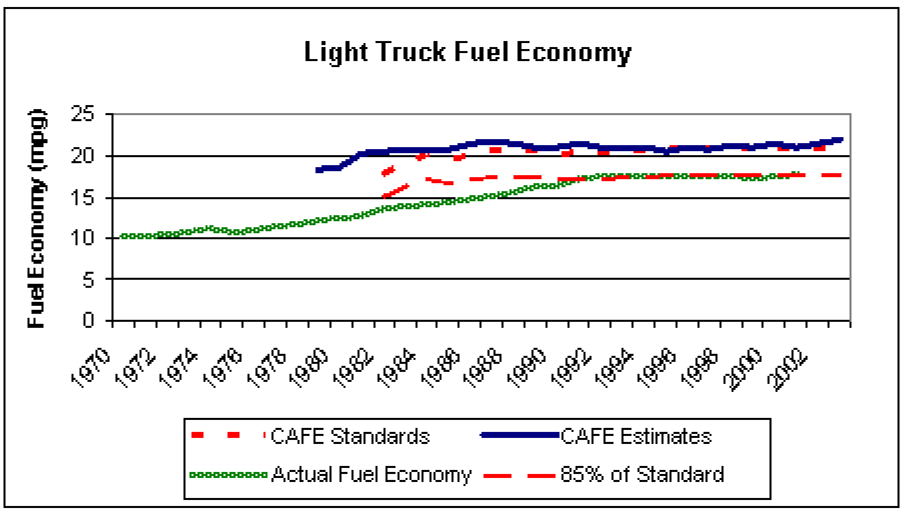


Figure 3.7: Historic data on the fuel economy of light trucks

One of the goals of this project is to understand how the amount of gasoline consumed in the U.S. will be affected by both the emergence of fuel cell vehicles and by the increasing fuel economy of internal combustion engine vehicles. To this end, three scenarios were created to predict future CAFE standards and to project how actual on-road fuel economy will be affected by these increases. One criticism of raising the CAFE standards is that increasing CAFE is a slow and inefficient means of achieving reductions in fuel consumption because of the significant lead times manufacturers need to change model lines and because of the time needed for the vehicle fleet to turn over. It is further argued that higher efficiency will likely be obtained by reducing vehicle size and weight, raising concerns about safety. However, proponents of a CAFE increase have argued that boosting the standards might bring about the introduction of technological improvements that do not compromise features that consumers value, but which would otherwise not be added because these improvements do add to the cost of a new vehicle (policyalmanac.org, 2004 [8]).

A study conducted by the National Academy of Sciences in July 2001 explored raising the CAFE standard for light-duty trucks. It concluded that it was possible to achieve a more than forty percent improvement in light truck and SUV fuel economy over a ten to fifteen year period at costs that would be recoverable over the lifetime of ownership. The study does suggest, however, that there may be safety consequences if manufacturers opt to meet higher standards by reducing vehicle weight.

To address these concerns, one scenario for future CAFE standards (the pessimistic scenario) assumes that no increase will be made to the standards through 2100. An optimistic scenario follows the ACEEE's (American Council for an Energy Efficient Economy) recommendations for fuel economy increases for both passenger cars and light trucks. This scenario increases the fuel economy five percent per year from 2008 to 2017, for a total increase of sixty percent, bringing the standard for passenger cars to 44 mpg and the standard for light trucks to 33.1 mpg. A moderate scenario for CAFE standards increases was also created, which increases the standards by three percent per year from 2008 to 2016, for a total increase of thirty percent for both passenger cars and light trucks.

Historical data on the CAFE standards and measured fuel economy was used to create a linear regression model to forecast fuel economy through 2100. A limit of 85% of the CAFE standard was imposed on the fuel economy projections to reflect a more accurate picture of driving conditions, as discussed above. The results of these forecasts are depicted in Figures 3.8 and 3.9, below. In the optimistic scenario, on-road fuel economies for the total vehicle population reach 37.4 mpg for passenger cars and 28.1 mpg for light trucks by 2029, for a sixty percent increase over todays average fuel economies. On-road average fuel economies increase by thirty percent by 2029 in the moderate scenario to 30.5 mpg for passenger cars and to 23.0 mpg for light trucks.

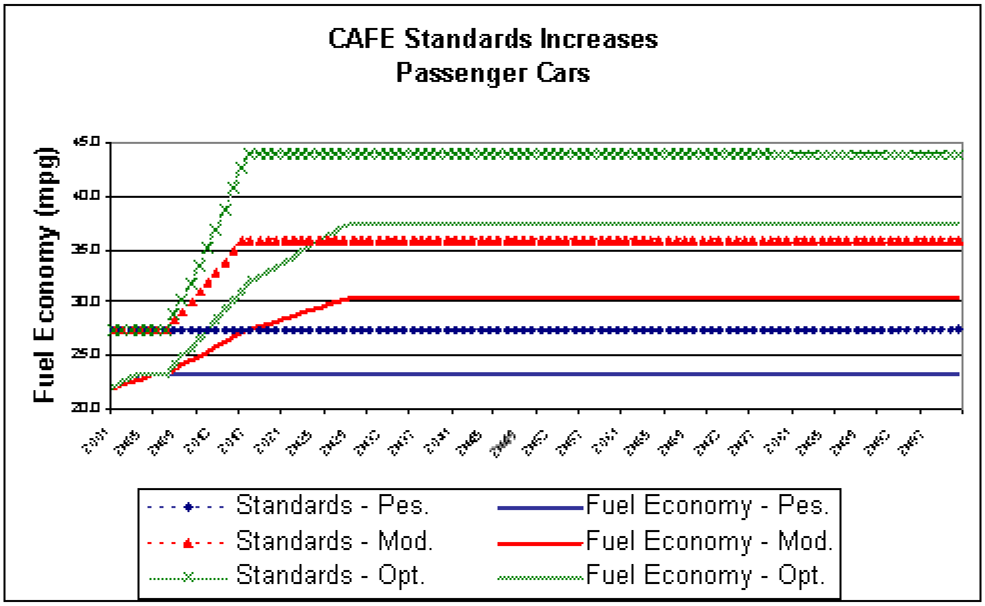


Figure 3.8: Three scenarios for CAFE standards increases for passenger vehicles and the resulting fuel economy increases. Moderate: 30.5 mpg in 2029; Optimistic: 37.4 mpg in 2029

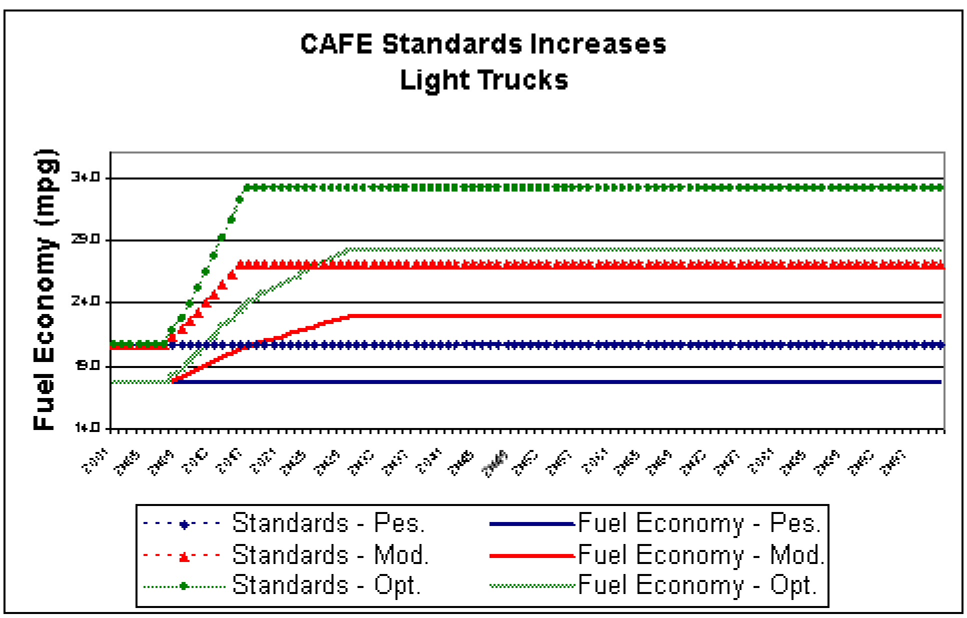


Figure 3.9: Three scenarios for CAFE standards increases for light trucks and the resulting fuel economy increases. Moderate: 23.0 mpg in 2029; Optimistic: 28.1 mpg in 2029

After projecting the total vehicle miles traveled for passenger cars and light trucks, estimates can be made for the amount of fuel saved by increasing CAFE standards. Compared to the pessimistic scenario for CAFE standards (leaving all standards constant), a moderate increase of thirty percent to the standards by 2016 would result in 5.6 billion fewer barrels of crude oil consumed by 2015 and 40.9 billion fewer barrels by 2030. Similary, an aggressive increase in standards, such as that outlined by the optimistic scenario will save 12.1 billion barrels by 2015 and 72 billion barrels by 2030. Figure 3.10 shows the cumulative oil saved by the moderate and optimistic scenarios for CAFE standards increases over the amount consumed by the pessimistic scenario.

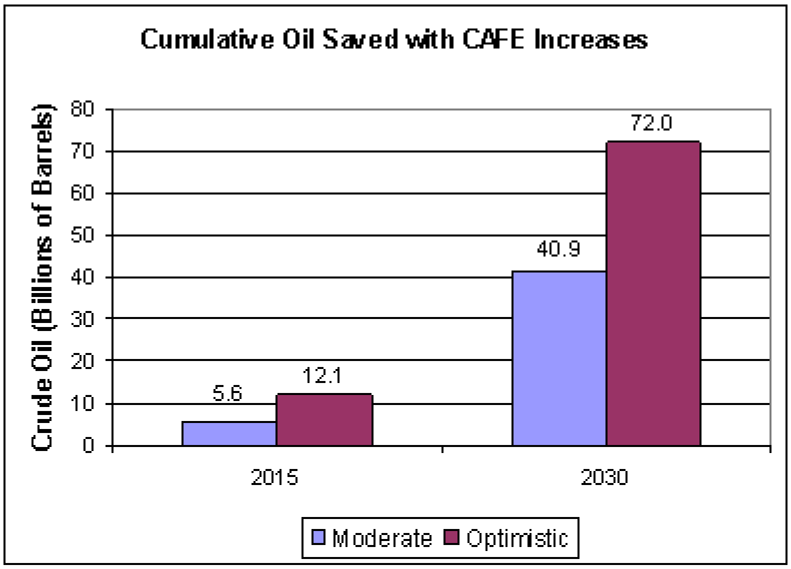


Figure 3.10: Oil savings due to increased CAFE standards

3.4 Projections for Oil Consumption

One of the goals of this project is to understand how using hybrid gasoline-electric vehicles (HEVs) as a transition to fuel cell vehicles will affect energy consumption due to transportation in the United States. To facilitate this, two broad pathways for future vehicle technology were created. The first is a direct pathway from the current internal combustion engine (ICE) vehicles to fuel cell vehicles (FCVs). As discussed previously, this pathway is broken down into two different scenarios: the first, the “direct” scenario, ignores HEVs completely; the second, the “limited” scenario, recognizes the current emergence of HEVs but predicts that they will never exceed a ten percent market share. Both of the scenarios in the direct pathway have the FCV as a common endpoint, and in both, the transition to FCVs lasts from 2020 to 2060.

The second pathway to future vehicles includes a full transition to HEVs and has fuel cell hybrid vehicles (FCHVs) as its endpoint technology. This hybrid pathway is further broken down into three scenarios pessimistic, base, and optimistic that control the speed of HEV market penetration. In all cases, the transition to FCHVs lasts from 2030 to 2070.

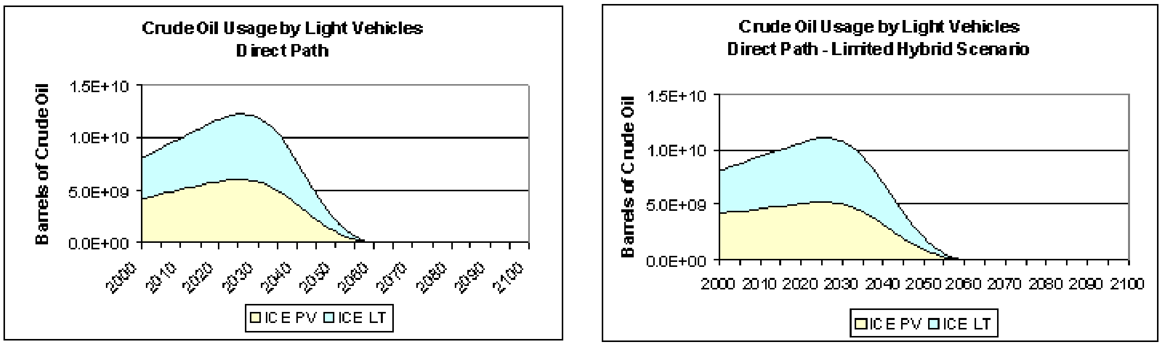
To project the amount of oil consumed with each scenario, the total vehicle miles traveled (VMT) first needed to be projected, as outlined in Chapter 2.2. The total VMT was then divided proportionally into miles traveled by ICE and HEV passenger cars, by ICE and HEV light trucks, and by FCVs/FCHVs. Then, using the HEV penetration scenarios described in Chapter 2.2, average fuel economy estimates were calculated for ICE passenger cars and light trucks, taking into account improvements due to the increased efficiency of HEVs.

The fuel economy of the HEV passenger cars was estimated to be 52 mpg, based on an average of the combined fuel economies of the three hybrid cars currently on the market (Honda Insight, Honda Civic Hybrid, and Toyota Prius). To reflect the difference between the estimated fuel economy and the actual fuel economy of the cars given real on-road driving conditions, the efficiency was reduced by fifteen percent, giving a tank-to-wheel fuel economy of 44.2 mpg for the hybrid passenger cars. This fifteen percent reduction is analogous to the difference between the sales-weighted fuel economies and the measured fuel economies of ICE vehicles, as discussed in Chapter 2.2. Similarly, the fuel economy of light truck hybrids was estimated to be 35 mpg (based on the fuel economy of the upcoming Ford Escape Hybrid), and was reduced by fifteen percent to 29.8 mpg to reflect accurate driving conditions.

These hybrid fuel economies were averaged into the ICE fuel economies for each scenario, taking into account both the different CAFE standards present in each scenario and the percentage of hybrids in each year. These combined fuel economies were then further reduced by thirteen percent to reflect the inefficiencies in well-to-tank oil production, giving a more accurate measure for the well-to-wheel fuel economies. Once the fuel economies and vehicle miles traveled are projected, it is straightforward to calculate the amount of oil consumed in each scenario:

$$\text{Oil (barrels)} = \text{VMT} \div \text{Fuel Economy (mpg)} \div 19.69 \text{ (gal/barrel)}$$

The constant 19.69 represents the gallons of gasoline that can be processed from one barrel of crude oil. As fuel cell vehicles consume no oil, this calculation only applies to the ICEs and HEVs.

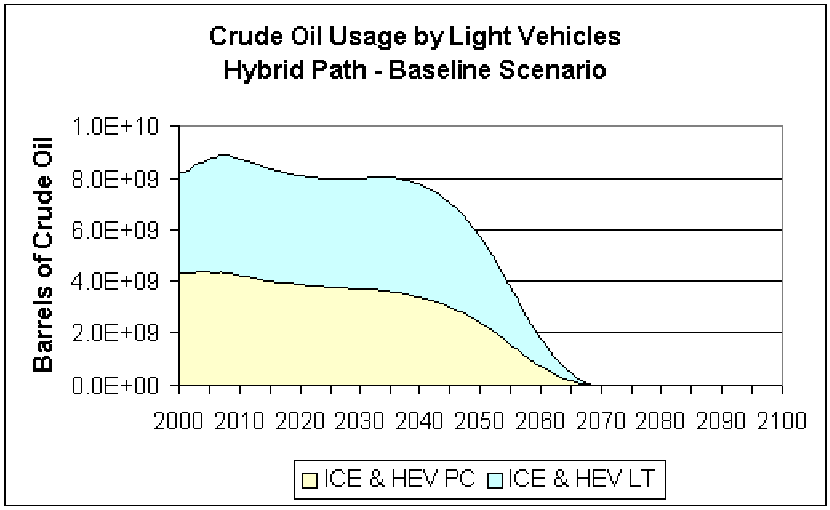


(a) Direct scenario – no HEVs

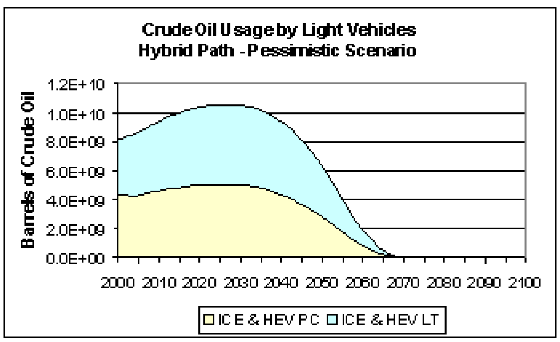
(b) Limited scenario – 10% HEV market penetration

Figure 3.11: Oil savings due to increased CAFE standards

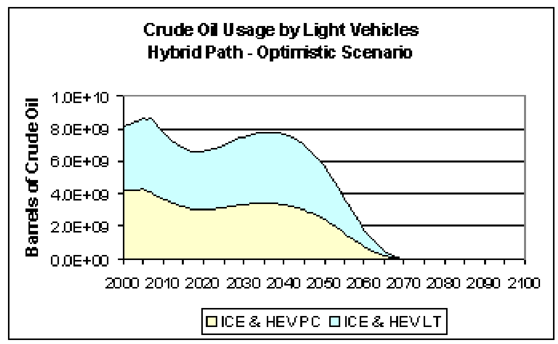
The graphs above show the annual oil consumption for the United States if a transition to fuel cells was made between 2020 and 2060. Oil consumption in the direct scenario peaks in 2026 at 12.3 billion barrels; consumption peaks in the limited scenario in 2026 at 11.1 billion barrels. By 2060, when the fuel cell transition finishes, 38.9 billion fewer barrels of oil are consumed following the limited scenario than the direct scenario. Again, in the direct and limited scenarios, it is assumed that no increases to CAFE standards would be made, so the oil savings in the limited scenario are due solely to the slight increase in fuel economy from the ten percent of hybrid cars and trucks in the market.



(a) Baseline scenario – assumes moderate CAFE increases and moderately-paced HEV penetration



(b) Pessimistic scenario – assumes no CAFE increases and slow HEV penetration.



(c) Optimistic scenario – assumes aggressive CAFE increases and rapid HEV penetration.

Figure 3.12: Three scenarios for a transition from ICEs to HEVs to FCHVs

The graphs in Figure 3.12, above, show the annual oil consumption for the United States if a transition to fuel cell hybrid vehicles was made from 2030 to 2070. Each of the scenarios contains a full transition to HEVs, but varies in the time of completion. In the pessimistic scenario, hybrids reach one hundred percent of the non-fuel cell market in the pessimistic scenario by 2080, in the baseline scenario by 2050, and in the optimistic scenario by 2025. Because the fuel cell transition ends in 2070 for all hybrid scenarios, HEVs never overcome the ICE market completely in the pessimistic scenario, and this is one reason why there is more oil consumed in the pessimistic hybrid scenario by 2070 than in the direct scenario, as shown below in Figure 3.13.

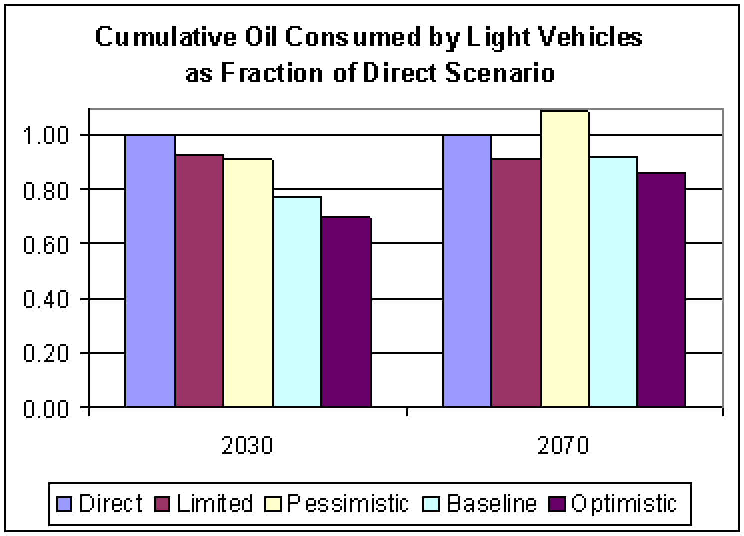


Figure 3.13: Cumulative barrels of oil consumed by light vehicles in the U.S. beginning in 2000, for various transition pathways, as a fraction of oil consumed in the direct scenario

The biggest reason for the small difference in oil consumption between the direct and hybrid pathways is the different timings of the two fuel-cell transitions. While the direct transition to fuel cells finishes in 2060 (i.e., no oil is consumed by light vehicles from 2060 to 2070), the hybrid transition to fuel cells does not end until 2070. Even with this difference, the baseline and optimistic scenarios in the hybrid pathway still consumes less oil overall than the direct scenario due to the increased fuel economies of hybrid vehicles.

3.5 Projections for Energy Use

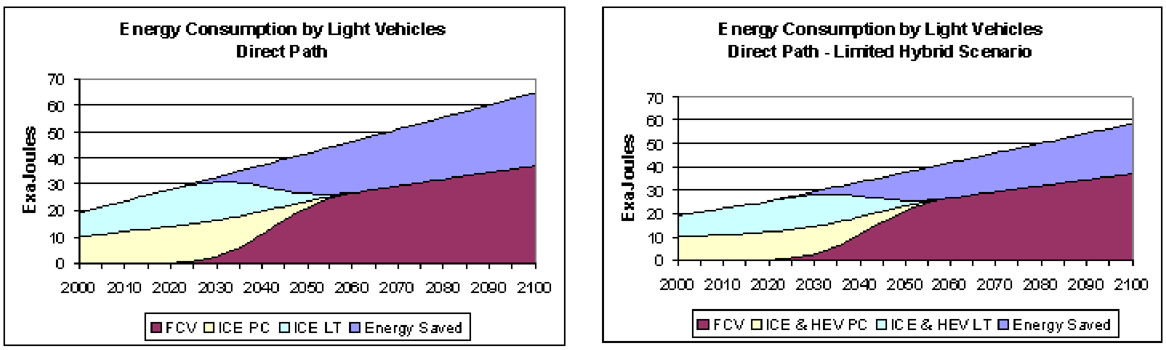
Fuel cell vehicles consume no crude oil, so it is difficult to see how much energy would be saved by a transition to fuel cell vehicles just by looking at graphs of oil consumption. Because the two pathways have two different endpoints (fuel cell vehicles versus fuel cell hybrid vehicles), it is important to look not just at the oil consumed, but the total energy used. To further understand how the transition will affect total energy use, graphs of the energy used by light cars and trucks were created using the five scenarios described in the previous section. Energy for ICEs and HEVs was calculated from the projected vehicle miles traveled (VMT) as follows:

$$\text{Energy (J)} = \text{VMT} \div \text{Fuel Economy (mpg)} \times 1.20{\times}10^{8}\ \text{(J/gal)}$$

The constant $1.20{\times}10^{8}$ is the total energy in joules present in one gallon of gasoline. The energy consumed by fuel cell vehicles can be calculated using a similar equation:

$$\text{Energy (J)} = \text{VMT} \div \text{Fuel Economy (miles per kg)} \times 1.19\times10^{8}\ \text{(J/kg)}$$

The constant 1.19×10^{8} is the total energy in joules present in one kilogram of hydrogen. The difference between the direct and hybrid pathways becomes evident here, because the well-to-wheel fuel economy of a fuel cell vehicle is 29.5 miles per kilogram (mpk), while the well-to-wheel fuel economy of a fuel cell hybrid vehicle is 38.8 mpk.

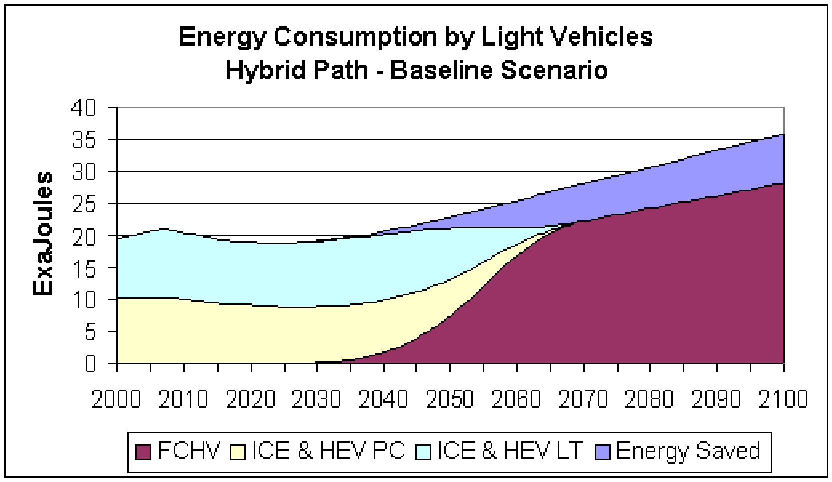


(a) Direct scenario – no HEVs

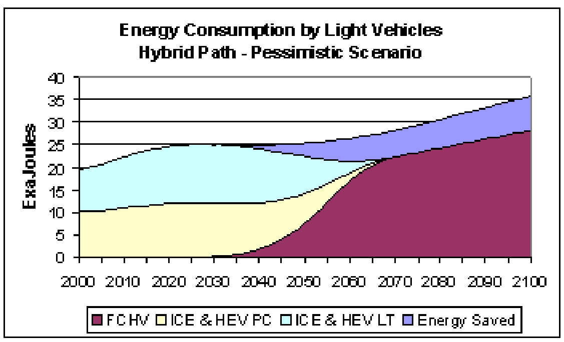
(b) Limited scenario – 10% HEV market penetration

Figure 3.14: Energy used in two scenarios for a direct transition from ICEs to FCVs

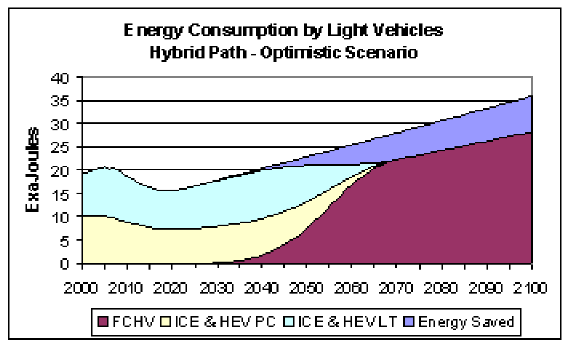
The graphs in Figure 3.14, above, show the annual energy usage for the United States if a transition to fuel cell vehicles was to be made between 2020 and 2060. The dark blue region of the graph labeled "Energy Saved" represents the addition energy required by ICEs and HEVs if no transition to fuel cell vehicles was made. Energy consumed by ICEs and HEVs peaks in 2026 at 29.1 EJ in the direct scenario and at 26.2 EJ in the limited scenario. As with oil consumption, this savings of 2.9 EJ is due solely to the increased fuel economy of the ten percent hybrid vehicles in the market.



(a) Baseline scenario – assumes moderate CAFE increases and moderately-paced HEV penetration



(b) Pessimistic scenario – assumes no CAFE increases and slow HEV penetration



(c) Optimistic scenario – assumes aggressive CAFE increases and rapid HEV penetration

Figure 3.15: Energy used in three scenarios for a transition from ICEs to HEVs to FCHVs

The graphs in Figure 3.15, above, show the annual oil consumption for the United States if a transition to fuel cell hybrid vehicles was made from 2030 to 2070. Each of the scenarios contains a full transition to HEVs, but varies in the time of completion, as in the oil projections discussed in the previous section. Unlike the oil projections, the projections for annual energy use take into account the increased efficiency of the FCHVs over the FCVs. This allows the hybrid pathway to save more cumulative energy than the direct pathway, as shown in Figure 3.16, even though the transition to fuel cells begins ten years earlier in the direct pathway. Figure 3.17 shows the difference between the two pathways over time.

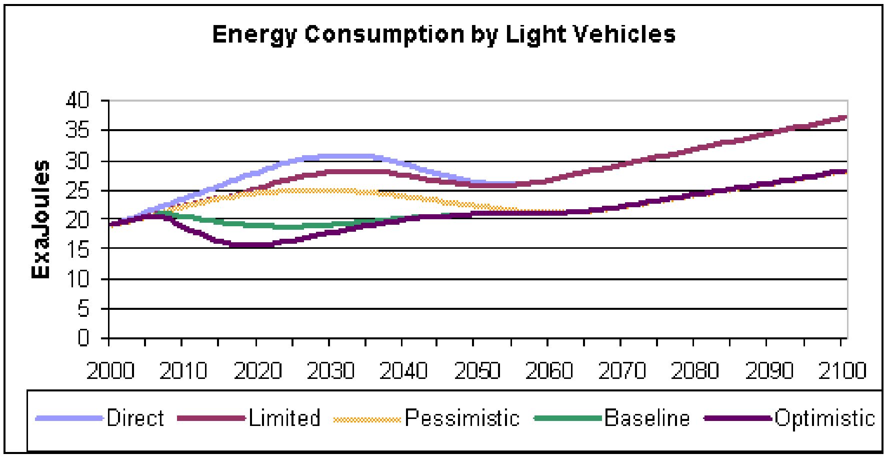


Figure 3.17: Annual energy consumption by light vehicles for five transition scenarios

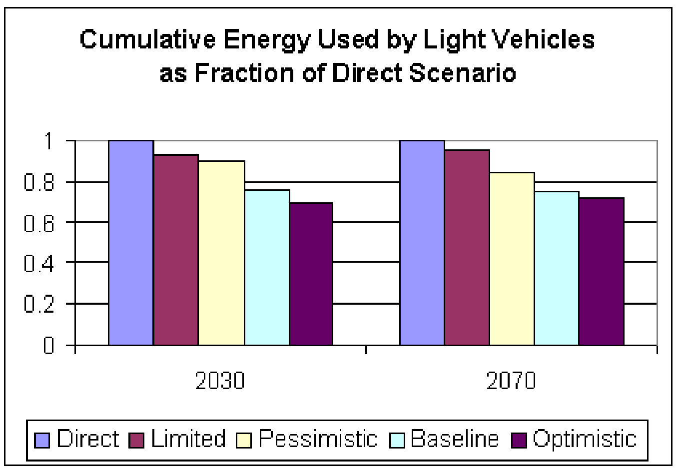


Figure 3.16: Cumulative energy consumed by light vehicles in the U.S. beginning in 2000, for various transition pathways, as a fraction of energy consumed in the direct scenario

3.6 CO_2 Projections

While the results of the oil and energy consumption projections are helpful in understanding the endpoint technologies represented in the direct and hybrid pathways to fuel cells, it is also important to look at the carbon dioxide (CO_2) emissions produced in all scenarios. There are a number of ways to produce hydrogen. However, hydrogen produced by the steam reformation of methane produces the least amount of CO_2 on a well-to-tank basis than production by other fossil fuels, so we chose to deal exclusively with this method in this section. The figure below shows the amount of well-to-tank and tank-to-wheels carbon dioxide produced by various transportation fuels. One advantage of a hydrogen-powered car is that when the hydrogen is burned, the only by-product is water. This means that there are no tank-to-wheels carbon dioxide emissions in a fuel cell vehicle, and the only emissions are caused by hydrogen production.

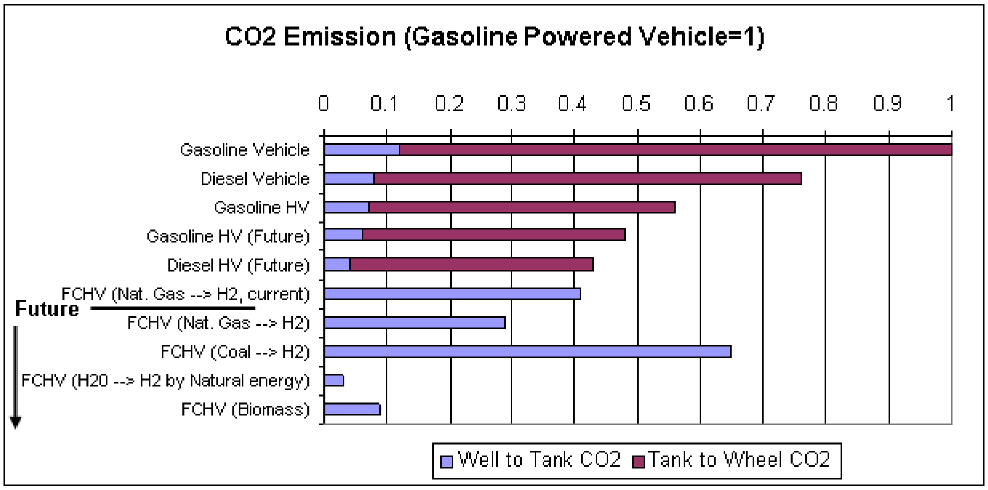


Figure 3.18: Carbon dioxide emissions of vehicles relative to an ICE (toyota.co.jp, 2004, [28])

Hydrogen production by the steam reformation of methane follows this process:

$$CH_4 + H2O <-> 3H2 + CO$$

$$CO + H2O <-> H2 + CO_2$$

Following this reaction, every mole of methane produces one mole of carbon dioxide and four moles of hydrogen. If all gases were treated as ideal, this would lead to 5.46 kg of carbon dioxide produced for every kilogram of hydrogen. However, inefficiencies in the steam reformation process cause the CO2 emissions to be much higher: 9.60 kg CO_2 per kg H2. The calculation of this number is described further in the Appendix. This value only reflects inefficiencies in the production of hydrogen however, so the CO_2 emissions are further increased by 12.5% to represent upstream inefficiencies from the transportation and collection of methane, resulting in well-to-tank emissions of 10.8 kilograms of carbon dioxide per kilogram hydrogen (Krieth, 2003 [26]).

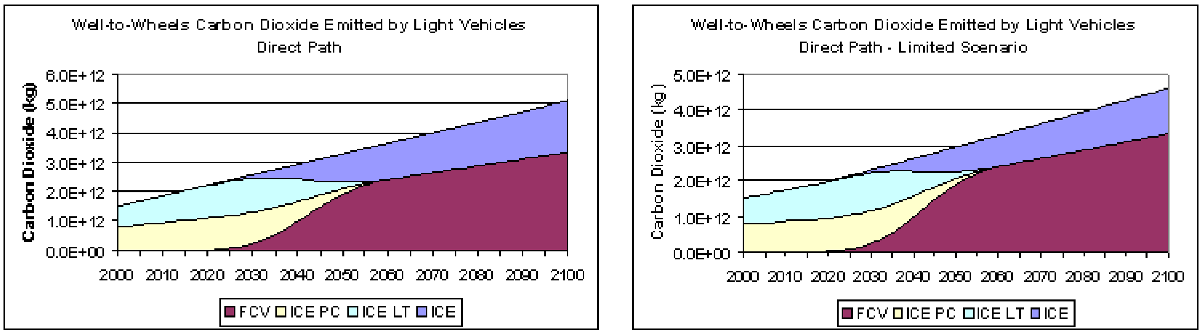
Once again, beginning with a projection of the total vehicle miles traveled (VMT), it is straightforward to project the annual levels of CO_2 emitted from passenger cars and light duty trucks. For FCVs and FCHVs:

$$CO_2 \text{ (kg)} = \text{VMT} \div \text{Fuel Economy (mpk)} \times 10.8 \text{ (kg } CO_2 \text{ per kg H2)}$$

The calculation is similar for ICEs and HEVs:

$$CO_2 \text{ (kg)} = \text{VMT} \div \text{Fuel Economy (mpg)} \times 9.46 \text{ (kg } CO_2 \text{ per gallon gasoline)}$$

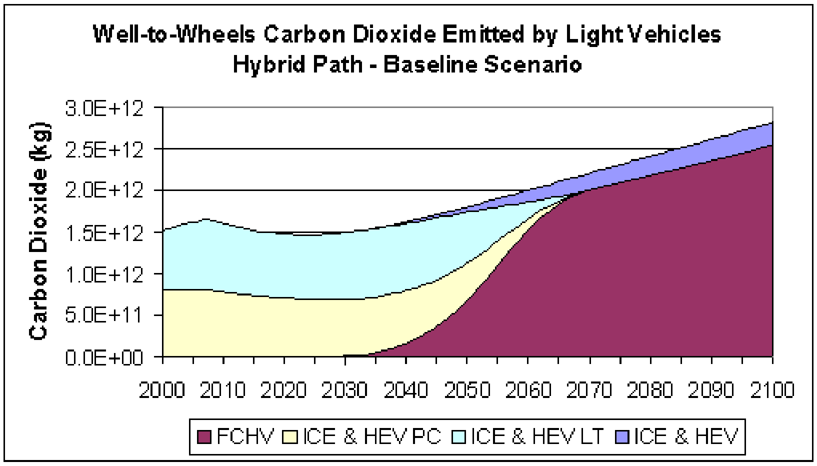
The number 9.46 kilograms of carbon dioxide per gallon of gasoline is a constant which takes into account the upstream inefficiencies in gasoline production (ucsb.edu, 2002 [10]).



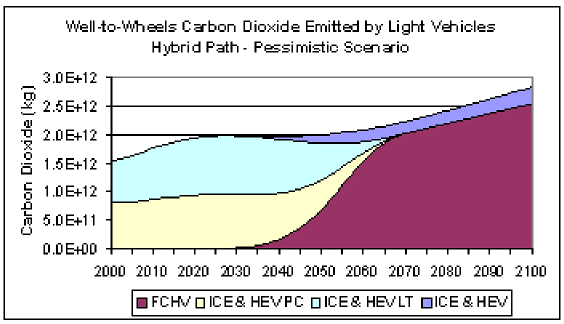
(a) Direct scenario – no HEVs (b) Limited scenario – 10% HEV market penetration

Figure 3.19: Carbon dioxide emissions in two scenarios for a transition to fuel cells vehicles

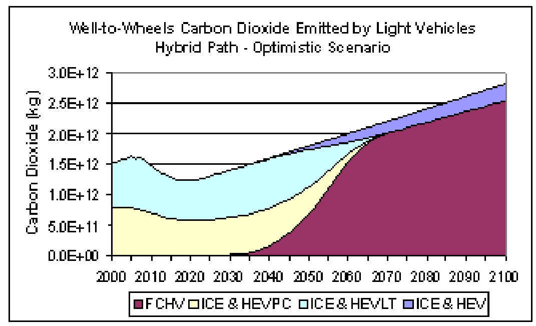
Figure 3.19 shows the carbon dioxide emissions in the United States if a transition to fuel cell vehicles was made from 2020 to 2060, following the direct pathway. The dark blue region of the graphs, labeled "ICE," represents the additional carbon dioxide emissions by light vehicles if a transition to fuel cells was not made. Although the two scenarios share the same endpoint technology (FCVs), the cumulative amount of carbon dioxide emitted in the limited scenario is lower, due to the higher efficiency of the hybrid vehicles.



(a) Baseline scenario – assumes moderate CAFE increases and moderately-paced HEV penetration



(b) Pessimistic scenario – assumes no CAFE increases and slow HEV penetration



(c) Optimistic scenario – assumes aggressive CAFE increases and rapid HEV penetration

Figure 3.20: Carbon dioxide emissions for a transition from ICEs to HEVs to FCHVs

Figure 3.20 shows the annual carbon dioxide emissions for the U.S. if a transition were to be made to FCHVs from 2030 to 2070. The dark blue area of the graph labeled "ICE & HEV" represents the additional emissions by ICEs and HEVs if a transition to fuel cells was not made. This area is smaller than the corresponding area in the graphs depicting the direct pathway transition (Figure 3.19) because the fuel economy of the HEV is closer to the fuel economy of the FCHV than the ICE is to the FCV. However, the cumulative emissions by light vehicles in the hybrid pathway are lower than that in the direct pathway, due to the increased efficiency of the FCHVs.

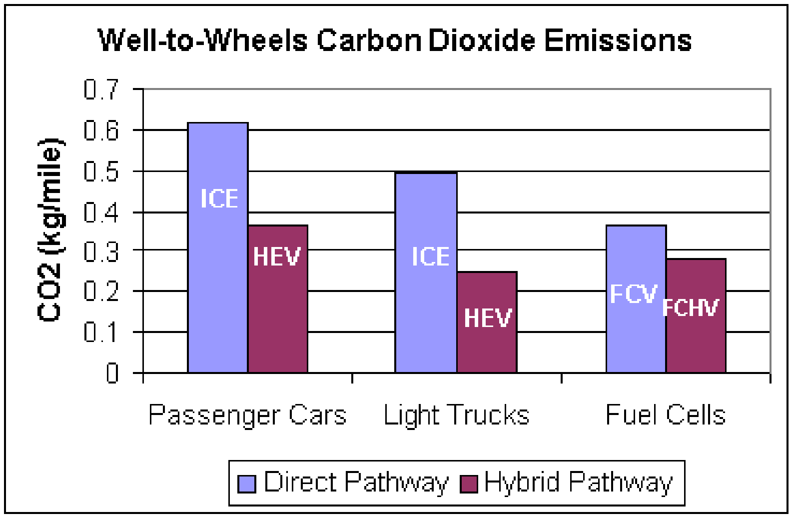


Figure 3.21: CO_2 emissions for various vehicles comprising the direct and hybrid pathways

Chapter 4

Emissions

4.1 Types and Controls

4.1.1 Emissions Types

Internal combustion engine vehicles produce four major categories of hazardous emissions: smog, hydrocarbons, carbon monoxide, and nitrogen oxides. Smog, the main byproduct of tailpipe emissions, is the result of unhealthy levels of ozone, O3, in the atmosphere (Allergy Consumer Review, 2003 [30]). Ozone is not directly emitted into the air from a vehicle. It is produced when hydrocarbons and volatile organic gases mix with nitrogen oxides from evaporated petroleum products in the sunlight (autorepair.about.com, 2004 [31]). Large amounts of smog can be very unhealthy. A 1984 study by Dr. Kay Kilburn showed that children raised inInternal combustion engine vehicles produce four major categories of hazardous emissions: smog, hydrocarbons, carbon monoxide, and nitrogen oxides. Smog, the main byproduct of tailpipe emissions, is the result of unhealthy levels of ozone, O_3, in the atmosphere (Allergy Consumer Review, 2003 [30]). Ozone is not directly emitted into the air from a vehicle. It is produced when hydrocarbons and volatile organic gases mix with nitrogen oxides from evaporated petroleum products in the sunlight (autorepair.about.com, 2004 [31]). Large amounts of smog can be very unhealthy. A 1984 study by Dr. Kay Kilburn showed that children raised in the South Coast Air Basin, which includes Los Angeles, suffer from up to 15% decrease in lung function, compared to those in less polluted areas (Allergy Consumer Review, 2003 [30]). Senior citizens are also highly vulnerable to the dangers of smog. During the “Great Smog Disaster” of London in 1952, four thousand people died from airborne pollutants, many of whom were over the age of 50 (lbl.gov, 2000 [32]). As Figure 4.1 shows, most smog is caused by vehicle exhaust. the South Coast Air Basin, which includes Los Angeles, suffer from up to 15% decrease in lung function, compared to those in less polluted areas (Allergy Consumer Review, 2003). Senior citizens are also highly vulnerable to the dangers of smog. During the Great Smog Disaster of London in 1952, four thousand people died from airborne pollutants, many of whom were over the age of 50 (lbl.gov, 2000). Figure 4.1 shows, most smog is caused by vehicle exhaust.

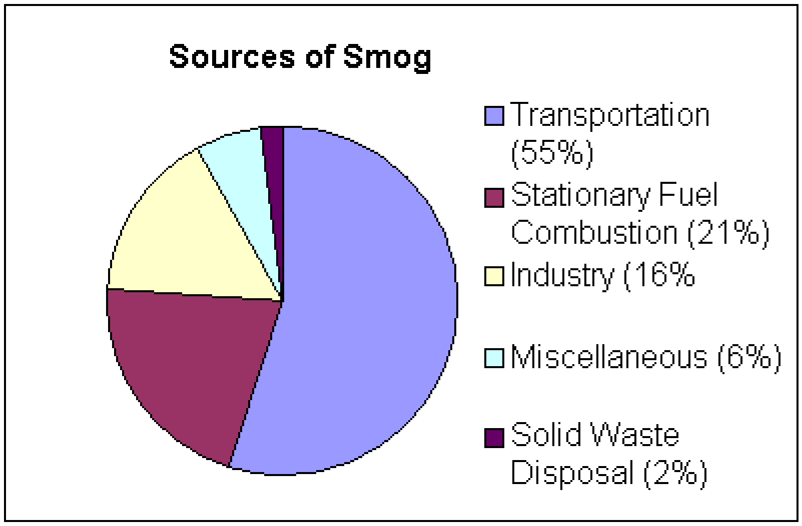


Figure 4.1: Sources of Smog

Hydrocarbons, hazardous vehicle emissions that cause smog, are basically unburned fuel. Besides engine exhaust, hydrocarbons can also come from fuel system evaporation and vapors from the crank-case (autorepair.about.com, 2004 [31]). Carbon monoxide, a very dangerous vehicle emission, forms during incomplete combustion, and is primarily emitted from the tailpipe. When breathed in, carbon monoxide interferes with the circulation of blood in the body, resulting in poor coordination, unhealthy cardiovascular respiration, headache, weakness, and nausea (nsc.org, 2004 [33]). In high doses, carbon monoxide is fatal. Figure 4.2 shows that vehicles produce the majority of carbon monoxide in the US. Nitrogen oxides, NO_x, form during combustion at temperatures above 2500°F (autorepair.about.com, 2004 [31]). These emissions are dangerous for their contribution to the creation of smog.

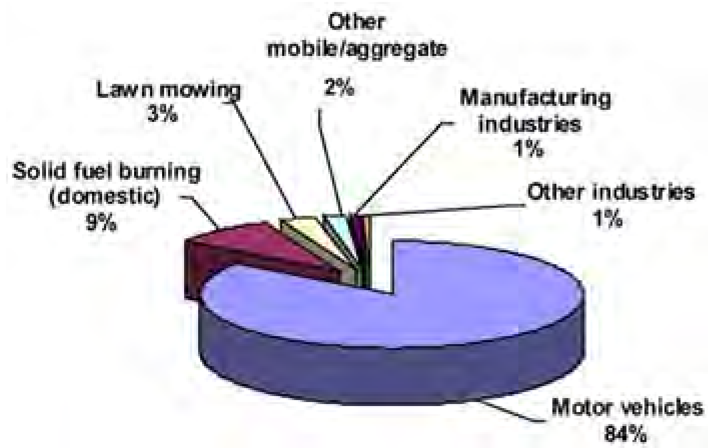


Figure 4.2: Sources of Carbon Monoxide in the US (Allergy Consumer Review, 2003 [30])

4.1.2 Emissions Controls

ICE vehicles have developed methods of reducing vehicle emissions. These systems include: fuel injection, catalytic converter, fill pipe restrictor, positive crankcase ventilation, evaporative control system, and improved combustion system (autorepair.about.com, 2004 [31]). Fuel injection is designed to supply fuel to the engine in precise amounts, using feedback systems that monitor atmospheric conditions and exhaust to adjust the amount of fuel supplied. The catalytic converter converts harmful pollutants into carbon dioxide and water. The fill pipe restrictor prevents larger diameter fuel nozzles from entering the car, which typically supply leaded fuel. Positive crankcase ventilation takes vapors from the crankcase and recycles them back into the air fuel mixture, where the vapors are subsequently burned (autorepair.about.com, 2004 [31]). The fuel tank also has a closed ventilation system that recycles fuel vapors, called the evaporative control system. Finally, design changes in the 1960s helped reduce hydrocarbon and carbon monoxide emissions through small changes to the carburetor, primary air system, and spark timing controls (autorepair.about.com, 2004 [31]).

4.2 Emissions Legislation

4.2.1 US Emission Controls History

Air quality legislation in the US dates back as early as 1881, when the cities of Cincinnati and Chicago passed laws to limit the amount of industrial air pollution being generated (American

Meteorological Society, 2003 [36]). The first piece of federal legislation on the issue came with the Air Pollution Control Act of 1955, which did little more than make citizens more aware of the issue (Green Nature, 2005 [37]). Eight years later, Congress passed the Clean Air Act of 1963, outlining standards for stationary sources of air pollution.

Air pollution legislation for vehicles did not come until the Clean Air Acts amendment in 1970 (American Meteorological Society, 2003 [36]). This major revision of previous air quality legislation outlined sweeping, ambitious standards and goals for stationary and mobile sources of pollution. The 1970 amendment also created the EPA to administer and oversee the legislations implementation (Plain English Guide, 2004 [38]). The technological and economic challenges that the automobile and other industries faced to meet these requirements seemed insuperable, so the deadlines were extended in 1977's Clean Air Act amendment (American Meteorological Society, 2003 [36]).

For over a decade, emissions and air pollution legislation saw no revision. Then, in 1990, another major revision of the Clean Air Act was passed. This amendment focused on five main areas: air-quality standards, motor vehicle emissions and alternative fuels, toxic air pollutants, acid rain, and stratospheric ozone depletion (American Meteorological Society, 2003 [36]). The amendment also introduced the Tier 1 standards for vehicles. This new standard called for 40% reduction in all emissions types from previous standards, set to become effective by 1994 (epa.gov, 2002 [39]). Figure 4.3 shows how effective the Clean Air Act has been to reduce ozone (smog), carbon monoxide, and nitrogen dioxide levels in the United States. This figure shows results for the entire fleet of operating vehicles, not just new ones. It is derived from estimates of vehicle travel and total fuel consumed.

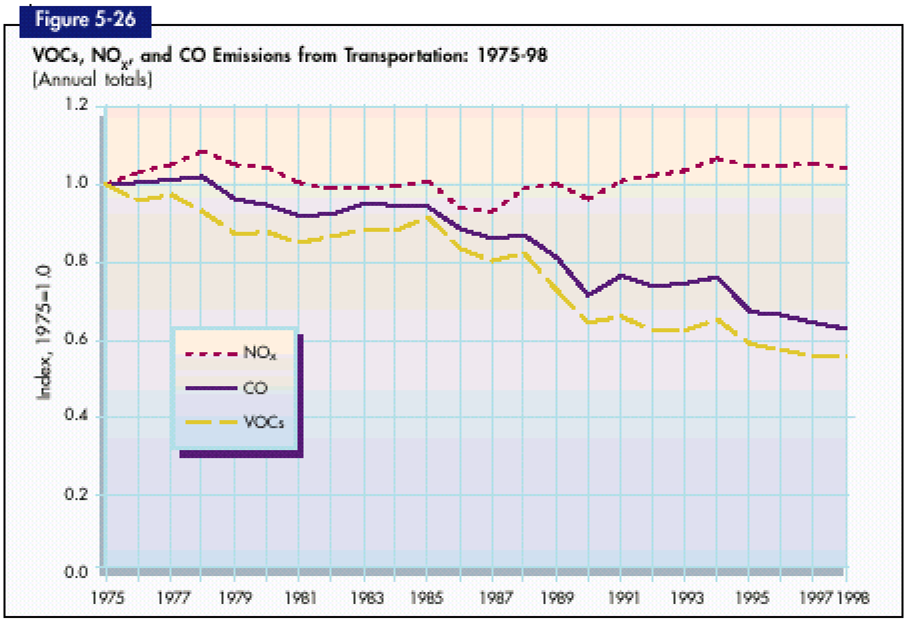


Figure 4.3: US Emissions Levels (bts.gov, 2005 [71])

In 1998, the Clinton Administration made agreements with states in the northeast to voluntarily produce cleaner cars before the Clean Air Act mandated it (epa.gov, 2002 [39]). These new vehicles were called National Low Emission Vehicles (NLEVs), and produced half the amount of nitrogen oxides than the Clean Air Act standards (NLEV light trucks saw only a 17% reduction). In the following year, Congress released its Tier 2 standards for vehicle emissions (epa.gov, 2002 [39]). These standards placed the same level of emissions restrictions on both passenger vehicles and light trucks, addressing the concern over increasing SUV sales and its impact on the environment (Green Nature, 2005 [37]).

4.2.2 California Emission Controls History

The state of California has always pioneered air quality legislation for the United States. The first incident of smog in Los Angeles in 1943 causes many in the city to feel nausea, eye irritation, and respiratory discomfort. Calling it a "gas attack," citizens blamed a local butadiene plant, but the problem persisted after its shutdown (California ARB, 2003 [40]). Subsequent air pollution concerns lead to the Air Pollution Control Act of 1947, which created an Air Pollution Control District in every county in the state (pbs.org, 2003 [42]).

The first auto emission tailpipe standards for hydrocarbons and carbon monoxide, as well as mandates for positive crank-case ventilation for all passenger vehicles sold, are introduced in California during the early 1960s, the first of such legislation in the world (platinum.matthey.com, 2004 [41]). In 1967, the California Air Resources Board, or CARB, is formed to administer air quality legislation. In the following years, the state amended and revised its vehicle emissions several times, introducing new and innovative policies to keep dangerous emissions controlled.

In 1990, California created a new standard system for classifying vehicle emissions rates. Coming into effect in 1994, the new standard system classified all vehicles into the following categories: transitional low emission vehicles (TLEV), low emission vehicles (LEV), ultra-low emission vehicles (ULEV), and zero emission vehicles (ZEV) (platinum.matthey.com). Figure 4.4 shows the standards for different emissions at each level.

TLEV, LEV, ULEV and ZEV Standards for Passenger Cars

Class	NMOG g/m	CO g/m	NOx g/m
TLEV	0.156	4.200	0.600
LEV	0.090	4.200	0.300
ULEV	0.055	2.100	0.300
ZEV	zero	zero	zero

based on 100,000 miles durability

Figure 4.4: California LEV Vehicle Classification (platinum.matthey.com, 2004 [41])

The 1998 follow-up to the LEV program, called LEV-II, created stronger regulations for the four existing categories, as well as creating two new ones: super-ultra-low emissions vehicle (SULEV), and partial-zero emissions vehicle (PZEV). This new system expected light trucks, including SUVs, to meet the same emissions standards as passenger vehicles, placing a burden on the auto industry (platinum.matthey.com, 2004 [41]). LEV-II standards planned to go into effect by 2004, and outlined subsequent tightening of emissions through 2016.

4.3 Emissions of Hybrid Gasoline-Electric and Fuel Cell Vehicles

Although the effect of the transition to fuel cell vehicles on carbon dioxide emissions was already studied in Section 3.6, it is also useful to look at how the transition affects other pollutants emitted by cars, such as carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOC). However, a detailed study of long-term emissions controls is outside the scope of this paper.

Studies of current emissions of gasoline-powered and fuel-cell vehicles show promising results and compelling evidence for a transition to fuel cell vehicles.

A study by Ross and Goodwin (1995, [11]) looked at the real-world emissions of passenger cars, which were averaged over the life of the car. The study includes estimates of emissions from a warmed-up car, from cold start, fuel evaporation, off-cycle operation at higher power than the test cycles, from malfunctioning of the pollution control devices and upstream emissions. To alter these results for an HEV, the off-cycle operation was factored out since the internal combustion engine in an HEV is never required to provide high peak power.

Estimates were also made for the real-world emissions of fuel cell vehicles, in a study by Thomas (2003 [12]). These estimates include upstream emissions from the hydrogen production operation using on-site steam methane reforming, but do not include upstream emissions resulting from the production and transmission of natural gas to the fueling station, nor emissions from the electric power plant to power the hydrogen compressor. The results of these studies are summarized in the table below.

Vehicle	VOC	CO	NOx
ICE	0.7553	7.5533	0.7040
HEV	0.3659	2.0244	0.2926
FCV	0.0039	0.0029	0.0010
SULEV	0.010	1.000	0.020

Table 4.1: Baseline Hybrid Sales Projections

The last row of the table lists the California SULEV emissions standard for reference. The fuel cell vehicle exceeds the standard in every category. Because of the higher efficiency of the FCHVs, it is expected that the FCHVs will produce even lower emissions than the FCVs. This provides further evidence for a transition to fuel cells following the hybrid pathway of ICEs to HEVs to FCHVs.

Chapter 5

Government Policy Analysis

5.1 History of government involvement in automobile transitions

5.1.1 The Fuel Injection Transition

The US government influences the automobile industry mainly through the use of emission control and tax policies. Its involvement was first made visible when Congress passed the Air Pollution Control Act of 1955, the first federal legislation of its kind. The Clean Air Act later succeeded the Air Pollution Control Act in 1963. It intended to improve, strengthen, and accelerate programs for the prevention and abatement of air pollution that first recognized the dangers of motor vehicle exhaust. With $95 million in granted funding, the legislature triggered a series of ongoing research, investigations, surveys and experiments to pollution control (The American Meteorological Society, 2004 [36]).

A major amendment to the Clean Air Act was passed in 1970. It was the first in a series of tightened automobile emission controls that forced the U.S. automakers to move from carburetors to fuel injection engines from the early-1970s to the mid-1980s:

- 1970 – A major revision of the Clean Air Act created the first set of emission standards for automobile to control the amount of CO, volatile organic compounds, and nitrogen oxides. At the time it was impossible for carburetors to meet these standards so automakers were forced to adopt to fuel injected engines.

- 1977 – Congress tightened standards for nitrogen oxide emissions for passenger vehicles.
- 1979 – New standards were extended to light trucks.
- 1988 – New standards were extended to heavy trucks.

(The US Environmental Protection Agency, 1999)

As a result, most domestic automakers completed the transition from the electromechanical carburetors to fuel injection by the mid-1980s.

There are many similarities between the fuel injection transition and the hydrogen transition such as technical difficulties and government support, but unfortunately we cannot make direct comparisons between the two. The fuel injection transition took place when the new technology had already been successfully adopted throughout Europe and clearly showed its advantages and benefit. The fuel cell technology is still too immature for the government to force a similar transition. This is why the Department of Energy set 2015 as its earliest target decision date in its latest roadmap for the hydrogen transition (DOE, 2004 [61]).

A more suitable comparison could be made to the current transition to HEV technology. If the government keeps tightening the emissions standards the current ICE engines will be hard pressed to meet future regulations. Furthermore, the HEV technology clearly shows that it is highly feasible and continues to produce better efficiency and performance, and lower emissions. The government, therefore, needs to balance its short term policies on helping both HEVs and FCVs.

5.1.2 The Hybrid Electric Vehicle Transition

The U.S. government has extended very limited additional support for HEV since its introduction in 2000 mainly due to resistance from the domestic auto industry. The federal emissions standards are still too relaxed to force a HEV transition and a $2,000 tax deduction initiated in 2004 is set to expire in 2006. The state and local governments, on the other hand, have put much more effort into the promotion of the HEVs.

California is the most actively involved state with HEVs. On September 23, 2004 California state governor Arnold Schwarzenegger signed a measure granting drivers of hybrid vehicles access to freeway carpool lanes (Oakland Tribune, 2004 [55]). The city of Los Angeles started a six month free parking program to all hybrid vehicles on Oct 1, 2004 and the city of San Jose also offers free street parking for all hybrid owners who purchased their cars within the city. These policy changes have led to long waiting lists for perspective HEV buyers in California. Other states have also offered similar promotions.

Government support may not be critical for the HEV transition anymore due to hybrids growing popularity and support. The transition, after all, is not as a big step forward as it is for a hydrogen transition. On the other hand, there is a chance that the fast market penetration of today's HEVs would falter if the government withdrew its support. Such government policy change has highly unpredictable market impacts and may require further research and studies. The U.S. government has much more to do, however, in meeting the challenges faced by the current fuel cell technology before a hydrogen transition could fully take place.

Colorado	The Colorado Department of Revenue offers a tax credit for the purchase of a hybrid electric vehicle (HEV).
Connecticut	The purchase of hybrid electric vehicles (HEVs) with a fuel economy rating of at least 40 miles per gallon (mpg) and the original purchase of dedicated natural gas, LPG, hydrogen, or electric vehicles are exempt from sales tax.
Florida	Inherently low-emission vehicles (ILEVs) and hybrid electric vehicles (HEVs) may be driven in high occupancy vehicle (HOV) lanes at any time regardless of vehicle occupancy.
Georgia	Hybrid electric vehicles (HEVs) shall be authorized to use high occupancy vehicle lanes, regardless of the number of passengers.
Illinois	The Illinois Alternate Fuels Rebate Program (Rebate Program) provides rebates for 80% of the incremental cost of purchasing an AFV or converting a vehicle to operate on an alternative fuel.
Maine	Maine law pursuant to MRSA 36, sections 1752 and 1760-79 allows a partial sales tax credit of approximately $500 for hybrid cars that do not have a comparable vehicle model, such as the Toyota Prius and Honda Insight.
Maryland	The Maryland Clean Energy Incentive Act provides tax credits up to $2,000 for electric vehicles (EVs) and up to $1,000 for qualifying hybrid electric vehicles (HEVs).
New Mexico	Hybrid electric vehicles (HEVs) with a U.S. Environmental Protection Agency (EPA) fuel economy rating of at least 27.5 miles per gallon are eligible for a one-time exemption from the motor vehicle excise tax.
New York	New York's Alternative Fuel (Clean Fuel) Vehicle Tax Incentive Program offers tax credits and a tax exemption for purchasing new hybrid electric vehicles (HEVs), alternative fuel vehicles (AFVs), and/or install clean fuel vehicle refueling equipment. Purchasers of qualified HEVs are eligible for a tax credit of up to $3,000, depending on the vehicle's fuel economy.
Oregon	A Residential Tax Credit of up to $1,500 is available for the purchase of a HEV or dual-fuel vehicle.
Utah	The state provides an income tax credit for 50% of the incremental cost ($3,000 maximum) of a clean-fuel vehicle built by an OEM and/or an income tax credit for 50% of the cost ($2,500 maximum) of the after-market conversion of vehicles purchased after January 1, 2001 and registered in Utah.
Virginia	AFVs displaying the Virginia 'Clean Special Fuels' license plate can use the Virginia HOV lanes, regardless of the number of occupants, until July 1, 2006.
Washington	Electric, CNG, and LPG vehicles are exempt from emission control inspections.

Table 5.1: State HEV incentives (Hybridcar.com, 2004 [48])

5.2 Summary of challenges to the fuel cell transition

It will take us decades to make our way through the fuel cell transition and we are only at the very beginning of a long journey ahead. There are still many challenges ahead of us with technical exploration, public education and government policies.

5.2.1 Technology Exploration

Figure 5.1: Building a Hydrogen Transportation System (USCAR, 2003 [50])

Many tiers of building blocks must be accomplished before a hydrogen transportation system can be made. For now the first tier of technical issues need to be fully resolved before we could move on the next.

5.2.2 Lightweight Materials

Lightweight materials are highly desirable for the construction of fuel cell vehicles. Fuel cell vehicles, especially the first generation of commercially available fuel cell vehicles, are expected by some experts to be much less powerful compared to conventional vehicles. In today's cars and light trucks, plastic and composite materials are only about 7.5% of total vehicle mass, and their applications are generally non-structural (Wards Communications, 1999 [69]). The presence of these light weight materials in FCVs must increase, but the cost is still too high.

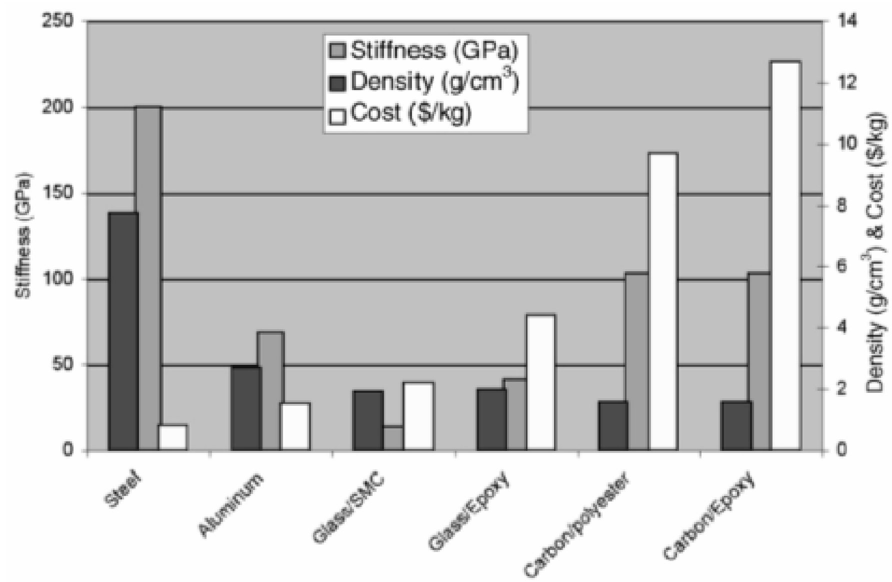


Figure 5.2: Relative materials properties and costs (Lovins, 2004 [50])

Carbon fibers are ideal materials in constructing the body of FCVs but its current cost is as high as $11-22/kg compared to only $ 1.3/kg for steel (Lovins, 2004 [50]). The cost of composite materials has to be dramatically reduced, or the fuel cell drivetrain must cost the same as internal combustion engines for the same amount of power, before FCVs can become affordable to average income families.

5.2.3 Fuel Cell Technology

Although the fuel cell technology still needs further improvement it has already made enough progress to allow the creation of several prototype fuel cell passenger vehicles. The primary task today is to reduce the extraordinary cost of the fuel cell systems within these vehicles for them to become marketable.

	Peak Stack Power (kW)	Fuel Cell System Cost ($) at $5,000/kW	Range (km)
Hyundai Santa Fe FCV	75	375,000	402
GM HydroGen III	94	470,000	400
GM HyWire III	94	470,000	129

Table 5.2: Cell unit cost / car (Lovins, 2004 [50]), assuming a FC system cost of $5,000/kW

The current cost of internal combustion engine power plants is around $25-35/kw (DOE, 2003

[61]). The fuel cell system cost has to be greatly reduced before the fuel cell transition could begin.

5.2.4 Hydrogen Fuel Storage

Pure hydrogen gas is highly flammable. It has one of the highest energy densities of any known fuel yet it is the lightest of them all. To overcome public fear and to develop high range fuel cell vehicles, reliable and high capacity hydrogen storage has to be developed before the commercialization of any fuel cell vehicles could come to reality.

Earlier studies in hydrogen storage attempted to produce hydrogen onboard from hydrocarbon materials such as methane and gasoline. Yet most onboard hydrogen processors have been unable to produce high quality hydrogen gas efficiently and effectively to meet the high purity demand of fuel cell systems. This lack of performance forced the Department of Energy and researchers to reevaluate their strategy in hydrogen storage.

Figure 5.3: Compressed Hydrogen Storage Tank (DOE, 2004 [63])

Most of today's hydrogen storage comes either in compressed or liquid form. Liquidation of hydrogen requires substantial amount of energy and could be much more hazardous than compressed hydrogen. Most of the current fuel cell vehicles thus use compressed hydrogen for fuel storage. Solid state hydrogen storage emerged as a promising fuel solution in the recent years with the introduction of metal hydrides, but it still needs more work before it can be fully implemented. The U.S. DOE, in conjunction with industry, has developed a series of hydrogen storage targets for calendar years 2005, 2010 and 2015 (US DOE, 2003, [61]).

Storage Parameter	Units	2005	2010	2015
Specific Energy	kWh/kg	1.5	2.0	3.0
	kg H2/kg System	4.5	6.0	9.0
Energy Density	kWh/L	1.2	1.5	2.7
	gm H2/L System*	36	45	81
Storage System Cost	$/kWh	6	4	2
	$/kg H2 capacity	200	133	67
Refueling Rate	$/kg H2/min	0.5	1.5	2.0
Loss of Usable H2	(g/hr)/kg stored	1	0.1	0.05
Cycle Life	Cycles (1/4 to full)	500	1000	1500

*For reference, liquid H2 density is 70 gm/L

Table 5.3: U.S. DOE Hydrogen Storage Targets (US DOE, 2003, [63])

Specific Energy and Energy Density need to be improved for better vehicle range. Lower storage system cost is also needed to make fuel cell vehicles affordable to the public. The current cost of hydrogen storage is in excess of $100/kWh, much higher than the current $6/kWh goal set by the DOE for 2005 (Lovins, 2004 [50]). Further research on storage needs to be conducted to meet the even more challenging goals set for 2010 and 2015.

5.2.5 Hydrogen Fueling

The establishment of a hydrogen distribution network is one of the most challenging parts of the fuel cell transition. The network will require hundreds of billions of dollars in investment and years if not decades of development to build. Aside these challenges the government has not yet laid out an official construction plan. Much assessment is still being made between different distribution alternatives. One important choice still needs to be made between building a centralized distribution network and establishing a decentralized distribution network.

According to the result of a study conducted by the Argonne National Laboratory, cost and result of these two types of network are very different:

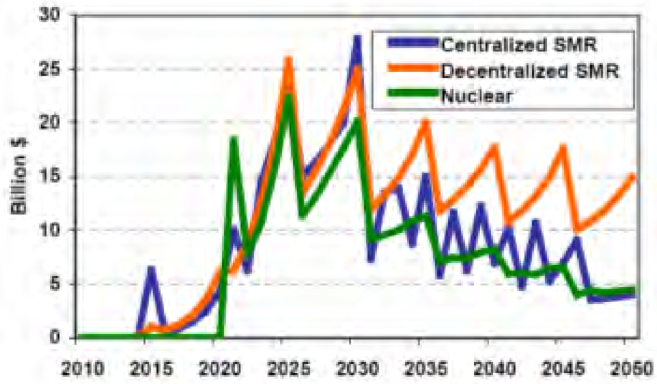


Figure 5.4: Capital Costs of Natural Gas and Nuclear Well-to-Pump Pathways (Argonne National Laboratory, 2005 [11])

(Note: SMR -> Steam Methane Reforming, Nuclear -> Thermal chemical water splitting using advanced nuclear reactors.)

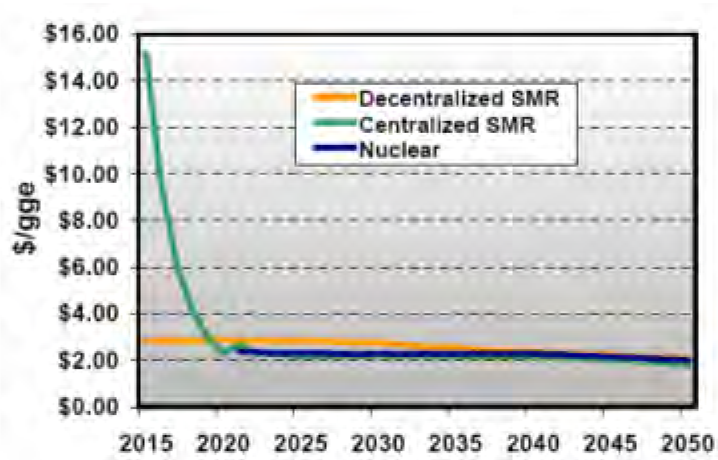


Figure 5.5: Projected Cost of Hydrogen per Gasoline Gallon Equivalent (Argonne National Laboratory, 2005 [11])

As we can see from Figure 5.4 and 5.5, the decentralized model promises low fuel cost in the early years of the network development while the centralized model promises better cost reduction later on. The decentralized model clearly shows its advantage. Fuel cell vehicles would be extremely expensive when they first come out in the future. Consumers are extremely unlikely to tolerate an alternative fuel that is as much as 7 times more expensive than gasoline on top of the high price they paid for the car. In addition the centralized model could always be added to a decentralized network later on as hydrogen popularity grows and more fuel cell vehicles are sold.

The government needs to decide on the structure of the distribution network soon to meet the refueling needs of the fuel cell vehicles in the future.

5.3 President Bush's Hydrogen Fuel Initiative

President Bush, at his State of Union address in 2003, announced a $1.2 billion Hydrogen Fuel Initiative to reverse America's growing dependence on foreign oil by developing the technology for commercially viable hydrogen-powered fuel cells to power cars, trucks, homes and businesses with no pollution or greenhouse gases. Under this initiative, the first car driven by a child born today could be powered by fuel cells (The U.S. White House, 2003 [67]).

Soon after the presidents call for hydrogen, the Energy Efficiency and Renewable Energy Agency produced an internal fuel cell report to the U.S. Congress. The report recommended: (1) Core Technology Development and Supporting Initiatives to overcome existing technical barriers to the hydrogen transition. (2) Public-Private Cooperative Partnership to share the resources and the costs of the transition. (3) Codes and Standards to guide R&D programs to ensure technology compliance prior to development. (4) Education at all levels to inform the public about the technology, overcome public fear and resistance to hydrogen projects and implementations (EEREA, 2003 [65]).

It also proposed the first road map of the hydrogen transition, shown in Figure 5.6 below:

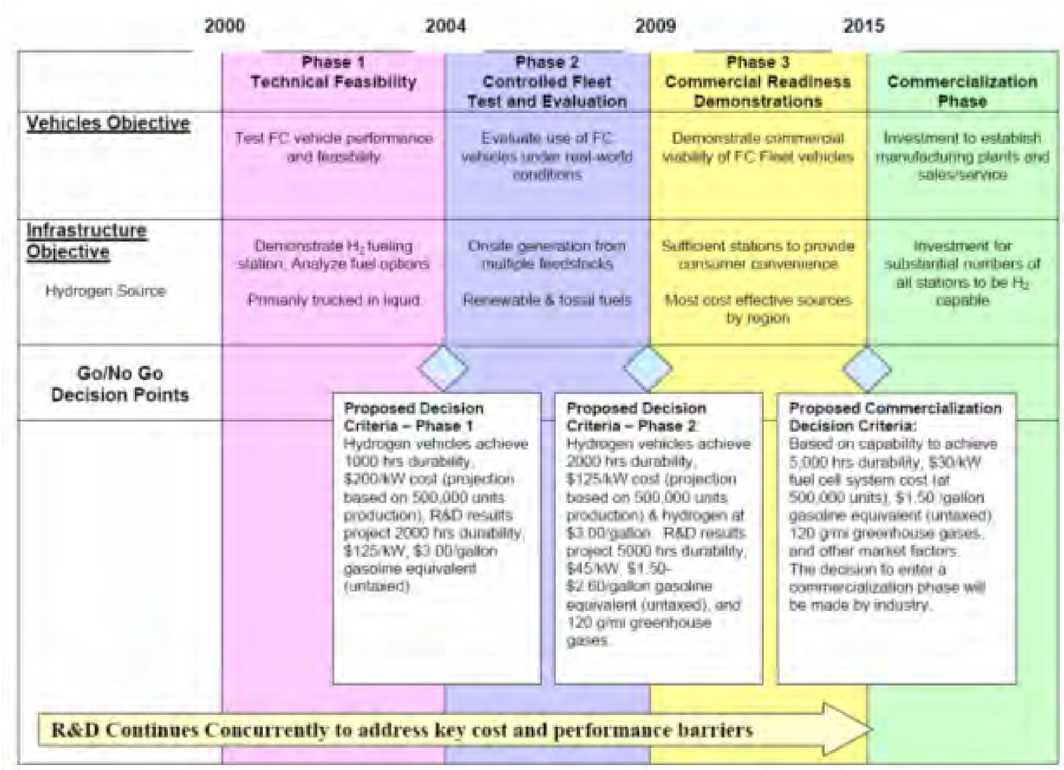


Figure 5.6: Transportation and Infrastructure Timeline to Obtain Commercialization Information (EEREA, 2003 [67])

After a full year of research and preparation the U.S. Department of Energy laid out a detailed long term strategic roadmap for the hydrogen transition in February 2004:

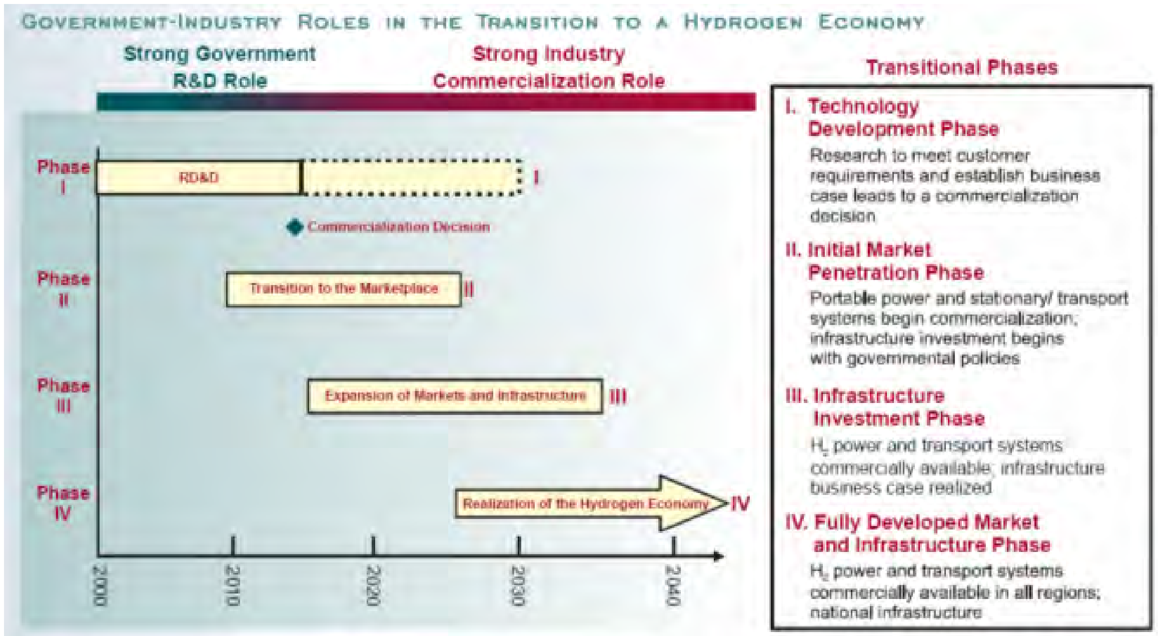


Figure 5.7: Government-Industry Roles In The Transition To A Hydrogen Economy. (DOE, 2004 [64])

Based on the original roadmap, the new plan had its time horizon extended to 2040 and set the clear roles for both government agencies and private industries at each stage of the development. Under the plan, the Department of Energy and other agencies of the government will play a big role in the early stage of the hydrogen transition, providing strong research support for producing, storing, and delivering hydrogen in an efficient, clean, safe, reliable, and affordable manner (DOE, 2004 [62]). If the technology proves to be feasible, the government will mainly serve as an early technology adopter in the mid stage of the transition before full-scale commercialization could take off. Early adoption programs will provide business incentives such as guaranteed volume purchase of fuel cell vehicles for public transportations and government fleet.

5.4 Suggested changes to the roadmap

The U.S. Department of Energy created a solid roadmap for the hydrogen transition. Domestic automakers' lack of incentives for technical innovations, however, could potentially jeopardize the entire project.

When Partnership for a New Generation of Vehicles was first founded under the Clinton Administration in 1991 the U.S. automakers largely ignored the call for hybrid electric vehicles due to cheap gas price and slow-evolving emission standards. Ironically, Japanese auto manufacturers quickly recognized the HEV opportunity in the early 1990s and soon became leading players in the hybrid market by offering HEVs to the public at least 3 years before any American automakers introduced theirs. (Edmund, 2005 [46]) History shows strict government emissions and efficiency controls help to speed up domestic automakers' effort in making major transitions in their products. The transition from carburetor to fuel injection engines in the late 70s was successful mainly because of the government pressure and the hybrid transition initiatives failed to have much impact mainly because of lack of government mandate. The hydrogen transition is set to happen if the government could take firm steps to further tighten the U.S. emission standards in the years to come.

Even if the domestic automakers could persuade the federal government not to raise its standards, the state of California has already passed new regulations in 2004 to mandate the reduction of light truck emissions by 25 percent and SUV emissions by 18 percent. Under the new rule, carmakers have until 2009 to introduce cleaner technology and 2016 to meet the new exhaust standards (MSNBC, 2004 [52]). Many states have already switched from the federal standards to the California's standards in recent years. Automakers thus have no choice but to reduce emissions sooner or later.

The transition to a cleaner energy source is inevitable. Although many challenges are still ahead of us, the fuel cell technology is extremely promising, and only those who adapt quickly to can stand the fierce competition of the future.

Part II

Heavy-Duty Vehicles

Chapter 6

Introduction

For the purpose of this report, heavy-duty vehicles are defined as vehicles that have more than two axles, including transit buses, combination trucks (such as tractor trailers), and single trucks with six or more wheels (such as Class 8 trucks and municipal waste disposal vehicles). This class of vehicles, which uses less than 20% of total transportation energy demand in the United States, accounts for a significantly high percentage the total amount of nitrous oxides and particulates emitted by the U.S. transportation sector each year (Gordon, 1991 [149], Farrell et al., 2003 [196]). For this reason, the use of alternative fuels is being investigated, particularly in the area of transit buses. Over thirteen percent of all U.S. transit buses are currently powered by alternative fuels (APTA, 2004 [75]). Transit buses are a great platform for alternative fuel demonstration since they run relatively short routes, the majority are part of a fleet, and they are well-maintained (Jollie, 2004 [159]).

Of the numerous types of alternative fuels, hydrogen is believed by many experts to potentially be the lowest cost option (Ogden, 2000 [173]). While a transition to hydrogen fuel is not expected to occur quickly, car manufacturers expect the first hydrogen fuel-cell powered vehicles to enter showroom by 2010, and many scenarios predict the mainstream use of low-emission and hydrogen fuel-cell vehicles by the year 2050 (Van der Veer, 2003 [189]). We will assess the potential for development of hydrogen-powered fuel cell heavy-duty vehicles, paying particular attention to the transit bus as a transition platform for this technology.

Researchers are embracing the fuel cell as the keystone for advancing hydrogen-based technology. Fuel cells operate at a higher efficiency than their internal combustion engine counterparts because they are not limited by the heat transfer limitations acting on cyclic engines governed by the Carnot cycle (autoweb.com.au, 1997 [117]). Additionally, fuel cells have a lower number of moving parts, leading to a smaller amount of wear due to friction and lower maintenance costs (Canadian Office of Energy Efficiency, 2004 [94]). The heat generated by a fuel cell is sufficient to provide ambient heat for a vehicle (autoweb.com.au, 1997 [117]), which removes the need for a dedicated heating system. Lastly, in mass-produced quantities, the cost of fuel cells engines would be comparable to the cost of an internal combustion engine (Ogden, 2000 [173]).

Much of the recent interest in hydrogen's potential use as a transportation fuel is due to concerns about pollutants. Fossil fuels account for most of the 6.5 billion tons of carbon that are emitted to the atmosphere every year. As worldwide population continues to increase, and nations continue to develop technologically, global energy use is expected to increase by 70% in the next fifteen years (Service, 2004 [179] [180]). With this increase in energy use, a corresponding increase in pollutant emissions is expected, as fossil fuels are the fueling method of choice for most energy applications. One attractive feature of hydrogen-fueled vehicles for public transit agencies exists in the fact that the only emissions produced are pure water vapor. Therefore, its use reduces levels of nitrous oxide, carbon dioxide, and particulate emissions in local and regional areas (CUTE, 2002 [139]).

The other major concern driving hydrogen's potential use as a transportation fuel is the highly volatile petroleum import market. Worldwide oil production is expected to peak within the next generation. This means that, as demand for oil exceeds production, prices can be expected to skyrocket (Service, 2004 [179] [180]). Also, as most of the remaining world oil reserves are controlled by countries that historically have had icy relations with the U.S., a domestically available fuel supply is highly desirable in order to reduce our dependence on these countries for fuel (Cromwell et al, 2002 [141]). Hydrogen, as the most plentiful element in the universe (Hoffmann, 2002 [152]) will enable our dependence on foreign energy sources to be reduced, since it can be produced from a variety of domestic sources. Furthermore, the demonstrated superior levels of efficiency in fuel cells, as compared to their diesel counterparts, would also promote significant energy reductions (CUTE, 2002 [139]).

Another benefit of the use of hydrogen fuel cells is noise reduction. Prototype vehicles that have combined hydrogen fuel with a high-efficiency fuel cell demonstrate quieter operation, which would reduce urban noise levels (Canadian Office of Energy Efficiency, 2004 [94]) and enhance the quality of life for transit customers.

Lastly, buses are a high-visibility means of transportation, and the public exposure that hydrogen power and fuel cells would receive as a result of an implementation in transit buses could jumpstart progress towards more widespread implementation of hydrogen as a transit fuel (CUTE, 2002 [139]).

The U.S. Government believes strongly in the potential viability of fuel cell technology, and has recently launched the U.S. National Fuel Cell Technology Initiative, a multi-year effort designed to develop and demonstrate fuel cell technology in transit buses with the goal of advancing fuel cell technology to the point of feasibly commercializing fuel cell buses. The hope is that, by implementing this program, and with the cooperation of the government and industry specialists, fuel cells will become more durable and responsive, with a corresponding drop in the cost per kilowatt of a fuel cell (Jollie, 2004 [159]). Prior to this initiative, hydrogen fuel cell bus projects in the United States have been limited to a few areas, most notably Chicago, Southern California, and Washington, DC. It is also worth noting that there are fuel cell bus demonstration projects throughout Europe, Australia, and Iceland.

Since there are only prototype fuel cell buses in existence, the cost of these vehicles is extremely high; the average fuel cell bus cost about one million dollars more than its diesel counterpart (cleanairnet.org, 2004 [85]). This already high cost does not include the high infrastructure and support costs associated with the production, storage, and distribution of hydrogen, which varies based on the methods of hydrogen production used, the equipment in place, and the potential number of buses to be serviced (cleanairnet.org, 2004 [85]).

However, one major advantage of transit buses as a potential transition platform for hydrogen transportation is the fact that buses, like other fleet vehicles, are refueled in a centralized location (Ogden, 2000 [173]). As a result, the infrastructure requirements necessary to support a hydrogen-bus fleet will be much smaller than those needed to meet the market demand from non-fleet hydrogen-powered vehicles. Therefore, the methods used to produce, store, and distribute hydrogen to a bus fleet will provide insight into applications for a larger-scale transition, since the ability of hydrogen to penetrate the consumer energy market is highly dependent on the ability to develop a wide-scale infrastructure (Ogden, 2000 [173]).

6.1 Issues facing Hydrogen

A number of roadblocks exist along the pathway to a hydrogen economy. While hydrogen has great potential due to its properties as an energy carrier, it is not naturally available. Rather, hydrogen must be manufactured from another primary energy source (Farrell et al., 2003 [196]). Additionally, hydrogen gas is lighter than air and does not possess a high density, meaning that the onboard storage of hydrogen in an economical manner remains an unsolved problem. Solving the hydrogen storage issue would greatly help promote public acceptance and commercialization of hydrogen-powered vehicles. Another large obstacle is the necessity of a widespread hydrogen infrastructure, which many experts believe must be in place before market acceptance of hydrogen will occur (NAVC, 2003 [148]). People tend to be adverse to the use of hydrogen as a fuel due to the "Hindenburg Syndrome", a perceived danger inherent with hydrogen as a result of lasting images of a burning zeppelin (Howes, 2000 [153]).

Roadblocks also exist in the area of fuel cell technology. Fuel cells are still in the early stages of practical use and their cost per kilowatt remains high (NAVC, 2003 [148]). Current fuel cells also lack durability, particularly in extreme operating conditions, and respond sluggishly to transients in power demand (cleanairnet.org, 2004 [85]). Lastly, some skeptics worry that, by devoting major financial and technical resources toward demonstrations of a technology before its ready to achieve market penetration, there exists a high possibility of failed public acceptance of the technology, such as that which occurred with synfuels technology in the 1980s. Since fuel cell technology is not widely expected to achieve market penetration until the latter half of the 21^{st} century, these skeptics believe that the current emphasis on hydrogen research constitutea a failure to address the hazards posed by the ever-increasing levels of greenhouse gases and particulate emissions (Service, 2004 [179] [180]).

Estimates predict that a full transition in the U.S. to a hydrogen economy would require one hundred fifty million tons of hydrogen per year (Turner, 2004 [187]). Currently, the cheapest way to produce hydrogen is through steam reforming of natural gas. These reformers produce hydrogen with an efficiency rate of 85%, and production of a gas-gallon equivalent of hydrogen by this method costs roughly five dollars. While production costs of hydrogen have fallen about one dollar per gas-gallon equivalent over the past three years (Service, 2004 [179] [180]), the U.S. Department of Energy predicts that the cost of a gas-gallon equivalent of hydrogen must be approximately $1.50

in order to achieve market penetration (Service, 2004 [179] [180]). While this figure may be low due to the recent increases in the cost of gasoline, it is still apparent that continued improvements must be made in hydrogen production technology.

These advancements in hydrogen production may be possible through electrolyzer technology. With this technology, hydrogen is produced through the electrolysis of water. Currently, only about 4% of the hydrogen produced each year is by electrolysis (Heller, 2004 [151]). Most of the cost of hydrogen production by electrolysis is from the cost of electricity, and as most of the world's electricity is produced by the burning of fossil fuels, this entire exercise may seem counterproductive. However, economic ways to produce electricity from environmentally-friendly sources, or to produce hydrogen from fossil fuels without releasing CO_2 into the atmosphere, are currently being researched. For example, one transit company in California is using solar power to supplement grid energy as a source of power for its electrolyzer (Hydrogen Fuel Cell & Infrastructure Technologies Program, 2003 [156]). In Iceland, electricity is produced from the country's vast hydroelectric resources, and experiments with geothermal energy as the heat medium for electrolysis are also underway (Sigfusson, 2003 [181]). Generating electricity from wind is another environmentally-friendly method being considered. The European Wind Association predicts that wind will produce about 10% of the worlds power by 2020. According to the American Wind Energy Association, one kilowatt-hour of energy currently costs roughly three to five cents. Once the price of wind power drops to one-and-a-half cents per kilowatt hour, experts believe that the costs of generating hydrogen through wind-powered hydrolysis will be competitive with projected gasoline equivalent prices (Heller, 2004 [151]). The U.S. Department of Energy also reports that in some areas of the country, wind power prices are competitive with natural gas prices.

Another major issue facing hydrogen technology is storage. Due to hydrogen's low density, it would require twenty-one tanker trucks to transport the energy equivalent of one gasoline tanker truck. Hydrogen can be liquefied to increase density, but in order for hydrogen to reach its liquid state, it must be cooled to -253°C, and up to 30% of the energy in a volume of hydrogen would be lost in maintaining hydrogen in this liquid state (Service, 2004 [179] [180]). Also, the low energy density of hydrogen requires storage systems which are currently larger than their diesel counterparts, and may translate into decreases in vehicle range and payload volume (Farrell et al., 2003 [196]).

While hydrogen may have the greatest potential out of all the alternative-fueling methods, it simultaneously poses the largest infrastructure challenge. In addition to the aforementioned production and storage issues, cost-effective methods for distribution of hydrogen must be discovered and implemented. Current estimates by Shell Hydrogen representatives place the initial cost of creating an infrastructure designed to provide hydrogen to 2% of U.S. vehicles at $20 billion (Van der Veer, 2003 [189]). The solution to the infrastructure problem may lie in the creation of small-scale hydrogen production facilities which serve a limited area, an idea similar to the "localized dairy farm" theory: since it is difficult to keep dairy products fresh during long transits, most major cities are surrounded by a number of dairy producers (Vanek, 2004 [190]). Shell Hydrogen believes that the cost of small-scale hydrogen production will decrease over the next five to ten years as the technology matures (Van der Veer, 2003 [189]).

Despite these obstacles, transit buses still provide an excellent way to demonstrate fuel cell technology, for a number of reasons. Transit buses comprise a tiny fraction of the number of vehicles on urban roadways (Gordon, 1991 [149]). From a spatial standpoint, buses do not have the same limitations as light-duty vehicles. In addition, the cost of a bus fuel cell can be higher, while staying competitive with the cost of diesel bus engines, the cost of which is higher than that of light duty vehicle engines (Ogden, 2000 [173]). Current hydrogen bus applications feature a rooftop fuel cell and storage system, promoting increased safety while preventing the reduction of passenger space (fuel-cell-bus-club.com, 2004 [93]). Using hydrogen fuel cells in practice would help to illustrate any potential problems with the technology. Once identified, these problems can be addressed and corrected (Farrell et al., 2003 [196]), thereby making fuel cell technology more viable. Increasing demand for fuel cell buses would also translate into increased production of fuel cells, resulting in a decrease in the per kilowatt cost of a fuel cell. Lastly, transit buses are high-visibility means of transportation. By interacting with hydrogen buses on a daily basis, consumer's fears about the dangers of hydrogen would be alleviated.

Improvements in technology alone will not drive a transition to a hydrogen-based transportation system. Factors such as an increased desire for improved air quality, lower emissions, as well as an increased need for security in our energy supply must be reflected in price signals within the marketplace. While the rate of improvements and the level of research in fuel cell technology have been increasing in recent years, the combined, enthusiastic efforts of the government, corporations, and consumers are required to further promote advancements in hydrogen-based technology (Van der Veer, 2003 [189]). The government can provide support in the form of increases in research allocations, rebates, and other methods to reduce the risks for investors embracing expensive pilot projects (Bennett, 2003 [134]), as well as creating educational programs to improve the public's perception of hydrogen. Despite plans to invest $1.2 billion in the hydrogen economy over the next five years, Energy Secretary Spencer Abraham is reluctant to allocate more money towards hydrogen technology research until positive results are seen (Bennett, 2003 [134]). Therefore, it is also imperative that private sector stakeholders, such as the automotive and energy industries, deliver large investments towards facilitating advancements in fuel cell technology and hydrogen infrastructure development (Van der Veer, 2003 [189]).

Chapter 7

The Transition Model

7.1 Introduction

When presented with a choice there are very few people who would not prefer it if vehicles in the United States were emission free and powered by renewable energy. This desire by many to see a shift to a more renewable and environmentally friendly technology in our transportation sector has led to a great deal of work being done examining the form a transition from oil based fuels to a “cleaner” technology like hydrogen fuel cells might take, especially in the area of commercial passenger vehicles. Despite this widespread enthusiasm there has been little actual work done regarding what exactly the transition period from diesel to hydrogen in heavy duty vehicles will be like. This is especially unfortunate considering it is this area, particularly transit buses, we not only consider to be the best starting point for a transition, but also the area most likely to drive all other aspects of a hydrogen transition.

Therefore, one of our main goals since the beginning of this project has been rectifying this unfortunate gap in the overall planning for the transition to a hydrogen based economy. To do this we have created a model that will show as accurately as possible what the transition from diesel engines to hydrogen fuel cells in urban passenger bus will entail. The first step towards creating this transition model was to forecast the number of buses that will be needed over the next 50 years. Once this forecast is completed is possible to create the actual transition model. Then finally the model was used to examine some of the scenarios that are likely to occur during the transition, paying particular attention to the feasibility of the Department of Transportation’s stated goals for the transition in terms of a timeline for hydrogen fuel cells penetration in the national bus fleet.

In the course of creating this model several possibilities that ultimately proved infeasible were pursued. As an alternative model for the transition to hydrogen fuel cells in passenger buses the use of an optimization model was considered. Another area of research that we originally viewed favorably was the possibility of creating a similar transition model for tractor trailers. As a result of our research and calculation it was ultimately decided that a transition in this area was simply not viable at this time, for reasons that are discussed in detail in later in this chapter. For a more detail analysis of these topics refer to Section 7.3.5 and Section 7.4 respectively.

7.2 Bus Demand Forecast

As discussed in the introduction, the first step in building the transition model was to obtain a forecast of the number of buses that will be needed in the future. This was a crucial step because the accuracy of all the other models will rest largely on the validity of the bus forecast, as this will be one of their core assumptions.

The first step in creating the bus forecast was to gather historical data on the number of passenger buses in the United States. This data, as seen in Appendix B.1, was obtained from the Bureau of Transportation Statistics. With this in hand it was then time to decide which forecasting method should be selected. The two most obvious choices are a linear regression and Holt's Method.

A graph of the results for the two methods can be seen in Figure 7.1 below.

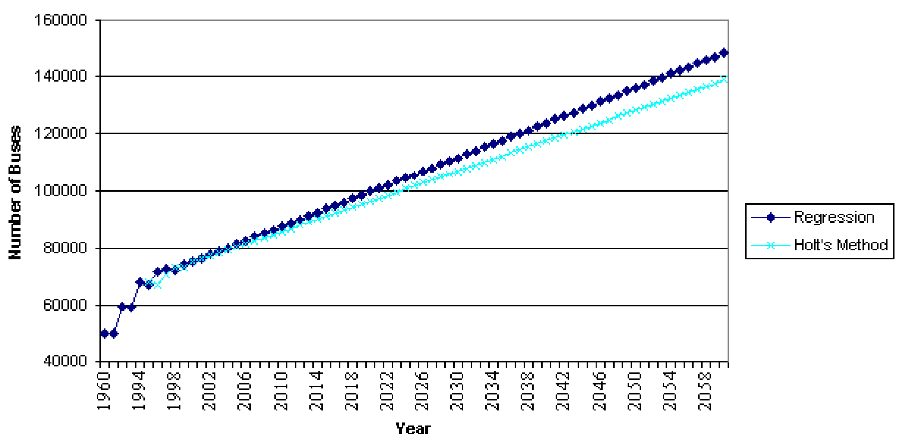


Figure 7.1: Number of Buses Forecast

To determine which method is better both were used and then the Mean Squared Error (MSE) of the two outputs were compared. The MSE is a means of determining the accuracy of a prediction by finding the average value of the squared difference between the predicted and actual value of the data points. Then by comparing the MSE of various forecasting methods it is possible to determine which method is most accurate in a particular instance. In this case the linear regression was founded to have a smaller MSE by a factor of approximately three, and was therefore chosen as the basis of all further bus forecasts.

This linear regression produced the parameters:

alpha	-2358530.143
beta	1216.857

These parameters are used to create a line that is best possible fit for the data. Alpha represents the y-intercept of this line and beta represents the slope. The forecast for the number of buses each year, through 2060, this linear regression produces can be seen in Appendix B.2.

7.3 The Transition Model

In this section all assumptions and steps in the physical creation of the transition model will be discussed in detail, as well as the various scenarios for the transition to hydrogen buses the model was used to create.

7.3.1 Assumptions

Before the practicalities of creating the transition model are discussed it is important to list all assumptions that went into the creation of the model, so that they can be kept in mind as the more mundane details of the model are examined. These assumptions, which we feel to be sufficiently conservative enough to not cast doubt on the structure of the model, are as follows:

1. All parties involved the hydrogen transition (government, vehicle manufacturers, energy companies, R&D organizations, the general public, etc.) will act in good faith, without attempts to interrupt or unduly influence the transition for personal gain

2. Technical challenges in adapting hydrogen to HDVs will be overcome; it is only a question of when this will happen.

3. There will be no unforeseen, revolutionary advances in technologies that render hydrogen fuel cells obsolete as a power source.

7.3.2 Designing the Transition Model

With the necessary data gathered, as discussed in Section 7.2, and the assumptions properly catalogued it is then possible to begin work on the transition model. The forecast generated earlier is use as an estimate of the total bus demand in the United States through the year 2060. This demand must be met by the combined diesel and hydrogen fuel cell bus fleets. This model assumes that the demand has been entirely met by diesel buses in the past up until the present time (2005), when hydrogen fuel cell buses first appear in the national bus fleet, having 10 buses currently in service. While it is a safe to expect that the hydrogen bus fleet will grow in size and ultimately come to hold an equivalent position in the total bus fleet that diesel buses do now, this model was designed to describe exactly how this transition will occur.

After careful consideration it seems clear that the size of the hydrogen bus fleet will, when viewed over time, come to form an "S-shaped" curve. This is almost always the case with the emergence of new technologies such as cell phones, and in this particular instance would account for the phases the transition to hydrogen buses is likely to go through. There should be a slow ramping up period in the early years of the transition as hydrogen buses first enter the market and begin to be used, then rapid growth in the middle years of the transition as the technology is refined and becomes more affordable, and finally a slowdown in growth as market saturation nears. The best way to implement this type of growth in a transition model is to use a logistics curve. The classic logistics curve describes the probability of an occurrence, in this case of a new hydrogen bus being added to the national fleet, as having a humped shape. Therefore there exists less probability of adding a hydrogen bus to the national fleet early and late in the transition, when we logically expect growth to be slower, and a high probability of adding a hydrogen bus in the middle of the transition, when there is rapid growth.

A graphical representation of the classic logistics curve can be seen below in Figure 7.2.

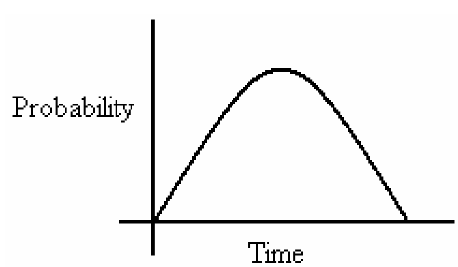


Figure 7.2: Classic Logistics Curve

The transition model uses a slightly modified version of this logistics curve to account for the fact that the total number of buses in the United States is not fixed, but grows over time to meet growing demand. This logistics curve will resemble the classic logistics curve in all aspects except the end of the right branch, which will asymptotically approach zero, as opposed to dropping directly to zero as the classic curve does.

With the type of model finalized, it was then time to implement it using the bus forecast derived earlier. The equation used to implement the logistics curve in Microsoft Excel is:

$$y_t = a/(1 + ce^{-bt})$$

where:
y_t =number of H_2 buses
a =upper limit on the number of possible H_2 buses
b =coefficient of imitation (to adjust the rate of transition)
c =constant (to adjust the time at which the transition occurs)

This general case equation can be made to fit the needs of our transition model by adjusting the coefficients above. The upper limit is the bus forecast from Section 7.2, as this is the line that the number of hydrogen buses asymptotically approaches. The constant determines at what time the transition will begin in earnest, and the coefficient of imitation determines the rapidity of the transition.

A variety of scenarios were created by adjusting the values of the constant and the coefficient of imitation to shift the start time and rapidity of the transition. A representative array of scenarios is discussed in greater detail in the following sections.

7.3.3 The Expected Scenario

To determine the most likely timeline for the transition is we researched comparable technologies in order to illustrate potential trends. A natural parallel can be found in the penetration of hybrid electric vehicles (HEV) into the commercial car market. Both hydrogen fuel cell buses and HEVs fill the same niche in their respective markets, replacing less environmentally friendly vehicles at an increase in cost. Since the introduction of HEVs their numbers have grown steadily at between 30-40%. Therefore this is the growth range one can reasonably expect to see in the size of the hydrogen bus fleet.

To model these specific growth rates, the necessary parameters can be set to the following values:

Boundary	Lower	Upper
Growth Rate	30	40
B	0.25	0.325
C	10000	10000

The 30% growth rate, which makes up the lower bound of the expected scenario, passes one percent penetration in 2024 with just under 1200 hydrogen buses and then reaches saturation, which we call anything above 97.5% penetration, in 2057 which means that the transition will take roughly 33 years in total. We chose to call saturation 97.5% penetration, as opposed to requiring 100% penetration, because it is likely that there will always be a few diesel buses operating in niche markets, much as there are still steam locomotives in operation. A graphical representation can be seen in Figure 7.3, and a table containing the number of hydrogen buses by year can be found in Appendix B.3.

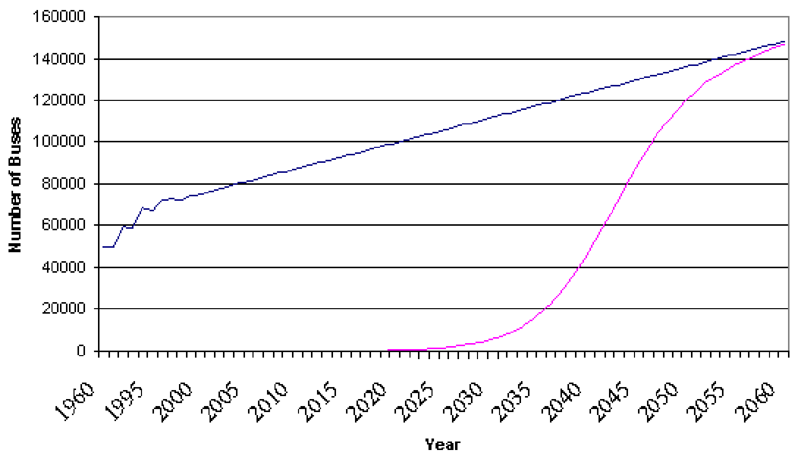


Figure 7.3: 30% Growth Rate Transition Model

The 40% growth rate, which makes up the upper bound of the expected scenario, passes one percent penetration in 2020 with just over 1200 hydrogen buses and then reaches saturation, which as stated about is when penetration passes 97.5%, in 2045, which means that the transition will take roughly 25 years in total. A graphical representation can be seen in Figure 7.4, and a table containing the number of hydrogen buses by year can be found in Appendix B.4.

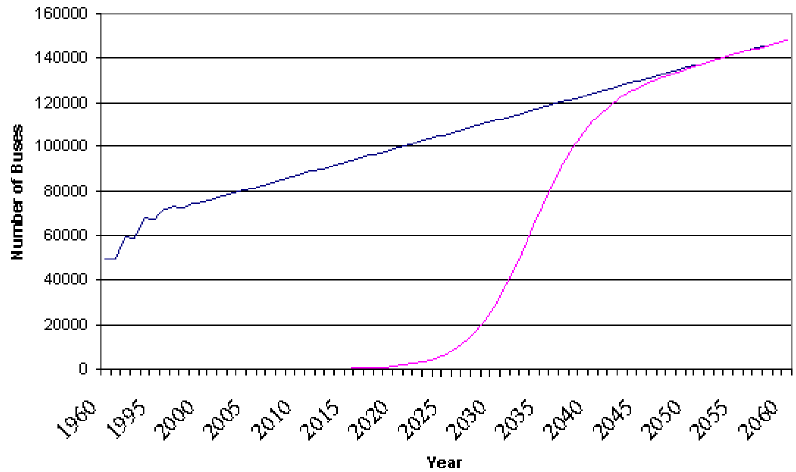


Figure 7.4: 40% Growth Rate Transition Model

To summarize, we believe that the transition from diesel transit buses to buses powered by hydrogen fuel cells will be underway within the next 20 years, and furthermore that once this transition commences it will be completed within 25-35 years, based on the example of hybrid vehicles and our best analysis.

7.3.4 Pessimistic Scenario

For the sake of balance, this section and the following section will attempt to illustrate two more extreme scenarios for the transition. The scenario in this section will illustrate what could happen under more conservative estimates of the growth rate. In this scenario for the transition the growth in the number of hydrogen buses would be significantly slower, coming in at only 20%. This could illustrate anything from public resistance against the switch to a hydrogen based economy to the discovery of technical limitations on the growth and development of fuel cells.

The parameters that create this slower scenario are:

Growth Rate	20
b	0.17
c	10000

The 20% growth rate scenario grows at a much slower rate than the previous models, not reaching 1% penetration until 2033 and not reaching saturation before the end of the timeframe the model is examining. A graphical view of this model can be seen below in Figure 7.5, and a table containing the number of hydrogen buses by year can be found in Appendix B.5.

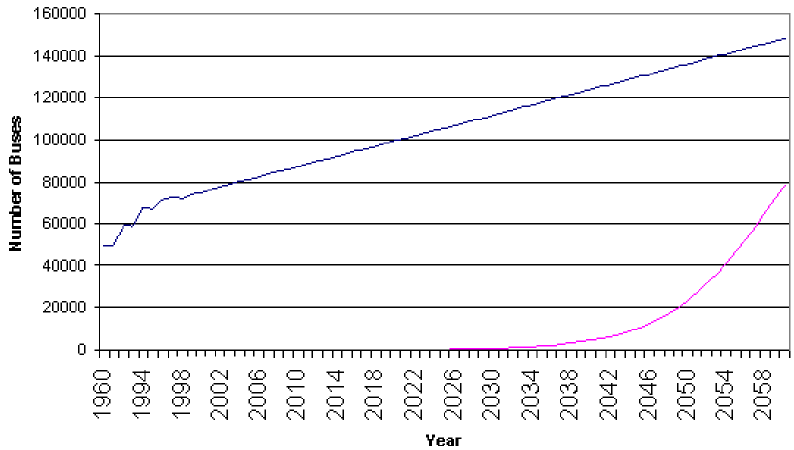


Figure 7.5: 20% Growth Rate Transition Model

This scenario illustrates a case where hydrogen fuel cell buses are not a major factor in the national bus fleet at all in the near future, and would likely occur in parallel with a proportional growth in another type of alternative fuel bus, which would have arisen to fill the need that was not being met by hydrogen buses.

7.3.5 The Department of Transportation Goal

Now, to examine the opposite extreme scenario we look at the Department of Transportation (DOT) has stated that their goal for the transition to hydrogen fuel cells in buses. This goal is to have converted at least 10% of the nation's passenger bus fleet to fuel cells by 2015. Using our model we can see that in order for this goal to be met one of two possible scenarios must occur.

1) Assuming the growth rate stays within the expect range (30-40% per year) there must be a huge push in the next year to get H_2 buses on the road, placing approximately 489 buses in service by next year. The longer this push is delayed, the higher the number of buses will have to be to start with.

The constants that illustrate this in the model are:

constant	232
coef. of imitation	0.325

To see what the transition would look like in this front loaded scenario with the highest expected growth rate (40%) see Figure 7.6 below. The table containing the number of hydrogen buses by year for this scenario can be found in Appendix B.6.

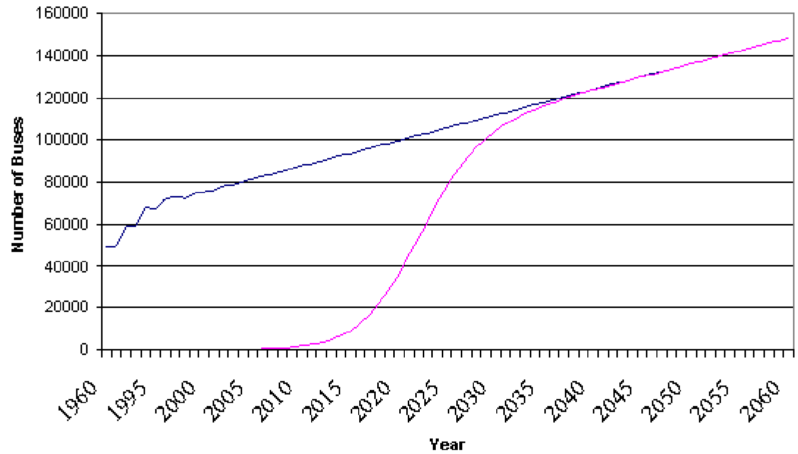


Figure 7.6: DOE Front Loaded Scenario

2) Assuming the growth rate is not limited to the expect range, but that the initial growth (that being the growth in the first year of the transition) will be in line with later growth, then the number of buses that must be on the road by next year is much smaller (22 buses) but the growth per year must be extremely high (117% after the first year and then slowly declining).

The constants that illustrate this in the model are:

constant	8100
coef. of imitation	0.7558

To examine this transition scenario, with its more rapid growth, in greater detail, see Figure 7.7 below. The table containing the number of hydrogen buses by year for this scenario can be found in Appendix B.7.

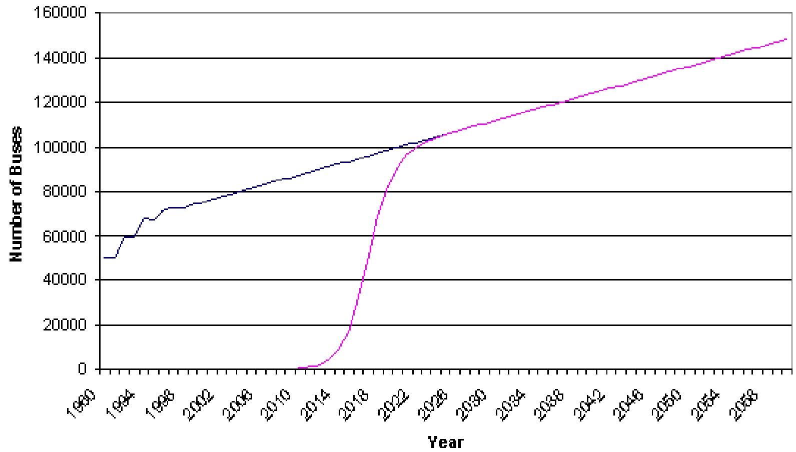


Figure 7.7: DOE Rapid Growth Scenario

As these two scenarios for reaching the DOTs goal of 10% fuel cell penetration by 2015 illustrate the Department of Transportations goal is an extremely ambition one and is unlikely to be reached simply by allowing the market to take its natural course. There will have to be intensive involvement by government agencies, especially in the early years of the transition, when there is traditionally small scale, slow growth with a new technology.

7.3.6 Optimization Model

As a possible alternative to the transition model an optimization model was created to predict the rollout of Hydrogen transit buses on a nationwide-scale. The model attempts to minimize the total cost of purchasing enough buses to transition every transit bus in the United States to hydrogen power. The model uses the costs as determined in the cost model discussed in Chapter 9, and a projection for the number of buses nationwide using Holt's method. The following assumptions govern this model:

1. The transition will be completed by the year 2060. If this assumption is not included, the model would not perform as desired since it would minimize the overall cost by purchasing one bus in 2060.

2. The model only takes into account the cost of purchasing buses. It does not factor into account the cost of creating supporting maintenance and refueling infrastructures. For simplicity's sake, we are assuming that those costs are the "sunk costs" of transitioning to a hydrogen-based fleet.

3. A demand for hydrogen bus technology.

4. A bus' service life is only 10 years. Currently, the average bus service life is a little over 7 years (APTA, 2003). With the advent of fuel cells and the corresponding reduction in the number of moving parts, it can be assumed that bus service life can be expected to increase as a result.

5. A demand for buses of 10% of the estimated number of vehicles required for a given year based on this service life of 10 years, this model assumes. This is due to the fact that, with a 10-year service life, it can be assumed that approximately 10% of a bus fleet requires replacement in a given year.

6. That a higher priority will be placed on replacing already-transitioned hydrogen buses before transitioning existing diesel buses to hydrogen. This ensures that the model is not "back-loaded", with all purchases coming in the later time frame. This also ensures that hydrogen buses are being continually manufactured, thus facilitating a continued reduction in costs.

7. That at least 10% of the nationwide bus fleet will be transitioned by the year 2015, in accordance with Department of Energy goals.

The optimization model can be described mathematically as follows:

$$\begin{aligned}
&\text{MIN } \Sigma\, C_n \\
&\text{s.t. } X_n \leq D_n - R_n \\
&\Sigma X_n \leq A_n \\
&\Sigma X_n \leq Z_n \\
&\Sigma X_n = 0.1 * Z_{2060} \text{ n is all years from 2005 through 2015} \\
&\Sigma X_n = Z_{2060} \\
&\text{All } X_n \geq 0
\end{aligned}$$

where:

C_n = cost of Hydrogen buses in year n

X_n = number of Hydrogen buses purchased for transition in year n

D_n = demand for all buses in year n

R_n = number of Hydrogen buses requiring replacement in year n

Z_n= estimated total number of transit buses nationwide in year n

A_n= potential total number of Hydrogen buses manufactured by year n

After attempting to implement this model, a number of shortcomings were noted. In particular, Microsoft Excel Solver was unable to determine a feasible solution for a year-by-year rollout, as the required number of variables exceeded its capacity. Modifications to the data set were required to reduce the number of variables in order to achieve any functional answer. Eventually, the optimization model was shortened to a modified biennial rollout model. However, the shape of the resultant solution appeared to have three steps, meaning that the rollout would occur in three distinct phases. This does not appear to be a realistic depiction of a rollout, as most historical rollouts have taken the form of an s-shape in terms of cumulative distribution.

Another factor that contributed to the inability to successfully implement this model was the lack of sufficient data. Data with respect to fuel cell bus cost, number of fuel cell buses in existence, bus demand, expected growth of bus demand, budgets for new bus purchases, and revenue generated by bus travel in the various national bus fleets would have been extremely helpful in creating an optimization function to minimize the overall cost of transitioning to hydrogen buses and realistic constraints governing such a transition. This lack of data led to the generation of an unrealistic solution, and contributed to the high degree of uncertainty inherent in this model.

In conclusion, an optimization model, while highly successful in predicting short-term strategies with solid foundations of data, may not be appropriate for developing long-term strategies for situations with highly speculative data, as is the case in this situation.

7.3.7 Possible Impact of Alternative Technologies

As with all real world situations, the question of what should be done with the national bus fleet to combat the problems of rising emissions and fuel costs does not necessarily have only one solution. In this section the four leading alternatives to hydrogen fuel cell technology will be examined and their potential impact on the transition to hydrogen buses will be considered. Each technology will be examined independently in one of the three following sub-sections.

Hybrid-Electric Buses

Hybrid-Electric, or HEV, buses are conventional diesel buses that included some means of recharging a battery during operation, usually a form of regenerative braking where the force applied when the brakes are used is harnessed to generate electricity. This battery is then used to drive an electric motor in situations when the use of the ICE engine is inefficient. The use of this system of an ICE and electric motor in parallel makes it possible to both simultaneously increase fuel efficiency and reduce emissions. The HEV buses function, for all intents and purposes, exactly as if they were conventional diesel buses while still gaining the benefits of this new technology. This makes HEV buses extremely attractive to many transit companies, as they can be used by those unwilling, or unable, to pay the extensive costs inherent with the transition to hydrogen buses while still allowing them to achieving at least some of the benefits of a cleaner and more efficient technology. All without the need for a commitment to a new technology and infrastructure that the hydrogen transition requires.

This makes hybrid technology simultaneously the largest direct competitor and the greatest source of potential improvement for hydrogen fuel cell buses. Opponents of the hydrogen transition often recommend that research efforts be devoted to improving and adapting hybrid technology and treat resources spent on hydrogen technology as practically wasted (Keith, 2003 [196]). While hybrid technology may be more cost-effective in the near term, and provides its nearly comparable benefits, this view is very short sighted. No matter how efficient it uses fuel, hybrid diesel buses still use diesel, which is created from a finite supply of oil. As time goes on the world's supply of oil will inevitably become scarcer, and eventually be depleted. Hydrogen is under no such constraint and is available in effectively infinite supply, assuming it is made from non-fossil fuel sources.

The potential improvement hybrid technology can make in hydrogen fuel cell buses arises from the fact that the hybrid technology can just as easily be adapted to work in parallel with fuel cells as it has been adapted to work with conventional ICEs, providing a large array of benefits. With an electric motor in parallel it would be possible to use a smaller fuel cell, which would greatly reduce overall costs, especially in these early years when the technology is at its most expensive. The parallel system would also reduce the strain placed on the fuel cell during peak power draws. The improvements to the fuel efficiency of hydrogen buses can also be expected to be comparable to that found in diesel hybrids, which could both reduce the size of on board storage and increase the range of hydrogen buses (FCW + IE).

While hybrid technology is the one most likely to come into direct competition with hydrogen fuel cells, it will ultimately provide a boon to the hydrogen transition by improving the performance of the hydrogen buses. It is likely that diesel HEV buses will grow at a quicker rate that fuel cell buses, but in 20 to 30 years, when we expect the transition to hydrogen fuel cells to begin in earnest, HEV buses will fall by the wayside along with the other diesel vehicles due to its inextricable ties to a limited source of fuel.

Hydrogen Internal Combustion Engine

As is well known, due to the highly publicized accident aboard the Hindenburg in 1937, hydrogen is highly flammable. A possible practical application of this fact in transportation is to use hydrogen as the fuel in an internal combustion engine (ICE). This is exactly what is done in the class of buses we will refer to as H_2 ICE buses.

This is a very new technology and the first vehicles implementing it are not expected to roll off assembly lines for several more years though major automotive makers such as BMW and Ford have committed to producing H_2 ICE vehicles. These buses work by injecting hydrogen gas, instead of gasoline, into the engine's cylinders, where it combines with oxygen and combusts, driving the pistons and powering the bus. A benefit of using hydrogen as opposed to gas or diesel is that the hydrogen will still burn even when the air-fuel mix contains too little hydrogen to consume all the oxygen. Unfortunately, a downside of using hydrogen in this kind of application is that its low density means less oxygen can fit into the cylinder, leading to a decrease in overall power (53).

The H_2 ICE technology is one that can greatly assist the hydrogen transition. Many of the companies involved in research in this area often consider it to be an ideal bridge technology between current ICE buses and hydrogen fuel cell buses. The automotive industry is well acquainted with building ICE vehicles, which means there will be little uncertainty or new knowledge needed to beginning producing hydrogen ICE buses in large quantities. This will allow the industry to focus on developing a hydrogen infrastructure to support these new hydrogen ICE buses. As this is an endeavor for which there are no parallels in recent decades, it is likely to be extremely complicated and will require a great deal amount of effort and expertise. This hydrogen infrastructure will be readily in place when the hydrogen transition finally takes place, which is yet another benefit of H_2 ICE technology (53).

Hythane Buses

Another alternative transportation technology is to adapt compressed natural gas (CNG) buses to run on a combination of hydrogen and natural gas, called Hythane. This gas is made of 80% methane (CH_4) and 20% hydrogen. Use of this combination as opposed to the traditional CNG fuel, which is composed primarily of methane, reduces NO_x emissions by as much as 43% and CO_2 emissions by 7%. Sunline, which services 9 cities in California, has been running Hythane buses in an experimental capacity for several years and have found that the efficiency is comparable to other CNG buses and that there have been no increase in maintenance problems and safety issues, though the buses have not been run during extremely hot periods in the summer due to the cost of installing A/C systems on board (Cromwell et al, 2002 [141]).

Many companies, including Sunline, are pursuing Hythane technology purely as a bridge technology to hydrogen fuel cells. These companies believe that Hythane buses are the best choice for the present, and are also an excellent means to develop hydrogen as a major transportation fuel, as well as the national infrastructure this entails. Hythane buses also create a market for renewable hydrogen that will be invaluable later in the transition. Also considering fuel cell and H_2 ICE buses are not widely available commercially at this time, Hythane buses are commonly regarded as the best way to begin the hydrogen transition now and accelerate it as much as possible.

7.4 Medium Duty Vehicles

Medium Duty Vehicles (MDVs) are those that fall between Light Duty Vehicles, such as small trucks, and Heavy Duty Vehicles, such as the passenger buses and tractor trailers this report has dealt with. Specifically, when we discuss MDVs in this section we are referring to delivery trucks, such as those used by the United States Post Service and companies such as UPS and FedEx.

UPS recently launched a program to test the feasibility of replacing their diesel delivery truck fleet of 88,000 trucks with hydrogen fuel cell trucks. The beginning stage of this test involves running three hydrogen delivery trucks in Los Angeles, Sacramento, and Ann Arbor Michigan. These delivery trucks use DiamlerChrysler's second generation fuel cells and have a range of approximately 155 miles, which is equivalent to that of traditional diesel delivery trucks. These new delivery trucks have the same handling and pickup as the diesel delivery trucks, as well as an additional 10% cargo carrying capacity due to the more compact drive train fuel cells use. These experimental vehicles have been fueling at 10 hydrogen refueling stations available to commercial fleets in California, and at the EPA's refueling station in Ann Arbor (Nguyen, 2004 [172]).

These hydrogen fuel cell delivery trucks can only help accelerate the hydrogen transition. There is no direct competition between hydrogen buses and delivery trucks, so there will be no negative competition. Any situation that leads to more fuel cells being produced, in this case for use in delivery trucks, will lead to increases in the performance and reductions of the cost of fuel cells, both of which will accelerate the transition to hydrogen.

7.5 Fuel Cell Tractor Trailer Infeasibility

There have not been any major prototype fuel cell tractor trailer projects. This may be due to the fact that the drive cycle for trucks hauling freight great distances is an excellent application for Diesel internal combustion engines, which translate the high energy density of Diesel fuel into the massive power outputs needed to tow freight trailers long distances at highway speeds (NAVC, 2003 [148]). Since fuel cost is a major consideration for freight trucking corporations, and since Diesel fuel is an extremely cost-effective option, there is no incentive to switch to fuel cell power (NAVC, 2003 [148]), as imposing the additional costs of hydrogen fuel would lead to lower profits and higher prices for consumers, who would be likely to take their business elsewhere (Farrell et al., 2003 [196]). However, improving fuel economy would result in lower overall costs (Farrell et al., 2003 [196]), and many studies have shown that fuel cells are much more efficient at converting fuel to energy than their Diesel counterparts. In addition, freight trucks are responsible for generating twice as many nitrous oxide pollutants and ten times as many particulate emissions as the average passenger vehicle (Farrell et al., 2003 [196]). Using hydrogen would eliminate these emissions from these high-polluting vehicles.

To determine the feasibility of producing a fuel cell-powered tractor scenario, two scenarios were investigated. The first scenario assumes replacement of the internal combustion engine with a fuel cell, with no gain in overall efficiency. The second scenario assumes a gain of fifty percent in efficiency by using a fuel cell instead of an internal combustion engine.

Scenario 1: This scenario assumes that the overall efficiency of a hydrogen fuel cell will be the same as that of a diesel ICE.

Amount of Power needed for example tractor trailer = 425-525 HP => 317-391.5 kW

Energy Density of Fuels:

Diesel = 39 MJ/m^3
Liquid Hydrogen = 10 MJ/m^3
Compressed Hydrogen = 3 MJ/m^3

Fuel Economy of tractor trailer = 6.1 miles/gal

Two 140 gallon fuel tanks are standard on example tractor trailer (Freightliner Coronado)

Overall range = 2*140*6.1 = 1,708 miles

140 gallons = 0.53 m^3 => 2 tanks = 1.06 m^3 of diesel storage space

Required amount of energy = 39 MJ/m^3 * 1.06 m^3 = 41.337 MJ

Liquid Hydrogen tank parameters:

0.5 meters diameter
5.5 meters length
90 pounds fully loaded

For a cylindrical liquid hydrogen gas tank, volume = $\Pi r^2 h = \Pi(0.5/2)2(5.5) = 1.08\ m^3$

Liquid Hydrogen storage space required = 41.337 MJ / 10 MJ/m^3 = 4.137 m^3 = 4 tanks

Compressed Hydrogen tank parameters:

20-inch diameter = 0.508 meters
22-inch length = 0.5588 meters
100 pounds fully loaded

For a cylindrical compressed hydrogen gas tank, volume = $\Pi r^2 h = \Pi(0.508/2)2(0.5588) = 0.113\ m^3$

Compressed Hydrogen storage space = 41.337 MJ / 3 MJ/m^3 = 13.779 m^3 = 122 tanks

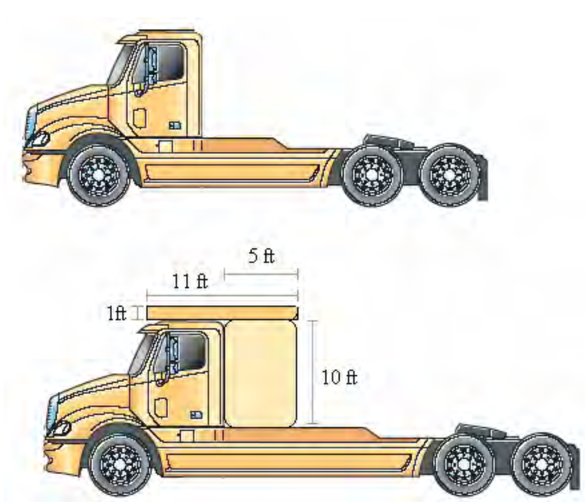


Figure 7.8: Before and After Illustration of FC Tractor Trailer (adapted from www.freightlinertrucks.com).

Thus, using hydrogen as a fuel would cause a dramatic increase in the number of compressed hydrogen storage tanks required. At 100 pounds per tank (fully loaded with hydrogen fuel), the overall weight of a FC tractor trailer should increase by about 11,600 pounds (assuming that a fully-loaded 140 gallon fuel tank weighs about 300 pounds). This translates to a 23.2% percent increase in the weight of a fully-loaded tractor trailer, which is about 50,000 pounds. This increase in weight can be expected to lead to a reduction in fuel efficiency. This reduction in fuel efficiency is not considered in this scenario. Also, using hydrogen as a fuel would result in an addition of five feet to the overall length of the truck.

The amount of hydrogen needed can be calculated as follows:

15 gallons of diesel = 5 kg of Hydrogen in LDV applications

HDV fuel efficiency/LDV fuel efficiency
= 6.1 mpg/22.1 mpg = 0.276

15(.276) = 4.14 gallons of diesel = 5 kg of hydrogen in HDV (estimated)

=> 280 gallons of diesel
=> 338.16 kg Hydrogen

Cost of FC stack and Compressed Hydrogen storage tanks now

= 317 (5,000) + 122 (35,000)
= \$5.855 million (425 HP version)
= 391.5 (5,000) + 122 (35,000)
= \$6.2275 million (525 HP version)

⇒ This is much more than the \$125,000 selling price of a new tractor trailer!

Cost of FC stack and Compressed Hydrogen storage tanks at goals

= 317 (50) + 122 (350)
= \$58,500 (425 HP version)
= 391.5 (50) + 122 (350)
= \$62,275 (525 HP version)

⇒This is about twice the cost of an ICE and 2 fuel tanks in the current tractor trailer

This calculation assumes that all power for a tractor trailer, even at peak demands, comes solely from a fuel cell-powered engine. Thus, there is no "hybrid drive" system, where another power source is present to provide additional power if needed.

In actuality, the fuel cell, at least in bus applications, has demonstrated an efficiency of 46%, compared to the 20% of its Diesel ICE counterpart (Cole, 1998 [140]). However, buses spend the majority of their operational time making continuous starts and stops, with frequent intervals of acceleration and deceleration. For an application like tractor trailers, which spend the majority of their operational time traveling continuously at highway speeds, we can expect a smaller-scale improvement in the overall efficiency of a fuel cell as compared to its ICE counterpart. Also, despite the increase in tractor trailer weight due to hydrogen storage, the overall increase in efficiency due to the use of a fuel cell should still be much greater than that of its Diesel counterpart, leading to greater fuel efficiency. Furthermore, it can be expected that, with greater fuel efficiency, less hydrogen will have to be carried onboard, thus reducing the required area for storage.

> Scenario 2: This scenario assumes that there is a 50% improvement in efficiency by using a fuel cell in tractor trailer applications. Based on this increase in efficiency, we can determine the expected reduction in fuel storage area by using the ratio:
>
> (ICE Efficiency)(ICE Fuel Storage) = (FC Efficiency)(FC Fuel Storage)
>
> Setting the ICE Parameters as a baseline of 1, we see the following:
>
> (1)(1) = (1.5)(x) => x = 0.667
>
> = a 33% reduction in our originally calculated storage area can be expected.
>
> Applying this reduction to the appropriate calculations from Scenario 1 yields the following results:
>
> Liquid Hydrogen storage space required
> = (41.337 MJ / 10 MJ/m^3)*.667 = 2.76 m^3 = 3 tanks
> Compressed Hydrogen storage space required
> = (41.337 MJ / 3 MJ/m^3)*.667 = 9.19 m^3 = 82 tanks

At 100 pounds per tank (fully loaded with hydrogen fuel), the overall weight of a FC tractor trailer should increase by about 7,600 pounds (assuming that a fully-loaded 140 gallon fuel tank weighs about 300 pounds). This translates to a 15.2% percent increase in the weight of a fully-loaded tractor trailer, which is about 50,000 pounds. As in the first scenario, this increase in weight can be expected to result in a reduction in fuel efficiency. This reduction in fuel efficiency is not considered in this scenario.

The amount of hydrogen needed can be calculated as follows:

4.14 gallons of diesel = 5 kg of Hydrogen in HDV applications (estimated)

=> 280 gallons of diesel
=> 338.16 kg * 0.667 = 225.56 kg Hydrogen

Cost of FC stack and Compressed Hydrogen storage tanks now

= 317 (5,000) + 82 (35,000)
= $4.455 million (425 HP version)
= 391.5 (5,000) + 82 (35,000)
= $4.8275 million (525 HP version)

⇒This is still much higher than the $125,000 selling price of a new tractor trailer!

Cost of FC stack and Compressed Hydrogen storage tanks at goals

= 317 (50) + 82 (350)
= $44,550 (425 HP version)
= 391.5 (50) + 82 (350)
= $48,275 (525 HP version)

⇒This is about one-and-a-half times the cost of its Diesel ICE counterpart.

While the greater efficiency of the fuel cell leads to better fuel economy, the required storage area for hydrogen is still much greater than the area needed for Diesel storage. This extra storage area results in close to a 4-ton increase in weight, as defined in scenario 2. While longer storage tanks can be used which would be lighter than an equivalent number of small storage tanks (since the increase in weight of a longer tank could be expected to be less than proportional to the weight increase of using an equivalent volume of smaller tanks), the discount in weight realized by using longer tanks will not alleviate the substantial overall weight increase as a result of in the required increase in storage area. Furthermore, this weight increase will impact other design factors of the tractor trailer, since the added weight may result in the necessity for stronger axles, shocks, and other weight-bearing components of a tractor trailer. As the need for stronger parts arises, costs for these parts will also be much greater than those currently used on tractor trailers. However, researchers at Pacific Northwest National Laboratory are investigating ways of producing lighter weight, higher strength materials cost-effectively in order to reduce the weight of tractor-trailer combo by 20%, or about 6,000 pounds (Breakthroughs, 2002 [102]). Hydrogen storage requirement would offset the effects of this weight decrease, but would eliminate the need for using stronger axles, shocks, and weight-bearing components, since the weight of the tractor trailer would be roughly the same as we see today.

Lastly, while it may seem that liquefaction of hydrogen is a better alternative for hydrogen storage in tractor trailers due to the vast difference in the required number of tanks (3-4 versus 82-122), the costs to liquefy hydrogen are extremely high, and 30% of the energy in liquid hydrogen is expended while keeping the hydrogen in liquid form (Service, 2004 [179] [180]). Thus, a few additional tanks would need to be added to compensate for this energy loss. Additionally, the potentially high cost of installing systems to keep the temperature of the liquid hydrogen below -253°C (the temperature at which hydrogen reaches a state of liquefaction), both onboard the vehicle (which has no large-scale prototype in existence), and at the points of refueling (which have relatively few large-scale prototype in existence), must also be considered. Since manufacturers and experts are focusing on gaseous hydrogen as the preferred state of hydrogen for transportation applications, it can be assumed that the total cost of using a liquid hydrogen-based storage system would greatly exceed that of using a gaseous hydrogen-based storage system.

Chapter 8

The Energy Model

This chapter will consider the future energy use of passenger buses, as well as the impact that a transition to hydrogen fuel cells may have on this energy use. Creating a model is a powerful tool for dealing with the diverse factors that can impact future energy use. The first step in creating this energy model is to create forecasts for the Vehicle Miles Traveled (VMT) and energy consumption of transit buses. The data for Vehicle Miles Traveled and energy consumption can also be used to generate historic values for energy efficiency (i.e. BTU/mile) in transit buses. These values can then be applied to a forecast to determine a trend for energy efficiency of transit buses in the future. These forecasts will be discussed in greater detail in the upcoming sections.

8.1 Vehicle Miles Traveled Model

The VMT model uses regression analysis to predict the number of miles to be traveled by the nations transit buses in future years. The historical data that forms the basis for this model can be found in Appendix B.8. Generally speaking, increases in the number of transit bus miles traveled have been proportional to increases in the number of transit buses on roadways. Therefore, this model could provide initial indication as to the demand for transit buses in the future. In this model, the independent variable is the year, and the dependent variable is the number of transit bus miles traveled in millions of miles. The results of the regression are as follows:

a = -141715
ß = 74.4017
R^2 = 0.8633

The results of this regression can be seen in here in Figure 8.1.

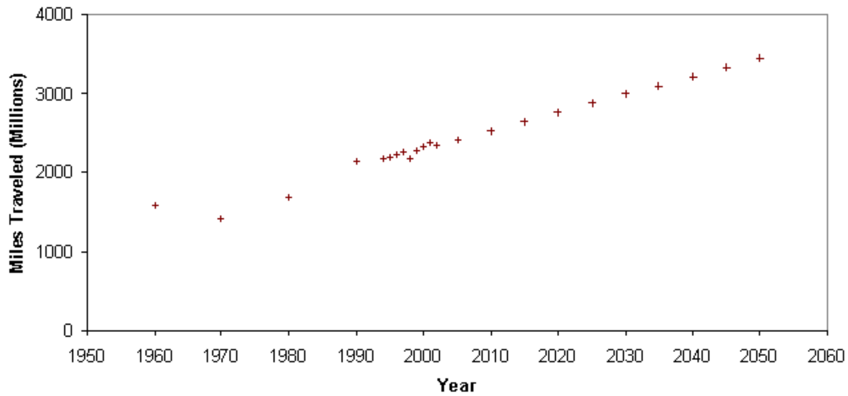


Figure 8.1: Transit Buses Vehicle Miles Traveled

8.2 Energy Model

The energy model uses regression analysis to predict the total amount of energy consumption by the nation's transit buses in future years. The historical data that forms the basis for this model can be found in Appendix B.9. This model could provide indication as to the demand for hydrogen, or any other fuel, by transit buses in the future. In this model, the independent variable is the year, and the dependent variable is the total energy consumption by transit buses in trillion BTU. The results of the regression are as follows:

a = -5051.53

ß = 2.6

R^2 = 0.8938

A graphical representation of this regression can be seen in Figure 8.2.

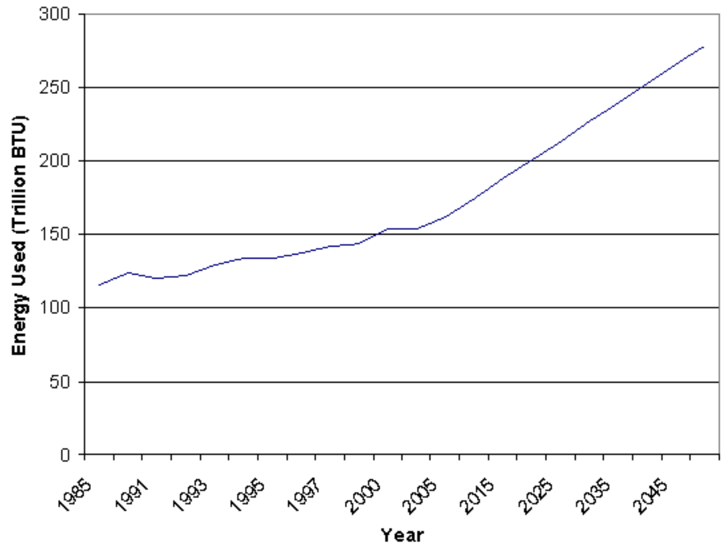


Figure 8.2: Transit Bus Energy Used

The energy efficiency trend of transit buses was predicted using regression analysis, in order to predict the total amount of energy consumption by the nation's transit buses in future years. The historical data that forms the basis for this model was generated by dividing the VMT data found in Appendix B.8 by the corresponding energy consumption data found in Appendix B.9. This model could also provide an indication as to the demand for hydrogen, or any other fuel, by transit buses in the future, since a decreasing trend in energy efficiency would indicate that technology is improving an engine's ability to utilize fuel. Thus, less fuel would be required in the future. In this model, the independent variable is the year, and the dependent variable is the energy efficiency expressed in terms of BTU/mile. The results of the regression are as follows:

a = 260561.7

ß = -120.097

R^2 = 0.9019

A graphical representation of the results of this regression can be seen in Figure 8.3.

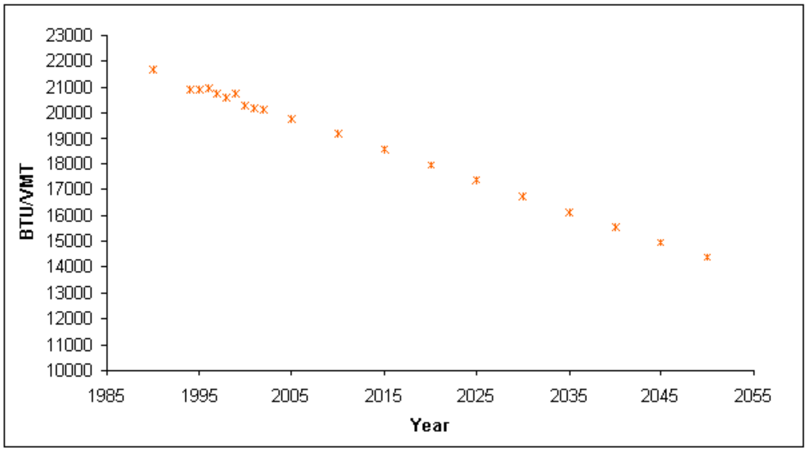


Figure 8.3: Bus BTU/VMT

8.3 Energy Conversion to Hydrogen

In this section the amount of hydrogen that would be needed to satisfy the energy demand modeled in previous sections. To do this we obtained the BTU values of both diesel and hydrogen, and then applying this to the energy consumption model to determine the amount that will satisfy the demand.

The BTU values of the fuels we are considering are:

$$1 \text{ gal. diesel} = 110{,}00 \text{ BTU}$$
$$1 \text{ kg } H^2 = 134{,}000 \text{ BTU}$$

Therefore, to determine how much of each would be required to satisfy future transit bus energy demands we apply these values to values for total energy consumption, which were found earlier in this chapter, and obtain the amount of each type of fuel needed. A graph of the amount of diesel needed, assuming there is no conversion to hydrogen fuel cells, can be seen in Figure 8.4.

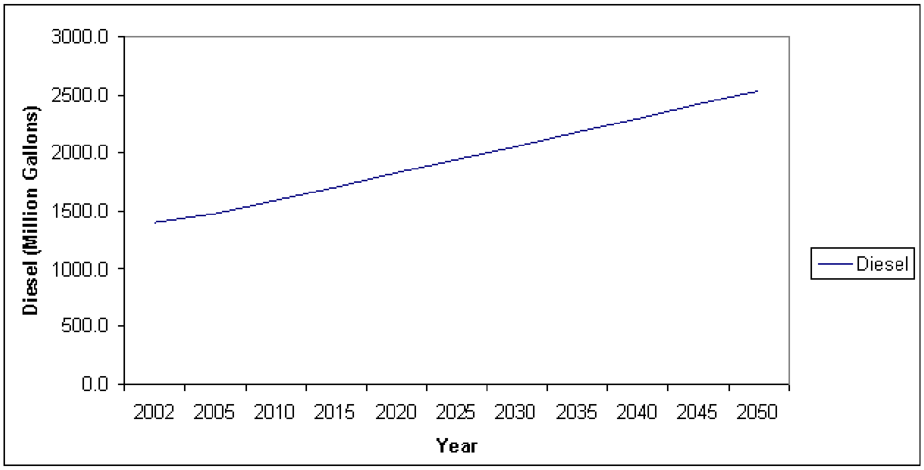


Figure 8.4: Amount of Diesel Needed

Alternately, a graph of the amount of hydrogen needed to meet the future transit bus energy demand, assuming no more use of diesel, can be seen in Figure 8.5.

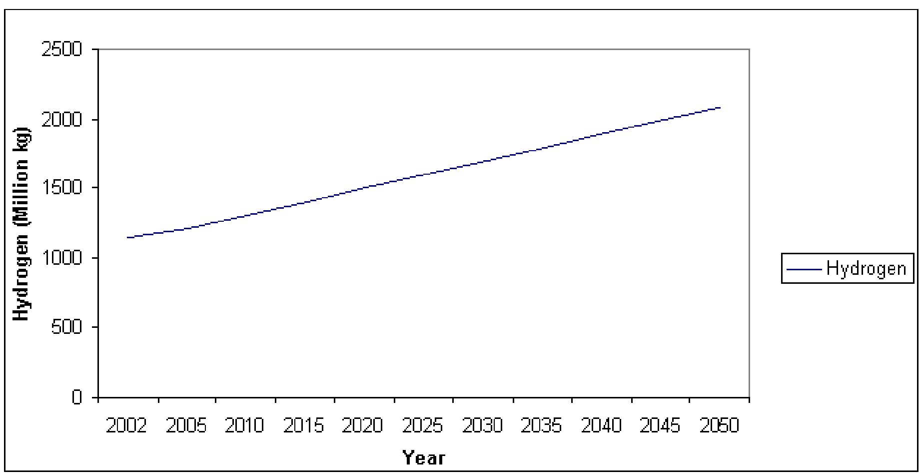


Figure 8.5: Amount of Diesel Needed

Chapter 9

Transition Requirements

Using fuel cells as an alternative to the internal combustion engine in heavy-duty vehicles will require the pursuit of three main objectives:

- Achieving comparable performance standards to an internal combustion engine;
- Realizing substantial reductions in cost to make fuel cell buses competitive in the market place; and
- Establishing a distributive fueling and maintenance infrastructure to accommodate extended travel distances.

9.1 Infrastructure

British Petroleum has stated that in order for a hydrogen economy to truly catch on hydrogen fuel must be available at 30% to 50% of refueling stations, but this can only happen when a large market for hydrogen has been established (Service, 2004 [179] [180]). Shifting from our oil-based fuel economy over to a hydrogen-based economy will be a difficult task since all of our equipment, as well as our automobiles, are dependent on oil. Despite venture capitalism and or sources of funding, the government will still have to shoulder the burden of funding in order to change the entire infrastructure. Researchers in Illinois have determined that creating the necessary infrastructure to fuel 40% of American cars with hydrogen could cost as much as $500 billion dollars (Cromwell et al, 2002 [141]). Different companies, including transit agencies, have already started to develop and construct hydrogen filling stations as examples of what to expect in the future. Currently there are a total of 74 compressed and liquid hydrogen fueling stations around the world, 27 of those in United States. In addition, 15 of these 27 are in California (Worldwide Hydrogen Fueling Stations, 2002 [126]).

These pilot projects are usually broken down into three separate phases, which can take as long as four years to complete. The first phase includes the overall design of the station, as well as feasibility studies. The second phase is to construct subsystem development, while the third phase is the assembly and demonstration of the fully intergraded system (Kumar et al, 2002 [161]). During the developmental phase, it is important to maximize the potential for technological innovation while keeping costs at a minimum, primarily by limiting the size of the refueling infrastructure.

9.1.1 Physical Requirements

The physical requirements for designing a hydrogen bus refueling station consist of a hydrogen generation system, compression system, storage system, fuel dispenser, and piping. A bus maintenance facility or holding bay is also needed. The hydrogen generation can use various methods to produce hydrogen gas, such as electrolysis, natural gas steam reforming, purification of chemical by-products. Fueling stations have the option of generating their own hydrogen on-site or having it delivered in liquid form.

For on-site production, most agencies are currently using electrolysis and natural gas steam reforming as the preferred method of hydrogen generation. As an example, Stuart Energy uses an electrolyzer to generate hydrogen at 363 psi. In order to supply hydrogen for 100 to 2000 cars per day, an electrolyzer would have to produce 5 to 8 Megawatts (MW) of electricity.

A compressor is then used to raise the pressure of hydrogen up to 6,000 psi before it can be properly stored. The storage module is built with either double wall carbon steel or carbon fiber composite tanks, and stores the hydrogen using a buffer or a cascade method. The buffer method stores hydrogen using a configuration consisting of a series of interconnected tanks that are filled and emptied as if they were one large tank. The cascade method stores hydrogen in a series of "banks," managed by a control system that determines which bank is able to receive or deliver hydrogen. When hydrogen is being pumped out, the first bank delivers hydrogen until the pressure inside this bank equals that of the receiving tank. As the pressure equalizes, the next bank begins to deliver its reservoir of hydrogen, and so on. This method is best for fast-fill vehicle fueling, as well as minimizing on-site hydrogen storage space.

The fuel dispenser module consists of a hose, nozzle, and a management system that controls the operation of the dispenser and the flow of hydrogen to the vehicle. The system has the ability to determine when the vehicle tank has reached full capacity, at which time it will automatically stop dispensing. The system dispenses hydrogen at high pressure and takes an average of 10 minutes to fill up a bus. The interface is the same as a gas station, which asks the customer to use a PIN number or a credit card as a form of payment (Stuart Energy Station, 2004 [110]).

For off-site hydrogen production a distribution network is necessary. The hydrogen transportation can be delivered using either pipelines or tanker trucks. It is preferable that the location of the filling station be in close proximity to the hydrogen production plant, in order to minimize transportation costs. In some cases, hydrogen will be delivered in liquid form, requiring storage in underground liquid hydrogen storage tanks. From the storage tank, there will be a pump that vaporizes the hydrogen and transfers gaseous hydrogen over to the filling station in compressed form. This type of system was used during the early onset of hydrogen technology in places like Chicago and Vancouver (The Bus of the Future, 2004 [113]).

During cold weather the buses must be kept warm in specially designed bays. If the buses were to be left out in the cold the water vapor residual would freeze, thus damaging the fuel cells. However, the newer generations of fuel cells being design are much drier and may not need this protection (Vogel, 2004 [191]). Xcellsis developed a "out-door style" bus maintenance facility, which can hold up to five buses at the time. This facility has tent-like structures consisting of aluminum frame, fire proof canvas, and explosion proof lighting. This facility is designed to allow the hydrogen to escape if in the event of a leak. However, this type of facility would not work in all climate zones, unless the facilities were to be heated during winter (Eudy et al, 2001 [145]).

The fueling facilities must follow specific guidelines for developing and constructing a hydrogen dispensing station. The facility must be located outdoors, away from any operating electrical machinery or overhead wires, and must provide appropriate mechanical design, electrical design, adequate clearances, safety provisions and equipment, appropriate use of materials, and security. As part of the mechanical design and electrical design of a filling station, there are many requirements that must be followed which include (Maintenance and Fueling Facility Guidelines, 2001 [100]):

- The hose, compressor, tanks, piping manifold, and other hydrogen containing portions must all be grounded properly.
- Check valves must be installed to ensure no blowback occurs.
- There must be pressure relief devices installed for the tanks in case of overpressure.
- The compressor must be explosion proof.
- The fuel dispenser must have a breakaway connection on each hose that limits the breakaway force to 150 lbs.
- The fueling system must prevent entry of air into the vehicle fuel system.
- The fuel system must be automatically interrupted when the bus fuel tank contains low pressure which indicates the presents of air.

- There must be an Auto shut off capability when the bus is full.
- The fuel dispenser must have temperature compensation system.
- There must be vent provisions capable of discharging entire contents of vehicles fuel storage into atmosphere.
- Any electrical equipment that produces sparks may not be used.
- All Electrical equipment must be grounded.
- Infrared or Ultraviolet flame sensors are required in the vicinity of the fueling facility.
- An emergency stop button is required, along with fire extinguishers.

One of the leading global providers of hydrogen refueling systems is Stuart Energy, which has teamed up with various cities around the world in order to develop hydrogen fueling stations as well as developing a hydrogen refueling system of their own at their headquarters in Mississauga, Ontario, Canada. The generator, which uses electrolysis, is capable of producing 25 kg/day of hydrogen (12 Nm^3/h) as well as storing 60 kg at 5,000 psi (Delivered Stuart Energy Stations, 2004 [78]).

There are a number of Stuart Energy Stations currently in use around the world, which have the ability to generate anywhere from 80 kg to 120 kg of hydrogen while servicing three buses a day. In Sacramento, California there is a hydrogen refueling station that consists of a 4,500 gallon liquid hydrogen storage tank, a compressor to raise the pressure to 6,250 psi, and two dispenser systems to deliver hydrogen gas at 3,600 psi and 5,000 psi (California Fuel Cell Partnership, 2004 [95]). The fill time for each bus is approximately four minutes. Luxembourg, which is part of the CUTE project, is running a two-year demonstration of a hydrogen dispensing system. In this case the hydrogen is delivered from off-site production. The fill time at this station is 10 minutes with a total of 40 kg of hydrogen per bus. Amsterdam has a similar system, except that hydrogen is produced on-site using electrolysis (The CUTE Amsterdam Project, 2004 [115]). AC Transit in California has two fueling stations in service, both using Stuart Energy electrolyzers. The first station produces 24 kg/day of hydrogen, and the second puts out 50 kg/day, which can refuel up to 3 buses at 5,000 psi (California Fuel Cell Bus Trials, 2004 [77]). Ann Arbor, Michigan has a station which stores up to 1,500 gallons of hydrogen in liquid form. The fuel is then vaporized to form compressed hydrogen gas, producing enough fuel to fill four to five buses at a time and eight or more per day (Hydrogen Fueling Station, 2004 [95]).

General Electric has developed a hydrogen generation system designed for vehicle refueling. The system uses a reformer to convert fuels to a hydrogen rich gas that can be easily purified. This technique can be applied for production of hydrogen from natural gas, diesel, coal, and renewable feed-stock, such as biomass. The system also includes a purification unit, hydrogen compressor, high pressure tanks, and a dispensing unit. The efficiency of the generator was calculated to be roughly 80%. However, some factors which could affect the efficiency of hydrogen production include the conversion in the reformer, recovery of hydrogen, utilization of process heat to generate process steam, and minimization of parasitic losses. The system is built to produce 40 kg of hydrogen and can refuel one bus or eight cars per day. (Kumar et al, 2002 [161]).

Sunline Agency in California uses two solar and grid power electrolyzers to produce hydrogen, though they also use steam reforming for hythane. The capacity of the electrolyzer is 1,400 standard cubic feet hour (SCFH). The storage system consists of a tube trailer and stationary tanks holding approximately 118,000 SCF of compressed hydrogen. In addition, there is a two-hose fueling station, one supplying compressed hydrogen gas, the other supplying Hythane. Since opening in 2000, Sunline has used the hydrogen gas to fuel vehicles including a number of prototype FCVs and Hythane buses. This has allowed them to learn how to transition from compressed natural gas buses to hydrogen buses while examining the reliability and maintainability of hydrogen powered buses (Cromwell III et al, 2002 [141]).

If the United States were to build larger hydrogen infrastructure systems to accommodate more buses then the refueling plants would have to change to meet new needs. To meet the needs of 6 to 30 buses a micro on-site generator would have to be built. For fleets of 30 to 200 buses, a small on-site steam reformer or production plant would be required in order to accommodate the fleet. For a fleet of 200 to 2,000 buses, an off-site production plant with pipelines connected to the rest of the system. Finally systems supplying 2,000 to 10,000 buses would require an integrated large-scale hydrogen plant to produce enough hydrogen.

As hydrogen technology evolves the United States must conduct initial demonstrations of hydrogen systems including buses, support and maintenance facilities. As the load at each site increases, the on-site plant must expand proportionally. The next step would be to create larger plants with local pipelines until a large centralized production plant is created with multiple modes of distribution (Raman, 2000 [175]). An even better solution to energy storage would be to build stationary reformers at existing compressed natural gas filling stations so hydrogen could be used directly as an energy carrier. The reformers would continuously run and would be shared by a large number of consumers, thus minimizing developmental cost.

9.1.2 Financial Requirements

In order to determine the financial requirements for building a hydrogen refueling facility, the cost of building each component and the current cost of hydrogen must be considered. For hydrogen to be a true, long-term, renewable alternative to fossil fuels, it would need to be produced with a clean, low-cost source of electricity such as geothermal energy in Iceland. Thus, there is potential for rapid development of hydrogen production using clean renewable energy. In the United States, wind and solar power seem to be the best choice in hydrogen production.

There are several problems associated with the production of hydrogen, which need to be addressed before significant changes to the infrastructure can be made. Currently hydrogen cost up to three times as much to produce when compared to gasoline or diesel fuel. But with the expansion of the hydrogen infrastructure a price of $1.50 per kg for hydrogen is anticipated in the future (Cromwell III et al, 2002 [141]). In addition, scientist cannot agree on the best way to store hydrogen, which could also drive the cost either up or down depending on what method is ultimately chosen. In other countries, especially developing nations, it will be hard to create a clean and effective hydrogen economy, because in those countries there are technological limits (Hutchison, 2003 [155]).

General Electric and Environmental Research Corporation have developed a hydrogen generation system with a target cost of hydrogen expected to be less than $2.50 per kg, when the refueling system is manufactured at a rate of 1,000 units a year, based on the natural gas price of $4.00 per MMBtu. As it takes 5 kg to fill one car the total cost of refueling would be approximately $12.50, which is less than the current $30 per fill up with gasoline. It is also important to note that it takes 40 kg to fill up one bus, coming out to $100 per fill (Kumar et al, 2002 [161]).

Kumar et al (2002) conducted an economic analysis to determine the costs of hydrogen production and the refueling system without mass production. Scaling laws were used to determine the cost of commercial system from the cost of the prototype unit, because as more units are built the cost is expected to decrease. As part of the analysis, the installed capital cost of both a 150 kW and 500 kW commercial fuel processors were estimated. The cost of hydrogen was estimated to understand the market position of the Autothermal Cyclic Reforming (ARC) based fuel processor. The installed capital cost includes equipment cost, design cost, and fabrication cost. It was assumed that piping and fabrication costs accounted for 30% of the total equipment cost. Below is a table depicting the total cost breakdown of the 150 kW ACR hydrogen generator (Kumar et al, 2002 [161]):

Cost	150 kW Prototype System	150 kW Commercial System
Equipment Cost	$350,000	$332,500
Design Cost	$90,000	$45,000
Fabrication Cost	$130,000	$97,000
Total Installed Capital Cost	$570,000	$475,000

Table 9.1: Cost Breakdown of 150 kW ACR hydrogen generator

This is only the cost of the hydrogen generator, which excludes cost of hydrogen compressor, storage tanks, and dispenser. It was assumed that the equipment costs of mass-produced units would decrease by 5% when commercial units are built. For specialty equipment such as the steam generator the design were reduced by 50% and the fabrication costs were decreased by 25% as more units are designed and built. The 500 kW system was scaled using the following power law:

$$\text{(cost of 500kW system)} = \text{(costs of 150 kW system)}(500/150)^{0.29}$$

It was assumed that the scaling factor from 150 kW to 500 kW was a constant value of 0.29. Results in an installed capital cost of $675,000 for a 500 kW commercial hydrogen generator. The cost of hydrogen generation for a 500 kW commercial unit was calculated based on the net revenue required, which was determined from the capital investment, operating and maintenance costs, and fuel and electricity costs. This was the cost estimated through the economical analysis that was conducted. It did not consider the cost reduction due to mass production and the cost of hydrogen compression, storage and dispensing (Kumar et al, 2002 [161]).

The Stuart Energy P3 electrolyzer has the capability to produce 1,400 SCFH of hydrogen. The cost of purchasing a Stuart elctrolyzer, which includes the compressor, is $350,000. Stuart's tube trailer storage unit can cost up to $115,000, while the fixed ground storage unit cost $54,000. Stuart's hydrogen dispenser is priced at $50,000. These prices are for the cost of the individual unit, but do not take into account the cost of design and fabrication (Cromwell III et al, 2002 [141]). If someone were to design a system with off-site hydrogen production, it is important to minimize the delivery distance. If the delivery distance were to exceed several hundred miles, then the transportation cost of hydrogen would exceed its production cost.

In 1998, Chicago Transit Authority, the second largest U.S. public transportation system, had a hydrogen station, including a maintenance facility, built as a part of a two-year demonstration program. The cost per bus was estimated to be $1.4 million, for three buses in total. The fueling station and fuel cost $600,000, along with $1.6 million for spare parts and technical assistance. During the winter the weather in Chicago can drop below freezing, which meant $1.5 million was needed to be spent modify the garage for the buses. An additional $1 million was spent on training, maintenance, and project management (Lang, 2000 [162]).

The cost of designing a new infrastructure can be expected to vary for different transportation agencies. It depends on the manufacturer, the state in which the agency is located, and the amount of funding received. Sunline Transit in California had developed an on-site partial oxidation reformer of natural gas which has the ability to fuel four or five buses per day. The cost of this system was $450,000. The storage system consisted of 16 tube trailer cylinder tanks (104,000 SCF), at a total price of $104,000, and two stationary cylinder tanks (14,000 SCF) at a total price of $54,000 (Eudy et al, 2001 [145]). Funding from the California Transportation Authority was divided amongst different agencies for the construction of buses, infrastructure, and operations. Sunline received $4 million while AC Transit and VTA were awarded $15 million and $18.45 million respectively (California Fuel Cell Bus Trials, 2005 [77]).

Los Angeles International Airport has built the first retail hydrogen fueling station, which opened in October of 2004. Praxair was contacted to design, engineer, equip, construct, and operate the 600 ft^2 state-of-the-art facility. The facility was built with high pressure hydrogen storage on the roof. The total cost came out to $1,580,048. Praxair funded construction by spending $550,000 of its own funds, while the rest of the money came from grants totaling $1,030,048. The airport currently has 50% of its vehicles running on alternative fuels, and is a great step toward changing the infrastructure. The lease agreement for this facility is for three years with no fees and has a two year option for Praxair to extend the lease at $27,355 a year (Hydrogen Now, 2005 [98]).

There are several other projects worth nothing around the world. The project that is currently underway in Amsterdam as a part of the CUTE program received funding worth $9.9 million to purchase hydrogen buses as well as design, construct, and operate the infrastructure. In Western Australia there is a two-year fuel cell bus demonstration that operates three fuel cell buses as a part of the CUTE program. The total funding for this project was calculated to be $9.95 million. As for the construction of maintenance facilities, Xcellsis redesigned a five bus holding bay in order to keep the buses warm during the winter season for $95,000.

9.2 Reconfiguration of HDVs

In the last ten years, fuel cell technology has made significant developmental strides in the automotive industry. Fuel cells have become the future, aiming to replace internal combustion engines with a clean, quiet, efficient, and environmentally sound alternative. The design of heavy-duty fuel cell engines has been refined to the point that 40 foot urban transit buses powered by one and weighing in excess of 13,600 kg, is able to carry 70 to 80 passengers up grades in excess of 15% and travel on the highway at top speeds of 65 mph, all while offering quick and more efficient acceleration. Despite this, there are many questions that still need to be answered, including sustainable levels of performance over daily duty cycles up to 15 to 17 continues hours, longer distances between fueling of approximately 300 miles, durability over five to six years, and competitive capital and life cycle cost.

When switching from a diesel powered transit bus over to a hydrogen powered bus, there are many considerations that must be taken into account. The reconfiguration of the buses drive train, hydrogen storage tank, and balance of system all play an important role in the fuel cell bus design. It is also important to keep in the mind the fuel economy for both the diesel power bus and hydrogen powered bus. Future fuel cell technologies such as auxiliary power units, possible uses for waste heat, and hydride storage can have significant impact in the reconfiguration of HDV's (Levin et al, 2001 [165]).

9.2.1 Drive Train

The hydrogen bus drive train is broken down into many components including the fuel cell supply unit, the fuel cell stack modules, a cooling unit, an electrical traction engine, an inverter, auxiliary components, a compressor, the transmission, and the propulsion shaft. Figure 9.4 is a visual diagram of a hydrogen bus.

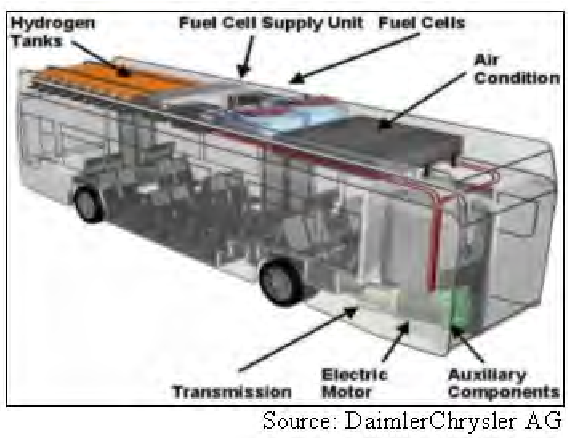


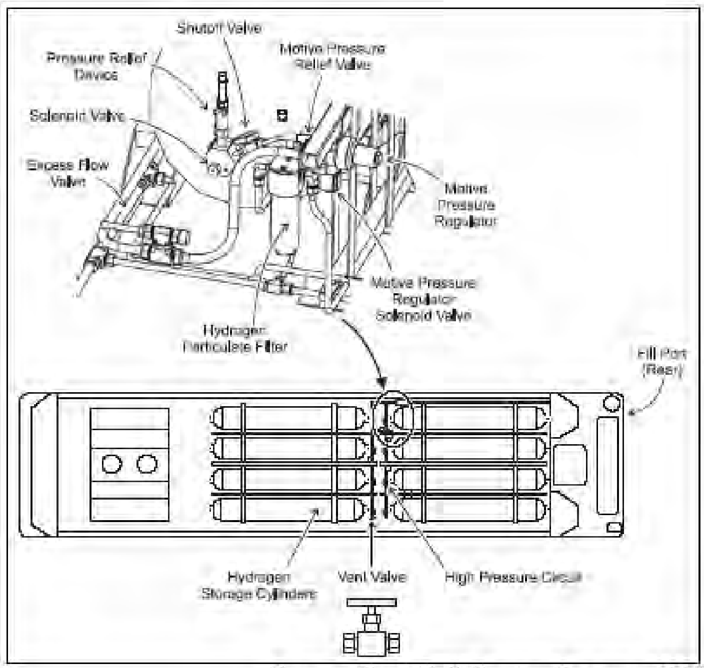
Figure 9.1: Schematic of a Fuel Cell Bus

The fuel cell supply unit is responsible for controlling the flux of hydrogen into the fuel cell, the air compressor, and the flux of air into the fuel cell. The fuel cell center unit also controls the flux of cooling water through the fuel cell stacks to ensure optimum temperature. The fuel cell stack module ensures that all components that operate on hydrogen are in close proximity. It also transforms chemical energy of hydrogen into electrical energy. There are usually two of these built into hydrogen transit buses. The cooling unit dissipates the waste heat of the fuel cell stack and provides cooling for the inverter, traction motor, and gearbox. The electrical traction engine's main purpose is to provide traction power, as well as power for auxiliary components. The electrical motor receives its power from the inverter, which is similar to that of a battery electric vehicle. The inverter converts the DC power from the fuel cell to AC power for the electrical traction engine. The auxiliary components are similar to that of a diesel bus in which the electrical engine provides power to move all the pumps, compressors, and alternators that require the bus to drive. This includes the following components: power steering pump, air brake compressor, alternator, radiator fan, cooling pumps, super charger for air supply, lube pump, and AC compressor. The compressor is then used to supply air at an overpressure to the fuel cell, providing oxygen for the chemical reaction. The transmission is comparable to that of a conventional transmission, except the gear ratios are adapted to the special torque characteristics of an electrical engine rather than combustion engine. A diesel engine has maximum torque at high revolutions, while electrical engines have maximum torque at low revolutions. Finally, the propulsion shaft is similar to its diesel counterpart, completing the fuel cell drive train (The Citaro Fuel Cell Bus, 2004; Fuel Cell Bus Club, 2004 [114]).

The drive train of a conventional 40 foot diesel bus has a much more simplistic design. It consists of an engine, transmission, and the differential (propulsion shaft). The drive train of a diesel bus is the same as that of a hydrogen bus, minus components connected to the fuel cell and the fuel cell itself. The engine is an internal combustion engine which compresses and ignites diesel to get its energy. This energy is also used to power the auxiliary components, including the power steering pump, air brake compressor, alternator, radiator fan, cooling pumps, super charger for air supply, lube pump, and AC compressor. Since fuel cells have no moving parts they can be expected to be more reliable than ICEs. In addition, fuel cells also require less maintenance than internal combustion engines due to the complexity of the parts. Chicago Transportation Authority's fuel cell buses are visibly different from its diesel collection. The fuel cell buses weigh 4,500 lbs more than the conventional diesel bus, and are eight inches longer and nine inches taller than the diesel counterpart (Lang, 2000 [162]).

9.2.2 Hydrogen Storage

The fuel storage system receives, stores, and dispenses the hydrogen fuel. The fuel storage system consists of a fueling circuit, the storage cylinders, a high pressure circuit, and a motive pressure circuit. The fueling circuit is responsible for receiving fuel from the dispenser and sending it through the high pressure circuit which in turn fills the cylinders. The cylinders then store the hydrogen as a high pressure gas. Hydrogen transit buses have either eight or nine high pressure vessels which are usually located on the front part of the roof shown below on Figure 9.5.



Source: Fuel Cell Engine System, 2001

Figure 9.2: Hydrogen Storage System

When the hydrogen flows from the cylinders to the fuel cell, it first goes through the high pressure circuit, which links the hydrogen storage vessels with both the fueling circuit and motive pressure circuit. The high pressured gas then flows through an excess valve to the motive pressure regulator assembly. The motive pressure circuit supplies intermediate pressure hydrogen to the fuel delivery system, reducing the hydrogen pressure from its storage pressure to approximately 175 psi. This type of pressure regulator is also used in a compressed natural gas bus. A solenoid valve automatically closes and isolates the high pressure circuit whenever the bus is shut off. There is a pressure relief valve that protects the fuel cell engine by releasing hydrogen through a roof vent if the motive pressure were to ever exceed 250 psi (Fuel Cell Engine System, 2001 [101]).

High pressure compressed hydrogen and cryogenic liquid hydrogen present significant barriers to mass market introduction. The problem with high pressure tanks is that they are very expensive, as compared to low pressure tanks, but low pressure tanks are not as compact. Furthermore, one tank would currently have to be ten times the volume of a gasoline tank to carry the energy required for the same driving distance. Higher fuel cell conversion efficiency could reduce the volume required to five times that of gasoline (Heller, 2004 [151]).

Possible approaches to hydrogen storage include: compression, liquefaction, chemical storage, metal hydrides, and adsorption. No approach currently satisfies the efficiency, size, weight, cost, durability, and safety requirements for transportation use, but high pressure compressed hydrogen tanks seems to provide the best near and medium term solution for hydrogen storage because significant cost reductions are possible with future optimization coupled with economics of scale (Sirosh et al, 2003 [182]).

Goals for hydrogen storage cylinders consist of cutting costs, increasing efficiency, and preparations for mass production. Therefore, funding for research is critical; the DOE has been asked to triple research funding from $11 million to $30 million for bus storage tanks in 2004. Currently a 5,000 psi tank can hold enough hydrogen for 182 miles while a 10,000 psi tank has an efficiency of 300 miles. The cost of these high pressured tanks ranges from $20,000 to $50,000 per tank. The goal is to bring the price range down to $200 to $500 per tank. To cut costs, researchers are working on finding ways to improve and mechanize tank construction by applying carbon fiber to the outside. Carbon fiber is one of the strongest yet lightest materials and costs $10 per pound (Bennett, 2003 [134]). The only problem is the cost of carbon fiber is too high to achieve DOEs cost goal of $5 per kWH, even if significant raw material cost reduction due to economics of scale is taken into account. Since carbon fiber cost is a large portion of the overall cost of building storage tanks, the amount of carbon fiber would have to be reduced while maintaining equivalent levels of performance and safety (Ko et al, 2004 [160]).

What makes hydrogen unique is that at room temperature and standard pressure, hydrogen takes up roughly 3,000 times as much space as gasoline. Thus, 10,000 psi tanks take up to eight times the volume of a current gas tank to store the equivalent amount of fuel (Cromwell III et al, 2002 [141]). The current dimension for a 5,000 psi compressed hydrogen storage tank for buses has a diameter of 11 inches and a length of 83 inches and weighs five kg.

The DOEs target for hydrogen storage systems in 2010 is to extract from hydrogen a usable specific energy of about 2.0 kWH per kg and a energy density of 1.5 kWH per Liter. The DOE request the hydrogen delivery temperature to be in a range of -30^{o}C to 100^{o}C with a cost of $4.00 per kWH and a cycle life of 1,000 cycles (Sachtler, 2004 [177]).

9.2.3 Balance of System

The balance of system for a hydrogen bus is similar to that of a conventional diesel bus. The only differences are the added safety features to protect the hydrogen tanks from direct impact as well as detect any possible leaks in the system. The opportunity for hydrogen to escape in large volume's is rare, but could occur due to tank rupture or breaking of connecting lines between tanks and the shut-off device. Also, the release of small quantities of hydrogen could be due to leaky fittings or connections. Therefore, a leak detection system is added to detect the presence of hydrogen and passes alarm signals to the vehicle's control system. The leak detection system consists of a series of leak sensors, leak indicators, and a junction box. The leak sensors are calibrated to measure hydrogen gas concentrations and are strategically placed with in the bus. The hydrogen leak indicator associated with the sensor compensates for resistance change by altering the electrical power fed which is proportional to the amount of gas present and records a measurement of the current gas concentration. Thus, each leak indicator powers a single sensor and displays the gas concentration detected by that sensor. If the gas concentration on any hydrogen leak indicator exceeds an internal threshold, a warning is sent from the indicator through a junction box to the control system, which in turn alerts the driver and shuts the engine down. There is also a fire suppression system organized in a series of zones that serve specific areas in the bus. The system is active at all times unless the battery power is interrupted. The fire sensors are located in areas of highest fire probability (Fuel Cell Engine System, 2001 [101]).

In order to protect the tanks from direct impact, mechanical safety features must be constructed in such a way as to prevent explosions from happening. All of the hydrogen buses must be built with a reinforced body frame to protect tanks in case of side collision. Earlier models like the liquid hydrogen buses which ran in Germany had the tanks mounted close to the centerline at the bottom of the bus due to limited knowledge of roof installation. There was also protective paneling beneath the tanks to prevent from stone chipping damage. Having the tanks located beneath the bus seemed like a dangerous idea, and they were then moved to the roof (Davis/Sacramento, 2000 [92]).

Weight discounts can be realized with advancement in technology. Pacific Northwest National Laboratory and the Northwest Alliance for Transportation Technology (NATT), in partnership with DaimlerChrysler, the DOE, and Alcoa, have developed three prototype lightweight vehicle frames that are steel and aluminum hybrids. This provides close to a 30% weight reduction in the Dodge Durango. Prototype windshields that are supposed to be 30% lighter than current windshield, which also retain optical, thermal and safety properties, are in the process of being developed (PNNL Breakthroughs Magazine, 2002 [102]).

9.2.4 Fuel Economy

The current generation of fuel cell buses have 205 kW PEM fuel cells on board. Most use compressed hydrogen gas and can travel between 124 to 250 miles before refueling (Fuel Cell Buses, 2000 [87]). During demonstration of the fuel cell bus, there have been many comparisons made to its diesel counterpart. It can be said that the system efficiency of fuel cell buses will be higher than that of diesel buses, resulting in lower fuel consumption. In fact, researchers have noticed that the fuel cell demonstrated 46% fuel efficiency, while the diesel engine demonstrated only 20% fuel efficiency (Cole, 1998 [140]). Since production, compression, cooling and transport of hydrogen require energy, the impact of fuel cell usage will depend on the methods and materials used in these processes. This means that well-to-wheel efficiencies and life cycle assessments must be calculated to determine the overall environmental and technical effects of fuel cell usage compared to diesel.

Currently, Sunline has the Thunderpower bus which is being used for fuel cell demonstration. The Thunderpower bus looks like a standard diesel bus but is able to cover 11 miles per gallon of diesel equivalent, which is currently three times that of the fuel economy of a 40 foot conventional bus which gets 3.5 miles per gallon of diesel. The Thunderpower accommodates 26 passengers and has a range of 175 to 200 miles before requiring refueling (Sunline Test Drives Hydrogen Bus, 2003 [156]).

9.2.5 Future FC Technology

In this section we will discuss potential future development in fuel cells, and their possible impact in heavy-duty vehicles. This will include the use of fuel cell auxiliary power units in tractor trailer trucks during idling, possible use of hydrides as a fuel storage medium, and possible use of waste heat to heat the hydride compound.

Fuel Cell Auxiliary Power Units

Fuel cell auxiliary power units (APU) have been discussed as a possible option for truck idling. Since truck drivers spend majority of their time on the highway, they often use rest stops as a place to sleep. Heavy-duty line-haul engines idle approximately 20-40% of the time the engine is running, to control heating in the cabin and sleep compartment accessories. The EPA estimates that a truck spends up to an average of 8 hours a day for 300 days in a year idling, in some cases with line-haul sleeper tractors up to a total of 10 hours each day. Idling is a big problem because it increases air pollution and energy use, as well as wear down the engine. Currently there is no federal law against idling, but a patchwork of idling rules has been adopted by local and state government (UCD, 2002 [81]). In Massachusetts there is a law that prohibits unnecessary idling of all motor vehicles that are stopped for a foreseeable period of time over five minutes. Effectively, if your vehicle is going to be stopped for more than five minutes, the engine must be shut down. Drivers who violate this law may be subject to a fine (EPA, 2004 [76]). Idling engines operate very inefficiently, with only a 3% energy efficiency, compared to 40% efficiency when running on the highway. An estimated $1 billion is spent on fuel for idling and another $1 billion on engine wear and maintenance due to idling. For this reason the concept of a fuel cell APU system was developed by Freightliner and Ballard Power Systems. The fuel cell APU diminishes idling time by utilizing advanced emissions free fuel cell technology to deliver electrical power. It has been said that the fuel cell APU could save between 0.2 and 1 ton NO_x which is between 6% and 29% NO_x emissions reduction in addition to reducing cost spent on fuel and engine repair (UCD, 2002 [81]).

Researchers are currently looking into using a 5 kW PEM fuel cell to provide electrical power to the cabin. The cost of a fuel cell ranges from $2,000 to $9,000 per kW, including fuel cell stack, auxiliary systems, and power & control electronics, but not the hydrogen storage system. Using an average price of $5,000 per kW the 5 kW PEM fuel cell would cost up to $25,000. There are additional capital costs associated with the fuel cell APUs, including fuel tank cost, installation cost, operation and maintenance, auxiliary heater and air conditioner, plumbing and wiring cost and trace inverter cost. Using these costs along with the price of diesel per gallon and the price of hydrogen per gigajoule, an optimistic payback period of approximately 4.5 years was calculated using a $3,000 per kW fuel cell. The number of years would increase if the price range per kW was higher (UCD, 2002 [81]).

The United States Army has also adopted the idea of using a fuel cell APU in their trucks in order to improve the efficiency of its mobile power systems through increased fuel economy, reduced emissions, and the prospect of significant logistical savings. A 5 kW solid oxide fuel cell was installed in one of their tractor-trailers. The 42 volts of energy provides power for air conditioning, environmental controls and other electrical equipment. The fuel cell provides a clean and quiet alternative energy source, which helps the army especially with stealth capabilities when on watch (Newswire, 2002 [121]).

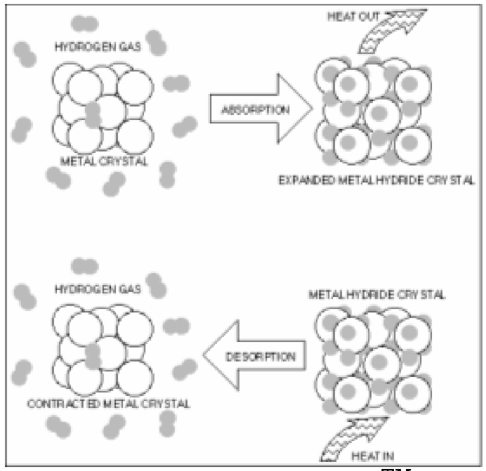
Hydrides and Waste Heat Use

One of the most significant barriers to the widespread application of hydrogen-based propulsion is the current state of on-board storage systems. Current hydrogen storage methods include compressed gas, liquid, metal hydrides and chemical hydrides. All have advantages and disadvantages, but none have proven to be more superior to the other (Anton et al, 2003 [127]).

Hydrides, believed by some experts to be the future of hydrogen storage technology, consist of metals, or other elements, and hydrogen. The metal hydrides are metallic compounds produced in much the same way as other metal alloys but have one differentiating factor. When exposed to hydrogen at certain pressures and temperatures, they absorb large quantities of gases, such as hydrogen (HERA, 2004 [118]).

Metal hydrides are the safest way to store flammable hydrogen gas. These metal hydrides react at near room temperature to hydrogen at pressures a few times greater than the earths atmosphere. The process of absorption works by taking a metal crystal and surrounding it with hydrogen gas molecules, forcing the hydrogen molecules to stick to the metal surface and break down into hydrogen atoms. The hydrogen atoms then penetrate into the interior of the metal crystal to form the metal hydride. In order for this process to begin the pressure must be above equilibrium, meaning heat will be released. The process of desorption takes in heat in order to force the hydrogen atoms to surface, recombine into hydrogen molecules, thus flow away as hydrogen gas. This will happen only if the pressure is below equilibrium.

Figure 9.6 below shows the process of absorption and desorption (Solid-H^{TM}, 2004 [107]).



Source: Solid-H^{TM}, 2004

Figure 9.3: Atomic Structure of Metal Hydride

Metal hydride equilibrium pressure is very sensitive to temperature changes. The equilibrium pressure of a typical hydride doubles or halves as the temperature rises or falls 15 to 20 degrees Celsius around room temperature. This temperature sensitivity of is very useful for hydrogen compression (Solid-H^{TM}, 2004 [107]).

There are two things that can happen if the hydrogen supplied to the metal hydride is not pure. Certain reactive impurities (oxygen) can attach themselves strongly to the powdered metal surfaces, while other impurities (argon) are inert with regards to typical hydrides, meaning the impurity becomes concentrated in the space between fine particles and lays loosely on the surface of the powdered metal hydride, leaving hydrogen as the only substance that will fit inside the metal crystal. The inert impurities can be flushed out of the metal crystal by venting a small percentage of hydrogen. Since the reactive impurities remain trapped on the metal's surface, the balance of hydrogen withdrawn is of ultra-high purity (99.999% purity) (Solid-H^{TM}, 2004 [107]).

Metal hydrides are currently being used in low pressure Ni-Hydrogen batteries. This battery uses a separate hydride-base low pressure storage tank. This allows for a flexible, lower-cost, lower weight battery design which is better suited to automotive applications.

Research, consisting of packaging hydrides in small diameter tubes and modules is currently being pursued. These tubular modules act as very efficient heat exchangers, as well as being capable of delivering high performance and efficiency in terms of heat management capabilities, modularity and for flexibility (Solid-HTM, 2004 [107]).

Chemical hydrides (complex hydrides) store hydrogen as a chemical compound. Chemical hydrides are more attractive than metal hydrides because metal hydrides are currently too heavy and expensive for on-board vehicle use. Also, reversible metal hydrides, such as MgH_2, which have the desired gravimetric densities, require high temperatures to release hydrogen. This is why there is currently there is no metal hydride that meets all of the DOE 2010 storage system targets. Therefore, complex hydrides, such as $NaAlH_4$, have been the focal point of research. They have the ability to reversibly absorb hydrogen at lower pressures and temperatures than MgH_4, and have a higher gravimetric capacity and lower cost than $LaNi_5H_6n$ (another metal hydride) (Lesch et al, 2004 [164]).

Metal hydrides and chemical hydride both have their advantages and disadvantages. In particular, a disadvantage of metal hydrides is their low hydrogen capacities, less than 2 wt% for alloys with discharge temperatures that the waste heat for a PEM fuel can provide. On the other hand, chemical hydride materials have high capacities but are classified as irreversible, meaning the entire material must be replaced during refueling, as opposed to being simply charged with hydrogen gas. There is research that focuses on the reversible chemical hydride, $NaAlH_4$, which has a capacity of 5.5 wt%, and seeks to enhance the material for improved charging and discharging rates as well as increased capacity. This could be applied to developing a storage system which will reversibly store a high wt% of hydrogen at lower pressure for an indefinite amount of time (Anton, et al, 2003 [127]).

Another problem with hydride-based systems is that they cost several thousand dollars per kilogram of stored hydrogen and for large prototypes it can cost up to tens of thousands of dollars. But in mass produced quantities this price will go down substantially. The hydrides currently used are nevertheless expensive and do not store enough hydrogen to allow their commercial consideration in vehicular applications (Hubert email, 2004 [154]). A small metal hydride unit can cost up to $60,000 per kg, with units having been constructed to hold as much as 27 kg of hydrogen (NREL, 1998 [128]).

9.3 Cost Model

Another useful tool in examining the potential of hydrogen as a fuel for transit buses is a model describing the aggregate production cost of a bus based on its major components. This is quite important, as the cost of hydrogen buses will be a major consideration in any transition. For the purposes of this model, the costs of transit buses were divided into three components; power system, fuel storage, and balance of system. The power system consists of the power system and all attendant systems, and in hydrogen fuel cell buses, is effectively determined entirely by the cost of the fuel cell. The fuel storage category contains the fuel storage tanks and the fuel delivery system, though again, in hydrogen buses, the cost is dominated by the more exotic technology; in this case the hydrogen storage tanks. Finally, the balance of system encompasses all other parts of the bus, and is consistent across both conventional and hydrogen buses.

9.3.1 Creating the Cost Model

The first step in creating the cost model is to determine the current cost of the three main categories for hydrogen buses. The cost of the power system is, as discussed above, effectively determined by the cost of the fuel cell, which can be determined by multiplying the cost per kilowatt, which can range between \$2,000 \$9,000 with an expected value of ~\$5000, by the necessary number of kilowatts, which average 205 kw.

Therefore, the cost of the power systems in a hydrogen bus is:

$$\text{cost} = (\$5{,}000/\text{kw})*(205\text{kw}) = \$1{,}025{,}000$$

The cost of the fuel storage system is determined by the cost of the hydrogen storage tanks in hydrogen buses. This cost is determined by multiplying the number of tanks, an average of nine per bus, by the cost of each tank, which range between \$20,000 - 50,000 with an average of \$35,000.

Therefore, the cost of the fuel storage systems on the hydrogen bus is:

$$\text{cost} = (9)*(\$35{,}000) = \$315{,}000$$

The cost of the balance of system is uniform between the various types of buses, and can therefore be determined on any type of bus and applied to the others. In this case it is easiest to determine the cost of the balance of system on conventional diesel systems by taking the overall cost of diesel buses and subtracting the cost of the power systems and fuel storage. The cost of a new bus engine ranges from \$14,500 to \$23,000 (www.industrialdiesel.net, 2005 [157]). For the purposes of our model, we assumed an engine cost of \$23,000. Additionally, due to proprietary concerns, exact costs of a bus fuel storage system are unavailable. Therefore, we assumed that the cost of a 105-gallon gas tank and associated fuel storage equipment is \$2,000. This means the cost of the balance of system is:

$$\begin{aligned} \text{cost} &= \text{total cost - power systems - fuel storage} \\ &= \$300{,}000 - \$23{,}000 - \$2{,}000 \\ &= \$275{,}000 \end{aligned}$$

With these starting costs determined, it is possible to create the function governing the cost model. After much consideration, it was decided that the best equation to use would be a progress ratio. The progress ratio is an equation that links the rate of growth (shown in the equation as a variable for the number of years it takes the number of buses to double) and the percent reduction to the cost, per doubling.

The form of this equation is:

$\text{cost}_y = \text{cost}_b * (\text{PR})^{cumulativedoublingsy}$

where:

cost_y = cost in year y

cost_b = base cost

PR = 1 percent reduction per doubling

cumulative doublings_y= number of doublings between base and year y

This equation is then applied to the power and storage systems each year, and these components are added to the balance of system, which holds steady, to determine the total cost every year. To gain as relevant an image as possible the cost model will be run for each of the transition scenarios discussed in 7. We will be assuming a standard 20% reduction per doubling in all scenarios.

9.3.2 Cost Model Scenarios

The first transition scenario we will examine the cost model for is the expected transition scenario, where the growth in hydrogen buses is between 30 - 40%. This will be approximated with a 35% growth rate in the cost model. A graphical representation of the results can be seen below in 9.4.

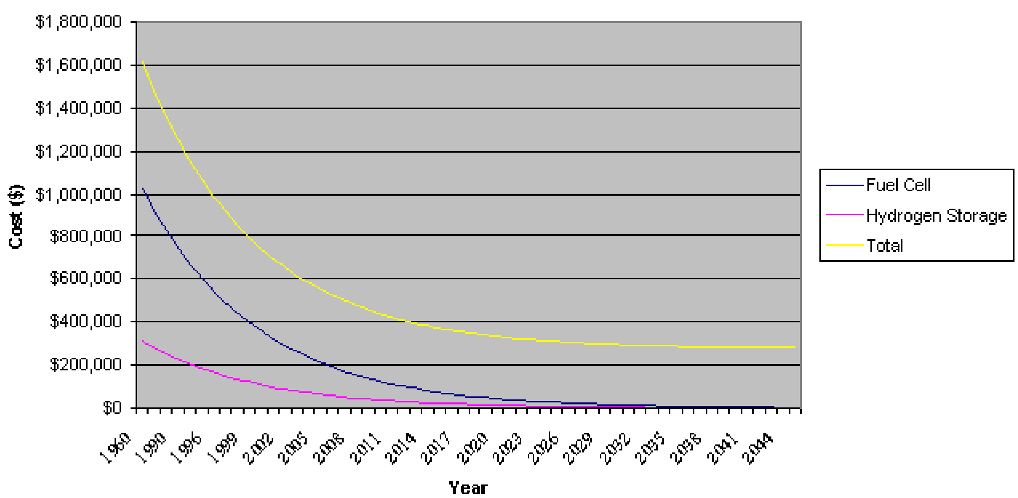


Figure 9.4: Expected Transition Scenario Cost Model

The second transition scenario we will examine the cost model for is the pessimistic transition scenario, where the growth is significantly slower, averaging only 20% per year. The graphical representation of the results can be seen in Figure 9.5.

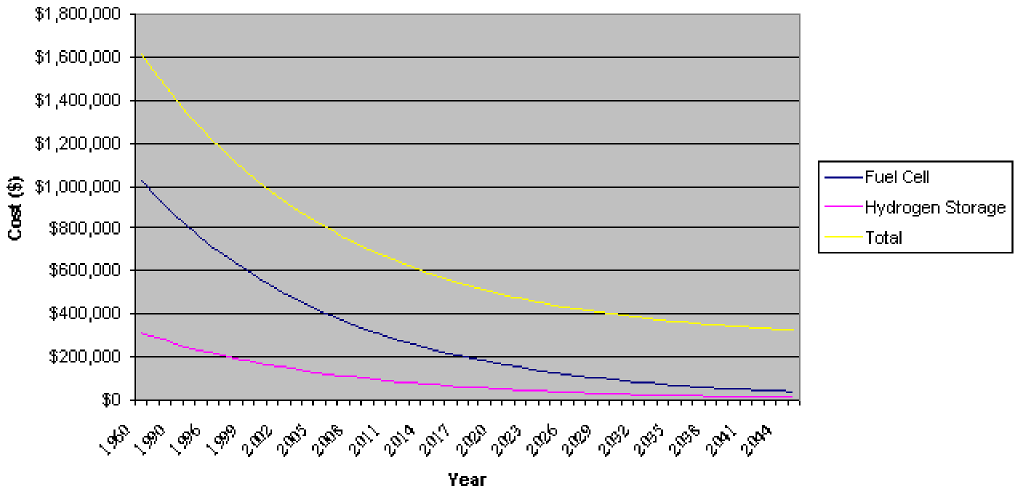


Figure 9.5: Pessimistic Transition Scenario Cost Model

The final scenario that will be examined is the DOT scenario, where they are hoping to achieve 10% penetration of hydrogen buses by the year 2015. Specifically, we will do a cost model for the rapid growth DOT scenario, as opposed to the front loaded scenario, as the rapid growth outcome is the more likely of the two. A graphical representation of the results can be seen in Figure 9.6.

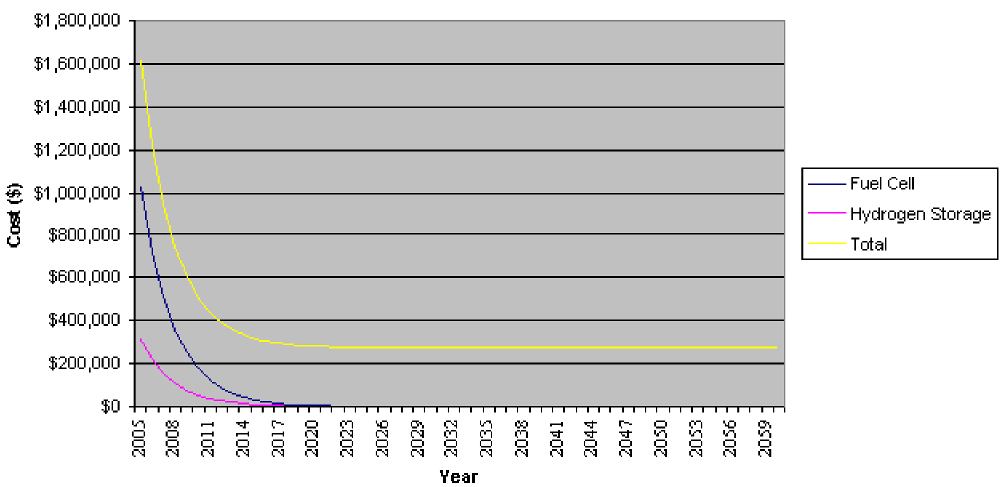


Figure 9.6: DOT Rapid Growth Transition Scenario Cost Model

As can be seen in all these models, the price will quickly drop once the transition begins, reaching levels comparable to diesel buses within approximately 20 years.

Chapter 10

Case Studies

10.1 Clean Urban Transport in Europe

Most interest in hydrogen's potential use as a transportation fuel is due to concerns about pollutants and the petroleum import market. As stated earlier, fossil fuels account for the majority of the carbon that is released into the atmosphere each year. As worldwide population continues to increase, and nations continue to develop technologically, global energy use is expected to increase drastically (Service, 2004 [179] [180]). As most of the worlds energy is generated through the consumption of fossil fuels, the projected increase in energy use will likely be accompanied by a corresponding increase in pollutant emissions. To counteract this, the world community is investigating the use of alternative fuels in a variety of applications. One example of this is the stated goal of the European Commission to have 20% of its energy provided by alternative fuels by 2020 (CUTE, 2002 [139]). Pursuant to this goal, a pan-European demonstration of hydrogen fuel-cell buses is in progress.

Clean Urban Transport in Europe (CUTE) is a pilot program with twenty-seven hydrogen fuel-cell buses in nine European cities: Amsterdam, The Netherlands; Barcelona, Spain; Hamburg, Germany; London, England; Luxembourg; Madrid, Spain; Porto, Spain; Stockholm, Sweden, and Stuttgart, Germany (CUTE, 2002 [139]). An additional three fuel-cell buses are operating in a satellite extension of the program in Perth, Australia (Davidson, 2003 [142]). The goal of CUTE is to demonstrate the possibility of a zero-emission, low-noise means of public transportation. Throughout the pilot program, data will be collected to determine the safety of hydrogen fuel, the additional maintenance requirements for hydrogen buses, and the lessons that can be learned from daily operations in a wide range of climates and road conditions. Additionally, environmental, technical, and economic analyses will be run throughout the pilot program, the results of which will be compared to conventional transportation fueling alternatives to determine the feasibility of a hydrogen-based transportation system (CUTE, 2002 [139]). Each hydrogen bus produced for the CUTE program costs roughly $1.67 million dollars. This bus cost is in-line with the prediction generated by our cost model (see Section 9.3). In light of these costs, as well as the extremely high costs of installing localized, small-scale hydrogen refueling stations, the financial burden of CUTE has been covered by a $28 million dollar grant from the European Commission (Bak, 2003 [131]), automotive and energy supply corporations, and local governments. The first bus of the CUTE program was delivered to Madrid in May, 2003 (Bak, 2003 [142]), and all buses have since been delivered. The program is estimated to be completed in the late 2005/early 2006 timeframe (CUTE, 2002 [139]).

The fuel-cell buses used during CUTE are specially designed prototypes. Each bus uses a Mercedes-Benz Citaro as its base, modified for fuel cell operations. In its new configuration, the fuel cell and storage systems are located on the roof of the bus. This placement was made possible due to improvements in fuel cell stack size and weight, and has produced a number of benefits. First, since buses are not prone to tipping in the event of an accident, the rooftop placement allows for maximum safety in the event of a collision with another vehicle. In addition, the rooftop placement of the storage system prevents the intrusion of hydrogen into the passenger compartment in the event of a hydrogen leak, since the lighter-than-air hydrogen gas will vent upwards and away from the bus. Lastly, the rooftop placement of the fuel cell and storage stack allows easy access by technicians for maintenance and upkeep (CUTE, 2002 [139]). Each bus holds 40 kilograms of hydrogen (EyeForFuelCells, 2003 [108]), enough to sustain a bus for a day's worth of operations, which is approximately 125 miles of travel (Transport for London, 2003 [186]).

The buses of CUTE will be exposed to rigorous operating conditions in a variety of climates. Most cities participating in CUTE experience highly congested traffic on a daily basis, and with the exception of Luxembourg, all have large public transit systems. A number of the cities have transit bus routes with slopes and inclines exceeding a grade of 10%. CUTE incorporates cities with cold climates like Stockholm, warm climates like Perth, and everything in between (CUTE, 2002 [139]). Additionally, with the large number of customers served by each of these public transit systems on a daily basis, the interaction with hydrogen buses will serve to educate the European public about hydrogen, as well as allay its collective fears.

During the CUTE program, a variety of hydrogen production methods will be demonstrated. While 40% of the hydrogen produced during CUTE will use renewable energy sources, the majority of the hydrogen produced will still be based on the burning of fossil fuels (Dodson, 2003 [143]). The main methods for producing hydrogen for the buses in CUTE will be electrolysis and steam reforming. For cities utilizing electrolyzers to produce hydrogen, the local electrical grid will be used to provide the bulk of the power, though alternatives methods specifically tailored to the climate and advantages of each region will provide supplementary sources of power. For instance, Amsterdam and Hamburg will supplement grid power with wind power. Barcelona, in sunny Spain, will use solar power as an auxiliary source of electricity. Stockholm, located in a country mostly surrounded by water, will use electricity generated from hydroelectric power to complement its fossil fuel-based electricity.

Those cities not using electrolysis will obtain their hydrogen by other means. Madrid, Porto, and Stuttgart will produce hydrogen through the use of a small-scale steam reformer. London and Luxembourg will receive liquid hydrogen through third party suppliers, which will be converted back to a gaseous state prior to refueling (CUTE, 2002 [139]). Perth will receive its supply of hydrogen from a local oil refinery which produces between fifty and one hundred tons of hydrogen per day (Davidson, 2003 [142]). The use of these various methods will enable researchers to compare the different methods of hydrogen production in order to determine the most technologically and economically viable methods for future expansion.

10.2 Iceland

Some experts believe that the hydrogen transition may be easily accomplished in developing countries that are not fully committed to using fossil fuels for energy generation. A practical demonstration of this theory is Iceland, a small island country in the North Atlantic with a population of roughly 300,000 (Vogel, 2004 [191]). The policy of the Icelandic government in the post-World War II era has been to make better use of renewable sources of energy (Maack and Skulason, 2002 [169]) in order to reduce the country's dependence on imported coal and heating oil (Howes, 2000 [153]). Having already switched the majority of its electricity and heat generation to hydroelectric and geothermal energy, leaders in Iceland shifted their focus to transportation after the 1990 Kyoto Protocol required that countries had to reduce non-industrial carbon dioxide emissions. Approximately 30% of the energy produced in Iceland is imported to power its vehicles and fishing fleet (Vogel, 2004 [191]), and one-third of Iceland's greenhouse gas emissions are attributed to transportation (Skulason and Bjarnason, 2003 [136]).

Iceland is the largest per capita oil consumer in the world (Howes, 2000 [153]). In addition, gasoline costs \$2 dollars per liter in Iceland. Icelandic consumers must pay roughly \$80 dollars to fill up the average car with a tank of gasoline (CBC Venture, 2003 [91]), with no sign of a decrease in price forthcoming. The desire for relief from escalating oil prices and the prospects of independence from an energy generation standpoint has jumpstarted efforts to promote a hydrogen economy in Iceland.

To implement this transition, the key Icelandic power companies, along with the University of Iceland, formed Icelandic New Energy in 1998 (Maack and Skulason, 2003 [170]). The mission of this revolutionary corporation is "to set up a joint venture company to investigate the potential for eventually replacing the use of fossil fuels in Iceland with hydrogen-based fuels and create the worlds first hydrogen economy" (Sigfusson, 2003 [181]). The main objective of Icelandic New Energy to dater has been to investigate the practical use of gaseous hydrogen and fuel cells (Maack and Skulason, 2003 [170]).

Their first practical demonstration is the Ecological City Transport System (ECTOS). ECTOS is a four-year project designed to demonstrate the feasibility of using hydrogen as a source of transportation fuel. The project is centered on a refueling station at a high-visibility Shell gas station, where hydrogen is produced, stored, and distributed to three hydrogen-powered fuel cell buses (ECTOS, 2004 [158]). ECTOS is providing valuable data and an opportunity for Icelandic New Energy researchers and stakeholders to gain experience in establishing a baseline, small-scale hydrogen infrastructure, and enabling experts to assess the overall time, material, and financial requirements of implementing a larger-scale transportation and infrastructure transition in the future. Through the use of high-visibility transit buses and extensive marketing and publicity, it is hoped that ECTOS will also help hydrogen gain worldwide acceptance as a transportation fuel. The total cost of purchasing the buses and establishing the maintenance and refueling infrastructure is \$8.85 million dollars, of which \$3.7 million dollars has been covered by a European Union subsidy (ECTOS, 2004 [158]). The difference has been paid for by the industry shareholders in Icelandic

New Energy. The ultimate goal is to transition Reykjavik's entire fleet of buses to hydrogen power.

The first hydrogen refueling station in Reykjavik, Iceland's capital, opened in April, 2003 (Maack and Skulason, 2003 [170]) and is part of Iceland's busiest Shell station, which is prominently visible from the main expressway in the area (Vogel, 2004 [191]). The location for the station was strategically selected to capitalize on its easy accessibility for refueling buses in service. The station is open to the public, and there are a variety of security measures in place to prevent tampering with the system. All equipment on-site is maintained in a glass cabin, allowing the public to see the equipment, but not to touch it (Maack and Skulason, 2002 [169]). The refueling station has no roof, allowing hydrogen to vent to the atmosphere in the event of a leak (Maack and Skulason, 2003 [170]). Hydrogen is produced overnight through electrolysis powered by electricity drawn from Reykjavik's power grid. This hydrogen is then stored as compressed gas on-site (Vogel, 2004 [191]). The overall cost to design the station, procure, and install equipment was $1.3 million dollars (Maack and Skulason, 2003 [170]).

ECTOS buses have been in operation since October, 2003, on normal transit routes throughout Reykjavik. Each custom-made fuel cell bus costs $1.67 million dollars (Howes, 2000 [153]). The bus storage tanks are filled daily with forty kilograms of hydrogen (Vogel, 2004 [191]), which provides enough fuel to sustain the buses through an average daily transit of 110 miles (Maack and Skulason, 2003 [170]). Refueling operations take about six minutes to complete (Vogel, 2004 [191]). The performance of the bus fuel cell is monitored by a state-of-the-art computer system. The system is designed to stop the bus in the event of a hydrogen leak, drive train malfunction, or fuel supply malfunction. Additionally, heat generated by the fuel cell system is directed toward the interior of the bus for heating purposes, supplemented by an additional, hydrogen-powered heating system. This demonstration of fuel cell technology in a coastal climate is extremely valuable since fuel cells are vulnerable to such things as seawater and coastal winds which contain salt, a substance whose ionic components can interfere with the conductivity and electrochemistry of the fuel cell and electric components comprising the bus drive train. Thus, the ECTOS project can provide insight into potential fuel cell performance problems in this climate that can then be identified and addressed in future fuel cell designs.

Unlike most cases, the economical production of hydrogen may not be an impediment to the transition to a hydrogen economy in Iceland (Sigfusson, 2003 [181]). Due to its geological assets, Iceland is able to produce most of its power through the use of renewable energy sources. Professor

Bragi Arnason of the University of Iceland, known as "Professor Hydrogen" for his enthusiastic support of hydrogen, notes that "many experts say that in twenty or thirty years, solar energy could be harnessed in an economic way and turned into electric energy. In Iceland, we don't have to wait for solar energy to become economic because we have this cheap hydropower and geothermal energy. We can start now" (Hutchison, 2003 [155]). Currently, hydroelectric and geothermal energy comprise 72% of Icelands primary energy supply, and produce 99.9% of its electricity (Skulason and Bjarnason, 2003 [136]). These clean energy sources do not produce carbon dioxide emissions (Howes, 2000 [153]). Icelandic President Olafur Ragnar Grimsson states that "the hydrogen project became a fascination for the people of Iceland because it combined our emphasis on clean energy, on the waterfalls, on the geysers, on creating electricity and energy from environmentally sound resources that are completely renewable" (Hutchison, 2003 [155]). Furthermore, scientists believe that only five to ten percent of Iceland's geothermal and hydroelectric resources are currently being tapped (Wheeler, 2002 [192]; Maack and Skulason, 2003 [170]). Since electricity prices are a huge factor in the production cost of hydrogen (Maack and Skulason, 2003 [153]) the widespread belief is that Iceland can produce a large amount of hydrogen cost-effectively through electrolysis (Sigfusson, 2003 [181]). The amount of hydrogen produced would not only satisfy Icelands demands, but would also enable Iceland to export hydrogen to other countries in order to meet their demands (Wheeler, 2002 [192]) once storage technology makes that possibility feasible.

Creating a serviceable infrastructure for hydrogen distribution in Iceland may also not be as great of a barrier as in other countries. In general, Icelandic citizens have a high regard towards technological innovation, particularly the use of hydrogen as a transportation fuel. Experts believe that Icelandic consumers will accept fuel cell applications in vehicles, even if a widespread infrastructure is not in place (Skulason and Bjarnason, 2003 [136]). This is especially true in Reykjavik, where two-thirds of Icelands population resides. Of the 175 filling stations in Iceland, it is believed that Icelandic consumers will purchase fuel cell vehicles if 10-15% of those stations have hydrogen refueling facilities installed (Maack and Skulason, 2003 [153]). This number could be reached with a transition of Reykjavik's bus fleet to hydrogen fuel, as the number of refueling stations installed to support that transition, supplemented by the addition of a few other stations along the 850-mile highway that encircles Iceland, would surpass the 10% boundary. Strategically placed, these refueling stations along Reykjavik's major roadways would enable consumers to be no more than ten kilometers from a hydrogen refueling station during their normal daily commutes

(Maack and Skulason, 2003 [153]). The addition of refueling stations outside of Reykjavik would also provide customers an equivalent freedom of travel to that which they currently experience. Estimates place the cost to create an infrastructure large enough to generate public acceptance in Iceland at approximately $7 billion dollars (Maack and Skulason, 2003 [153]).

The findings of ECTOS and other pilot programs for the hydrogen economy in Iceland will go a long way toward convincing governments, automotive corporations and energy suppliers whether a shift to hydrogen for use as a transportation fuel is plausible (Howes, 2000 [153]). As Professor Arnason points out, Iceland is an ideal proving ground for hydrogen technology because "it's easy to introduce a new technology in a small society because if it goes wrong, its less difficult to fix it. Then, you take the lessons you've learned here and apply them to larger societies" (Asmundsson, 2002 [130]). Since the transportation systems in Iceland are similar to those in other industrialized countries, the results of ECTOS, including the performance of fuel cell vehicles in severe weather conditions, seasonal changes, and a wide-ranging geography, can be applied to other transit systems (Italian Embassy in Oslo, 2003 [158]). This is the main reason why the European Union has provided financial sponsorship to the ongoing hydrogen projects in Iceland. The transition to a hydrogen-based transportation system has received overwhelming support, with a 93% approval rate from the Icelandic public (Italian Embassy in Oslo, 2003 [158]). Iceland's transition to hydrogen fuel, including hydrogen-powered fishing boats, is expected to be completed between 2040 and 2050 (Asmundsson, 2002 [130]; ECTOS, 2003).

10.3 Washington D.C. Rollout Model

As a specific example of our national study of the transition to hydrogen fuel cell buses, a model depicting a rollout in a single city, specifically Washington D.C., was created. The model illustrates what this transition would be like in its specifics, and will be discussed in this section

10.3.1 Current State of the Bus Fleet

Before discussing the model, it is important to provide some information on the current state of the bus fleet in Washington, D.C. There are currently 1460 buses operating in Washington, D.C., all of which are managed by the Metrobus system, a subdivision of the Washington Metropolitan Area

Transit Authority (WMATA) which handles all public transportation in the greater Washington D.C. area. While this fleet is currently composed almost exclusively of conventional diesel buses, 600 compressed natural gas (CNG) buses, 100 Hybrid-Electric (HEV) buses, and 125 clean diesel (CD) buses are scheduled to be delivered and integrated into the Metrobus fleet by the end of spring 2005 (WMATA, 2004 [124]).

10.3.2 Assumptions

In deciding how to form this model several basic assumptions were made. They are:

1. The average lifespan of a conventional diesel bus is 10 years
2. Washington D.C. will purchase 12 hydrogen buses in the next year, to start the transition
3. The Metrobus fleet will grow in size by 1.5% per year
4. CNG, HEV, and CD buses can be used longer if so desired, due to the clean burning nature of their engines and the smaller number of moving parts in the transmission (drive train)
5. In purchasing 825 CNG, HEV, and CD buses the WMATA faced a huge up front expense, which they would prefer to avoid facing again in 10 years time
6. All diesel buses will be replaced with cleaner bus technology when they are decommissioned, with preference being given to hydrogen buses if possible.

To account for the fifth assumption, we took advantage of the extended possible lifespan of the CNG, HEV, and CD buses as stated in the fourth assumption and phase the 825 CNG, HEV, and CD buses out evenly over the next 10-15 years, as opposed to doing so abruptly 10 years from now.

10.3.3 Building the Model

To start the model, the assumption was used that the city will purchase 12 hydrogen buses in the next year in order to start the transition. Ideally, these buses would be broken into two groups of six and placed into service in different areas. One group of hydrogen buses will service the area around the Departments of Energy and Transportation, while the other group of hydrogen buses will service the area near the Pentagon. This would create the largest possible exposure among people with the power the assist the transition to hydrogen fuel cells, as well as maximize the exposure and return on investment the city would see.

Over the first ten years of the model, it is assumed that the rest of the conventional diesel buses in the Metrobus fleet will be decommissioned, leading to an average of approximately 64 buses per year being replaced. Over this period, the number of hydrogen buses will grow at a steady rate, with the limit on growth being the number of buses decommissioned per year plus the overall growth of the Metrobus fleet. We assumed that any decommissioned buses not replaced by hydrogen buses were replaced by HEV or CD buses, which will still provide an environmental and efficiency improvement over conventional diesel buses.

The year after all the conventional diesel buses in the Metrobus fleet have been decommissioned, what would traditionally be considered the lifespan of the HEV and CD buses purchased in 2005 is completed. As mentioned earlier though, we stretched their use over the next five years to factor in the benefits of their cleaner burning engines. Assuming these buses are phased out evenly over the next five year period, that means 165 buses will need to be replaced each year. This replacement is handled in the same manner as the replacement of the conventional diesel buses was, with the hydrogen buses growing at a steady rate up to the number of buses being replaced and the growth of the Metrobus fleet, and any buses not replaced by hydrogen buses being replaced by HEV or CD buses.

Once this period of replacing the large number of HEV and CD buses is over, we then phased out the HEV and CD buses that were purchased to fill the shortfall between the number of buses being decommissioned and the number of hydrogen buses being purchased, and replaced them with hydrogen buses, as the growth in the number of hydrogen buses can easily accommodate the number being decommissioned at that point. From then onward we assumed the composition of the Metrobus fleet enters a steady state, where any new growth and hydrogen buses that need to be decommissioned were replaced by new hydrogen buses.

A graphical representation of this rollout, where we assume a growth rate for the hydrogen buses of 35%, can be seen below in Figure 10.1.

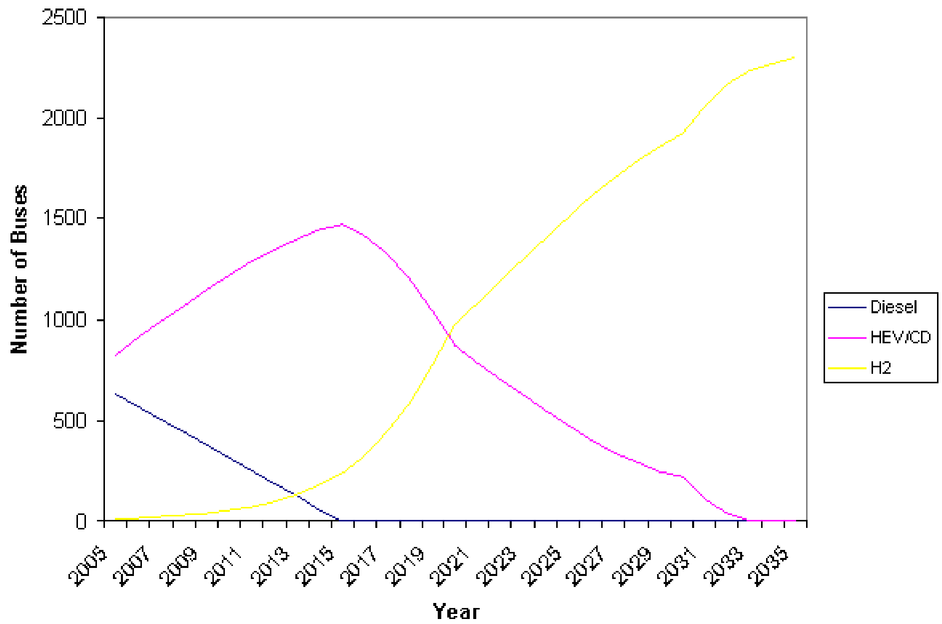


Figure 10.1: Washington DC Bus Fleet

10.4 National Fuel Cell Bus Rollout Model

It is believed that, with the infrastructure and transportation problems that hydrogen faces, the way for hydrogen to penetrate the consumer market will be through the development of small-scale production sites (Maack and Skulason, 2003 [153]). With this idea in mind, a nationwide model was created to predict the transition to hydrogen buses for ten major U.S. cities. The cities were selected for the model based on two factors. One major factor used in selecting cities was the presence of government regulations reducing pollutant emissions. At the present time, five states have low-emissions vehicle programs in place: California, New York, Maine, Massachusetts, and Vermont (Energy Information Administration, 2004 [144]). The other major factor used in selecting example cities was the apparent availability of cost-effective, renewable energy sources in the vicinity of the city, as electricity prices are a major fraction of the overall hydrogen production cost (Maack and Skulason, 2003 [153]). California, which has led the way in reducing emissions and improving air quality through the use of alternative-fuel technology (Eudy et al, 2001 [145]), and which boasts one of the sunniest climates in the country, is represented by four cities: Los Angeles County, San Diego, Santa Monica, and Oakland, which currently has fuel cell buses in operation. Three additional cities, Honolulu, Hawaii, Miami, Florida, and Phoenix, Arizona, were also selected for their sunny climates. It is assumed that, in these cities, electrolysis will be powered by electricity generated from solar power technology. Texas, widely regarded as a potential haven for wind-power stations (Heller, 2004 [151]), is represented by Dallas and Houston, home of NASAs Johnson Space Center. As the Space Shuttle is powered by hydrogen fuel, it can be assumed that the residents of Houston are familiar with the benefits of hydrogen from an energy generation standpoint. Lastly, Buffalo, New York, was selected because of its state's low-emissions laws and its close proximity to Niagara Falls, site of one of America's largest hydroelectric generators.

The size of each representative bus fleet can be found in the data provided in Appendix B.10. The size of each bus fleet's growth was determined using the slope from the projected number of buses Linear Regression model described in Chapter 7, adjusted to reflect the fraction of the total number of buses that each bus fleet comprises. The number of hydrogen buses as determined from the transition model was then distributed equally among the ten example cities on a year-by-year basis. This model assumes that these cities will be the only cities to receive hydrogen fuel cell buses during the duration of the transition. When the total number of hydrogen buses for a year exceeded the total number of buses projected for that citys fleet, the transition to hydrogen buses for that city was considered to be complete.

The results of the rollout model, based on the transition model with a 30% growth rate described in Chapter 7, suggest that the transition to hydrogen buses for the ten representative fleets will be completed between the years of 2027 for the smallest fleet (Santa Monica, California) and 2037 for the largest fleet (Los Angeles County, California). Predicted years for transition completion are as follows:

Buffalo, New York	2029
Dallas, Texas	2033
Honolulu, Hawaii	2031
Houston, Texas	2035
Los Angeles County, California	2037
Miami, Florida	2033
Oakland, California	2032
Phoenix, Arizona	2030
San Diego, California	2031
Santa Monica, California	2027

Chapter 11

Conclusion

In conclusion to our research and analysis, it can be said the transit buses provide an ideal starting point for the hydrogen transition for numerous reasons. The size of transit buses allows them to more easily accommodate the bulky nature of prototype fuel cells and hydrogen storage tanks. Size is less of a limiting factor on larger vehicles, and the removal of size as a constraint on the prototype technology will enable it to develop more quickly. The local, centralized, nature of transit bus fueling and maintenance greatly benefits early hydrogen technology, by reducing the amount of money that must be invested to develop the infrastructure at the beginning of the transition and makes the use of shorter range hydrogen technology viable as hydrogen storage issues are addressed (Levin et all, 2001 [165]). The high profile nature of transit buses will help maximize the public's exposure to hydrogen technology. Despite the fact that transit buses make up only 1% of the total vehicles on the road, a disproportionately large number of people interact with them each day. This makes transit buses an ideal way to raise awareness of hydrogen technology. The majority of transit buses operate in high traffic urban areas where pollution is a major issue, exactly the type of area where a zero-emissions technology is the most vital and will be most appreciated (Eudy et all,2001 [145]). Lastly transit bus fleets are, in nearly every case, subsidized by the government at either the local, state, or federal level. This counteracts one of the traditional faults of a new technology, its extremely high initial price.

It is important to note that not all heavy duty vehicles are a suitable launch pad for the hydrogen transition. For example, intercity trucking is one of the worst possible areas to begin the hydrogen transition. Intercity trucks cover long distances per trip, requiring a correspondingly large fueling and maintenance infrastructure to support them as they go about their duties. Intercity trucking is also a purely commercial venture, meaning that cost is an overriding concern.

Therefore we recommend launching the hydrogen transition through the creation of new pilot programs for hydrogen buses and the expansion of programs that are already in operation. Additionally we recommend the promotion of bridge technologies such as Hythane or hydrogen ICE buses in parallel with these pilot programs will help accelerate the growth of the hydrogen infrastructure. The combination of these programs will bring about the hydrogen transition in the quickest, most cost effective way possible.

Part III

Washington D.C. Rollout

Chapter 12

Introduction

One of the greatest challenges to the hydrogen transition is the lack of infrastructure in place. Ironically, this is a barrier to the development of both infrastructure and FCVs. If there was already a large infrastructure in place, as there is with gasoline stations, the decision to where and when to build would be fairly straightforward, and easily controlled by market forces. A hydrogen company could look at the network, determine what areas have high demand, choose a suitable location, and place itself in competition. Without an existing infrastructure, however, it is difficult to predict what areas would be most profitable to build in. This makes it intimidating to sink the money to build one station, let alone multiple ones.

The barrier to developing FCVs is more obvious. Without a strong infrastructure in place, it is difficult to get the public excited enough to purchase the cars. This also indirectly affects the research put into developing such vehicles, especially if the vehicle producers are unconvinced of hydrogen's feasibility.

Management, therefore, is a necessity in jumpstarting the transition. Market forces alone can not be expected to provide a swift and smooth transition, and perhaps not enough to start the transition at all.

In the following part of the report, we will explain in detail one method for determining a feasible network. It is unlikely that a single company would undertake this effort alone, but the design assumes that some authority oversees the development of the network and whatever companies are involved. This authority may be the government, or simply a consortium of companies that pledge to cooperate. In the first section that follows, we will discuss what sort of background information might go into the development of a network, including population statistics, driver preferences, the benefits of government involvement, and economic analysis. Next, we will outline a design algorithm, and the results of this algorithm if the network was designed today. Finally, we will discuss performance measures that could be used to guide the transition past the initial phase.

Chapter 13

Background Data

13.1 Zoning Regulations

13.1.1 Zones that allow gasoline stations

According to the District of Columbia Office of Zoning, the Zoning Regulations of D.C. were introduced in 1920 and their purpose was to restrict the density of population, sizes of property, uses of land and other related issues of each zoning division. It also prevents inappropriate use or overcrowding. By doing so, the D.C. area was divided in zone districts by different purposes and represented by different codes as shown in the table on the next page.

According to the Zoning Regulations (Zoning, 2004 [197]), the only zones allotted to gasoline service establishments are coded as follows,

C-1 (Zoning Regulation 701.1 & 706.1)

C-2 (726.1)

C-3 (741.1, 741.2 & 743.1)

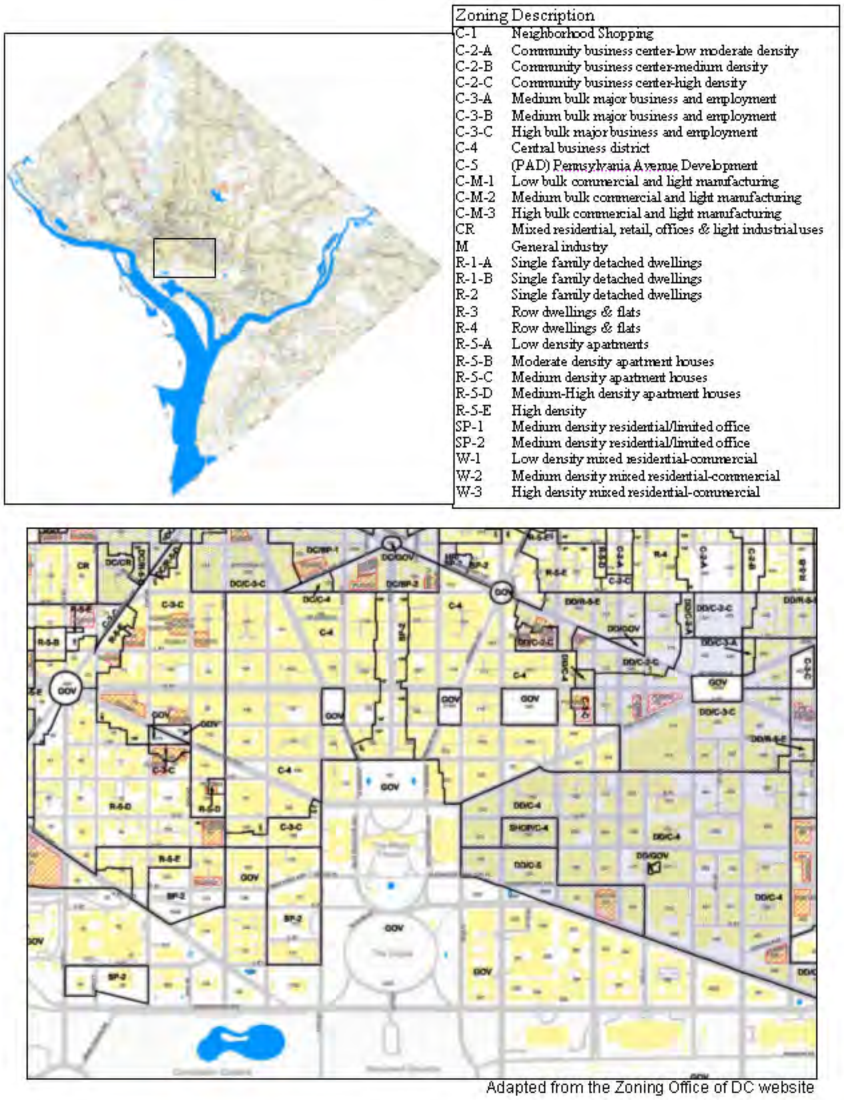
C-4 (&51.2)

C-5 (761.1)

C-M (2302.1)

M (2302.1)

Other zones used for other purposes are prohibited for any gasoline service. We assumed that the initial phase for hydrogen transition in D.C. area is to use the existing gasoline stations. The station location should be carefully verified so that the chance of any violations of regulations can be prevented or at least minimized. One example of a zoning map is shown on the next page with boundaries and codes that refer to the table of zones.



Zoning	Description
C-1	Neighborhood Shopping
C-2-A	Community business center-low moderate density
C-2-B	Community business center-medium density
C-2-C	Community business center-high density
C-3-A	Medium bulk major business and employment
C-3-B	Medium bulk major business and employment
C-3-C	High bulk major business and employment
C-4	Central business district
C-5	(PAD) Pennsylvania Avenue Development
C-M-1	Low bulk commercial and light manufacturing
C-M-2	Medium bulk commercial and light manufacturing
C-M-3	High bulk commercial and light manufacturing
CR	Mixed residential, retail, offices & light industrial uses
M	General industry
R-1-A	Single family detached dwellings
R-1-B	Single family detached dwellings
R-2	Single family detached dwellings
R-3	Row dwellings & flats
R-4	Row dwellings & flats
R-5-A	Low density apartments
R-5-B	Moderate density apartment houses
R-5-C	Medium density apartment houses
R-5-D	Medium-High density apartment houses
R-5-E	High density
SP-1	Medium density residential/limited office
SP-2	Medium density residential/limited office
W-1	Low density mixed residential-commercial
W-2	Medium density mixed residential-commercial
W-3	High density mixed residential-commercial

Figure 13.1: Example of Zoning Map and Zones

As one of the requirements for the network, the stations we picked are located in the legal areas for gasoline service stations. However, there will be two important issues after the hydrogen transition starts in the D.C. area. First, there might be different legal requirements between traditional gasoline service stations and hydrogen stations so that we are not sure if the current zoning regulation can be applied to hydrogen stations. If public conception of the safety of hydrogen energy is misevaluated and the acceptance of neighbor hydrogen stations declines, the regulations might become stricter for hydrogen stations. This point is highlighted in the next section. Second, if the new hydrogen stations are established based on the existing gasoline stations, the change of structure or capacity has to be evaluated to make sure that the new construction will not violate any regulations.

In summary, it is a good idea to check the potential hydrogen stations for zoning violations so that appropriate locations are chosen.

13.1.2 Public Sentiment

It is worthwhile to note that zoning regulations are intimately connected to public opinion. Planning and zoning boards determine what gets built in towns, and average citizens of the town sit on those boards. Currently, it looks like the first hydrogen stations will be piggybacked on the existing gasoline station infrastructure to reduce costs. While gasoline stations are already regulated under zoning laws, it is not necessarily true that those regulations will automatically be sufficient to regulate gasoline stations. While hydrogen is potentially much less dangerous than gasoline, since it does not pool on the ground and the connection is very carefully designed to prevent leaks, the public does not necessarily share this perception. This is evident in the following excerpt from an article about the opening of the DC Shell Hydrogen station on the Sierra Club's website:

> Some residents of the surrounding River Terrace community are not as upbeat about the station's launch. Residents accuse Shell Hydrogen and the city government of environmental racism for placing this station around the corner from an elementary school Key concerns cited by community members are the questionable safety of transporting a chemical into the community, the station's proximity to the school in case of emergency and the District's regulatory permitting process regarding the renovation of existing gasoline stations (Sierra Club, 2004 [198]).

In response to the community's concerns, Shell agreed to limit the times of day that deliveries took place. It also held open houses to educate the members of the community of its efforts to ensure that no accidents occur. Eventually, the residents became more positive. Commissioner Christine Tolson now says that the new station "represents vision for our nation as well as our community" even though she was not always a staunch supporter. She goes on to state that initially, she had some misconceptions about hydrogen due to some of the negative things associated with the element, but has since learned more.

Without the careful response and outreach that Shell engaged in, misconceptions might have gone unchecked and the community may have sought to block the pilot project through regulation and legislation, effectively sinking the project.

13.2 Driver Behavior

Driver behavior, while an important factor in how well a hydrogen refueling network will perform, is perhaps the most difficult to quantify in a meaningful way. Research suggests that two major areas of concern are whether consumers will be inspired to buy a hydrogen fuel cell vehicle by their observations of the network, and what patterns they follow when they own an FCV and need to refuel it.

13.2.1 Decision to Purchase FCVs

In "Refueling and the Vehicle Purchase Decision: The Diesel Car Case", (Sperling, 1987 [199]) the researchers explored the acceptance of diesel-fueled vehicles in the 1970s and 1980s in California to quantify what factors might affect the acceptance of a fuel with limited availability. The study concluded that prior to 1982, approximately 10%-20% of refueling stations offered diesel fuel. During this time, 80% of diesel fuel car purchasers were somewhat concerned or not concerned at all about being able to find diesel fuel. Further more, even though more than 20% of stations offered diesel fuel after 1982, the levels of concern remained about the same for new purchasers. Finally, the researchers determined that no matter what their initial level of apprehension was, most diesel vehicle purchasers reported that their concerns were the same or less after buying the car.

Although the paper does not directly address the acceptance of hydrogen fuel cell technology, it does talk about the possibility of a network that provides methanol and compressed natural gas as a fuel source. The paper expresses concern over acceptance of these technologies, especially if they did not have a network as extensive as the diesel one was at the beginning of the study period. In addition, these newer types of vehicles would likely have a shorter range than diesel vehicles, which were themselves improvements over the range and efficiency of more traditional gasoline cars. This shorter range would decrease purchaser confidence below that of the diesel users, which had a moderate to large amount of concern despite the favorability of diesel fuel.

Finally, the paper recommends a network size of at least 15% that of the existing gasoline network to reduce consumer concern and subsequently enable significant market penetration of the new technology. This number refers to the scenario where the primary users own vehicles that only use the new fuel technology. For hybrid technology cars that can accept the new fuel or traditional gasoline, the initial size requirement is slightly lower but still better than 10%. (Sperling, 1987 [199]).

13.2.2 Relationship to Design of Network –Where/When to refuel

According to the research in Davis, most drivers could not precisely identify the least and most expensive gas available to them. Drivers were also more aware of stations in downtown or neighborhood locations than freeway exit locations. In this research, the authors recommended that this study is applicable for the design of a network of refueling stations for alternative fuels such as alcohols, gas, or hydrogen.

According to the research in Davis, most drivers tended to refuel their cars out of habit. Home was the typical origin of the refueling trip, and work was the most common destination. Drivers tend to refuel without going out of their way or at least no distance exceeding two blocks. Davis states that drivers on a refueling trip were less able to identify the cheapest or most expensive stations than drivers on other kinds of trips. On average, the Davis drivers had more accurate mental map knowledge about their six closest neighborhood stations than they did about their seven closest freeway stations. The features of the three downtown stations were less well known than were those of the suburban neighborhood stations. Because of these facts, the Davis experience supports a strategy of selecting an in-town station instead of a freeway exit station to ensure that the maximum number of local residents will be made aware of the availability of a new fuel opportunity.

In the survey, Davis drivers are relatively unconcerned about the price of fuel. Most of the Davis drivers bought fuel often or always from the same station, simply out of habit. While some people in the Davis research exhibited some price-conscious behaviors, they are far from being optimizers. Many have habits of patronage at expensive but more convenient stations, and over 80 percent rank location and quality as more important than price in selecting their regular station

(Dingemans, 1986 [200]).

In summary, convenience of location was most important, especially for the 10 percent of refueling trips that were single purpose trips for refueling alone. This pattern of refueling close to home or work is expected to be found elsewhere, even in large metropolitan areas and more complex situations with more refueling options. In a parallel situation, few ordinary drivers could be expected to learn of the availability of an alternative fuel in Davis unless they had already begun to consider the possibility of buying an alternative fuel vehicle. Thus, local information dissemination programs might be needed to make all potential purchasers of a new fuel vehicle aware of the local availability of that new fuel. In locating the first few, decision makers should be most aware of the great premium placed on locational convenience (Diffusion, 2004 [201]).

Home was the most common origin or destination, accounting for 74.8 percent of trips. And the most popular time to refuel was when the home is the trip origin. Most people prefer to refuel five minutes from their origin or destination, accounting for 71.9% percent of trips. Drivers also show a strong tendency to refuel at the beginning of the journey. Kitamura and Sperling indicate that consumers prefer to refuel near their home, and to a lesser extent, their work. They suggest that a large amount of refueling occurs along the commute route (Kitamura, 1987 [202]).

13.3 Information Derived from Japan

Due to a scarcity of US data such as construction cost and hydrogen price, we researched Japan's hydrogen project data. Japan has one of the most advanced experiences in hydrogen fuel projects, with some of the most advanced technologies. The New Energy and Industrial Technology Development Organization (NEDO) and the Japan Hydrogen & Fuel Cell Demonstration Project (JHFC), both of which are established by the Japanese Government, have played important roles in developing hydrogen fuel vehicles and hydrogen fuel stations.

Although the JHFC project is ongoing and information about costs is confidential, NEDO has already conducted extensive researches on hydrogen fueling facilities that are available to the public. Since available US cost information is scarce, the Japanese research seemed to be a good alternative.

13.3.1 Hydrogen Project in Japan

The Ministry of Economy, Trade and Industry (METI) anticipates that as a long-term goal, 15 million Hydrogen Fuel Cell Vehicles (HFCVs) will be produced and 8,500 hydrogen stations will be constructed in Japan by 2030. This is the scenario of the hydrogen transition project planned by METI.

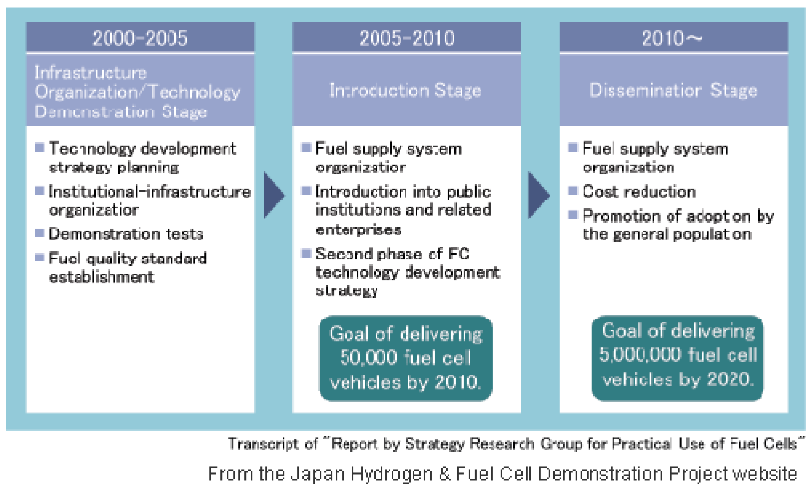


Figure 13.2: Hydrogen Transition project planned by METI

To raise public awareness, METI has run the Japan Hydrogen & Fuel Cell Demonstration Project (JHFC) in the Tokyo metropolitan area since 2002. This area includes Tokyo, Kanagawa and Chiba. Tokyo is the capital of Japan. According to the census of 2000 (The Ministry of Internal Affairs and Communications Statistics Bureau in Japan, 2004 [203]), the population of Tokyo is 12,064,101, that of Kanagawa is 8,489,974, and that of Chiba is 5,926,285.

The total population of this area makes up about 21 percent of Japans population (26,480,360 / 126,925,843). This makes Tokyo one of the most important markets of HFCVs worldwide.

13.3.2 About JHFC

JHFC consists of the fuel cell demonstration program (included in the support project for "empirical and other research on solid high-polymer fuel cell systems" under the auspices of METI) and the Demonstration Study of Hydrogen Fueling Facilities for Fuel Cell Vehicles.

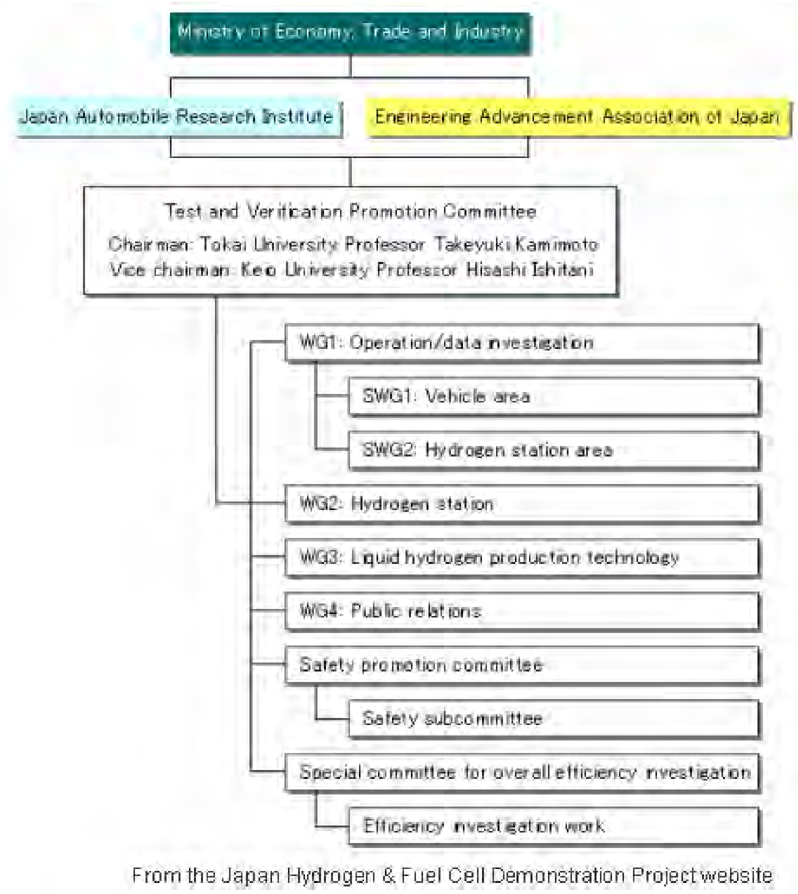


Figure 13.3: The Organization of JHFC

13.3.3 Features of the Project of JHFC

This project is Japan's first extensive research into the actual running of HFCVs for demonstration purposes.

From 2003, HFCVs from eight car manufacturers, as well as Heavy Duty Vehicles (HDVs) such as the hydrogen fuel cell buses for commercial routes, participated in trial runs on highways in the Tokyo area. Highway run data and hydrogen station usage data, such as drivability, reliability, environmental impact, and fuel consumption, have been obtained for evaluation.

A unique feature of this project is the world's first parallel operation of hydrogen stations based on different fueling and manufacturing systems. 9 kinds of hydrogen stations–desulfurized gasoline reforming, naphtha reforming, LPG reforming, liquid-hydrogen storage, methanol reforming, high-pressure hydrogen storage, lye electrolysis, petroleum reforming, and city gas reforming–have been constructed. A mobile hydrogen station has also been deployed on the premises of METI in central Tokyo. These stations are operated to provide free hydrogen to HFCVs. In return, JHFC obtains data from the HFCVs for evaluation.

13.3.4 Specifications of 11 types of hydrogen production facilities

Yokohama-Asahi Hydrogen Station, a Naphtha Reforming Hydrogen Supply Facility, operated by Nippon Oil Corporation

Yokohama-Asahi Hydrogen Station is Japan's first naphtha-reforming hydrogen station. High-purity hydrogen gas is produced from naphtha stored in an underground tank. This hydrogen gas is supplied to fuel cell vehicles as high-pressure gas. In the petroleum industry, companies are mass-producing hydrogen from petroleum product such as naphtha, removing sulfur and other impurities during the refining process. As one of these companies, Nippon Oil Corporation has long been accumulating expertise in hydrogen manufacture. Its accumulated expertise is embodied in many aspects of the hydrogen station.

Material	Naphtha
Hydrogen production method	<Naphtha cracking> Steam reforming <Hydrogen purification> PSA
Hydrogen production rate	50Nm^3/h (Hydrogen sufficient for one passenger car can be produced in about 40 minutes.)
Hydrogen purity	99.99% or higher (The amount of CO, which adversely affects fuel cells, is 1 ppm or less.)
Filling capability	<Compressed hydrogen> 25/35 Mpa <Continuous filling capability> Five passenger cars or one bus
Features	Skidding equipment shorten deployment time

Table 13.1: Specifications of the Yokohama-Asahi Hydrogen Station

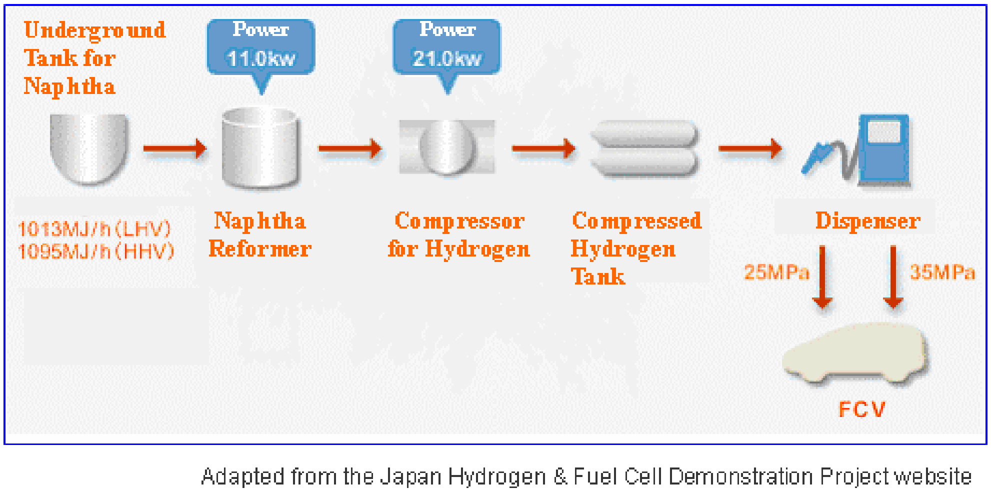


Figure 13.4: The Schematic for Yokohama-Asahi Hydrogen Station

Senju Hydrogen Station, a LPG Reforming Hydrogen Supply Facilities, operated by Tokyo Gas Co., Ltd. and Nippon Sanso Corporation

Senju Hydrogen Station is an LPG reforming station which is run by Tokyo Gas and Nippon Sanso. The hydrogen production equipment for the station is based on field-proven industrial technology for on-site hydrogen production by LP gas reforming. This equipment uses a small-size 6-tower PSA for reduced size and improved efficiency. The dispenser for the station is easy-to-use precision equipment utilizing Nippon Sanso's gas control technology.

Material	LPG (mixed butane and propane (7:3) gas, odorized)
Hydrogen production method	Steam reforming + PSA refinement
Hydrogen production rate	50Nm^3/h (Hydrogen sufficient for one passenger car can be produced in about 40 minutes.)
Hydrogen purity	99.99% or higher (The amount of CO, which adversely affects fuel cells, is 1 ppm or less.)
Filling capability	Large-size bus or five passenger cars Continuous filling is possible
Features	--On-site high-purity hydrogen manufacture facilities. Field-proven using LP gas.
	--Compact, highly efficient hydrogen refinement equipment. Based on small-size 6-tower PSA. --Easy-to-operate dispenser using a new filling method. --Automated operation control with adequate safeguards

Table 13.2: Specifications of the Senju Hydrogen Station

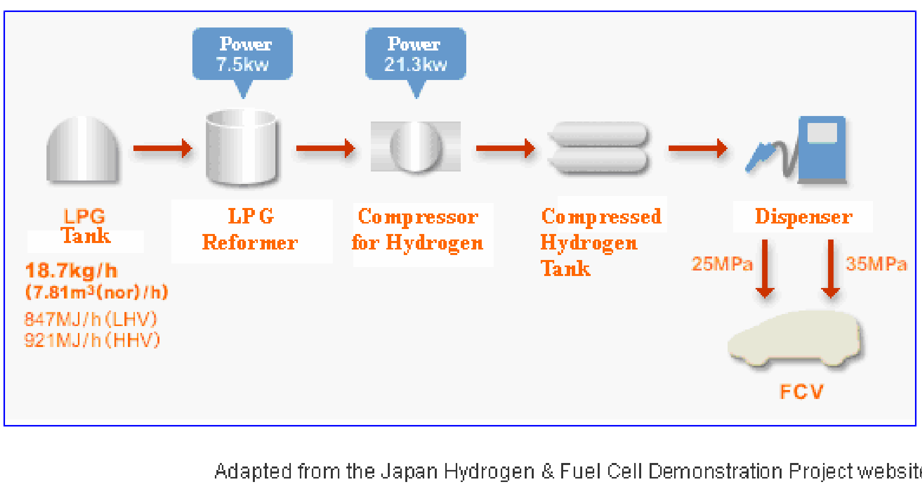


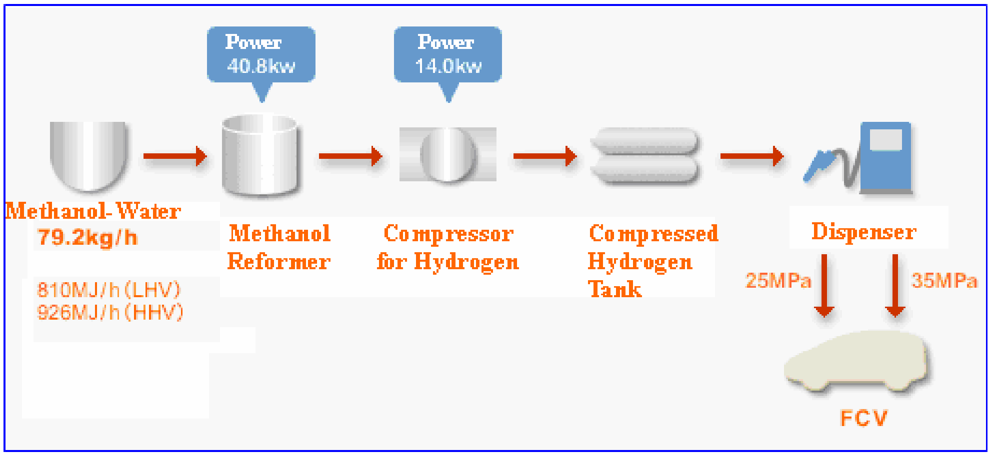
Figure 13.5: The Schematic for Senju Hydrogen Station

Kawasaki Hydrogen Station, Methanol-Reforming Hydrogen Supply Facilities, operated by Japan Air Gases Ltd.

Kawasaki Hydrogen Station is the world's first to supply hydrogen by methanol reforming. Methanol is a safe material available for hydrogen production because the reforming reaction for methanol can be carried out at a relatively low temperature of 250 to 300°C, compared with 600 to 700°C for natural gas, and a smaller amount of energy is required to heart it and to hold it at that temperature. Kawasaki Hydrogen Station evaporates methanol and water, then makes them react with each other through catalysis. After generation, this station separates and compresses the hydrogen gas to provide fuel cell vehicles with the high-pressure hydrogen.

Material	Methanol-water complex
Hydrogen production method	Methanol reforming
Hydrogen production rate	50Nm^3/h (Hydrogen for one passenger car can be produced in about 40 minutes.)
Hydrogen purity	99.99% or higher (The amount of CO, which adversely affects fuel cells, is 1 ppm or less.)
Filling capability	Five passenger cars or one bus
Features	--Relatively low reforming temperature --High-pressure reformer --2-stage diaphragm compressor --High-pressure gas supply facilities separated from drivers

Table 13.3: Specifications of the Kawasaki Hydrogen Station



Adapted from the Japan Hydrogen & Fuel Cell Demonstration Project website

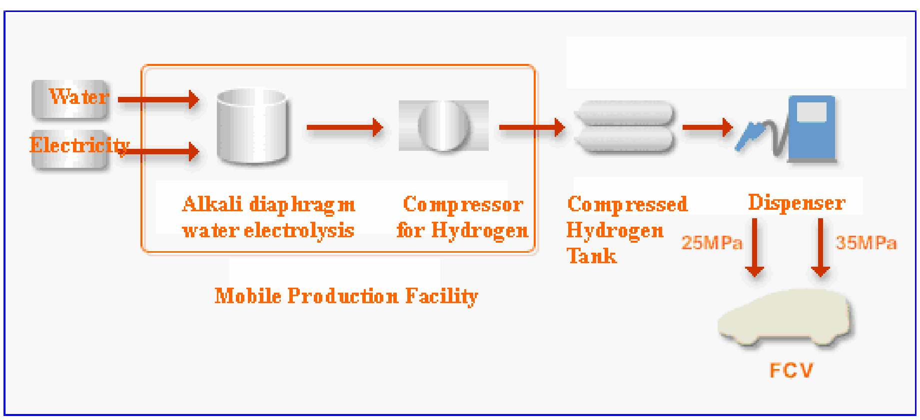
Figure 13.6: The Schematic for Kawasaki Hydrogen Station

Sagamihara Hydrogen Station, an Alkali Water Electrolysis Hydrogen Supply Facilities (Mobile), operated by Kurita Water Industries Ltd. / Sinanen Co., Ltd. and Itochu Enex Co., Ltd.

Sagamihara Hydrogen Station is the first station installed at an existing LP gas station supplying fuel to fleets of cabs and other low-pollution vehicles. By loading a hydrogen generator and a compressor on a truck, the station achieves a minimum configuration including only the gas storage facilities and the dispenser, resulting in significant space savings. This arrangement allows several hydrogen stations to share the same hydrogen production facilities. In this situation the hydrogen stations are operable whilst the original investments in the facilities remain productive.

Material	Water and electricity
Hydrogen production method	Alkali diaphragm water electrolysis
Hydrogen production rate	30Nm^3/h
Hydrogen purity	99.99% or higher (without generation of CO, which adversely affects fuel cells)
Filling capability	Five passenger cars or one bus can be fueled at a time.
Features	--Receives hydrogen from trucks on which a hydrogen generator and compressor are mounted (mobile production facilities) --Uses existing electricity and water supply infrastructure. --Capable of utilizing power generation by natural energy such as solar and wind power generation. --Station consists of only a gas storage unit and dispenser --Provides space savings by sharing existing facilities.

Table 13.4: Specifications of the Sagamihara Hydrogen Station



Adapted from the Japan Hydrogen & Fuel Cell Demonstration Project website

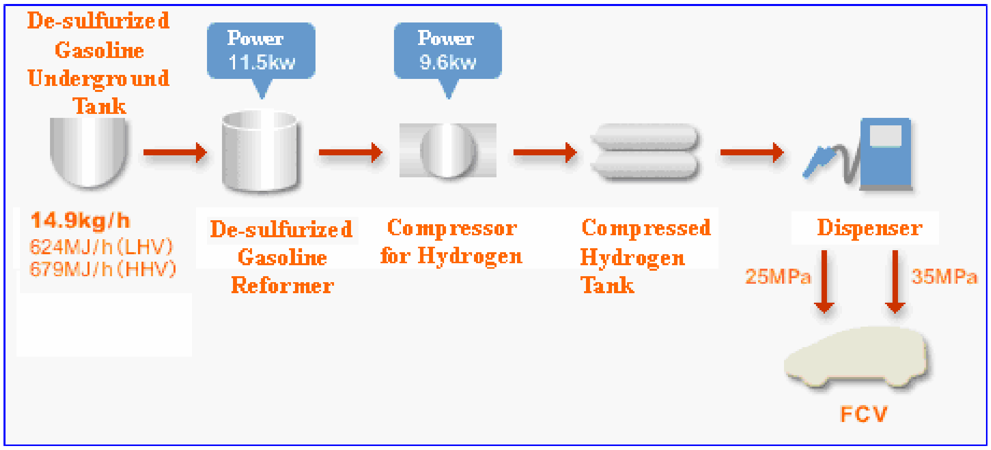
Figure 13.7: The Schematic for Sagamihara Hydrogen Station

Yokohama-Daikoku Hydrogen Station, a Steam-Reforming Hydrogen Supply Facilities, operated by Cosmo Oil Co., Ltd.

Yokohama-Daikoku Hydrogen Station includes steam-reforming hydrogen supply facilities which utilize the existing gas station infrastructure. Using Cosmo Oil's unique de-sulfurized gasoline, this station produces hydrogen of high purity through the hydrogen production expertise long accumulated by the company. It then supplies high pressure hydrogen gas to fuel cell vehicles. Next to this station are a showroom and garage for fuel cell vehicles. The showroom and garage, managed by the Japan Automobile Research Institute, provide effective means for promoting the dissemination of fuel cell vehicles.

Material	De-sulfurized gasoline
Hydrogen production method	Steam reforming
Hydrogen production rate	$30Nm^3/h$ (Hydrogen for one passenger car can be produced in about 60 minutes.)
Hydrogen purity	99.99% or higher (The amount of CO, which adversely affects fuel cells, is 1 ppm or less.)
Filling capability	Five consecutive vehicles (5 minutes/vehicle).
Features	--Small, packaged hydrogen production device --Automatic control (for the hydrogen production and accumulators) --Regenerative combustion system (regenerative burner), which can achieve high efficiency

Table 13.5: Specifications of the Yokohama-Daikoku Hydrogen Station



Adapted from the Japan Hydrogen & Fuel Cell Demonstration Project website

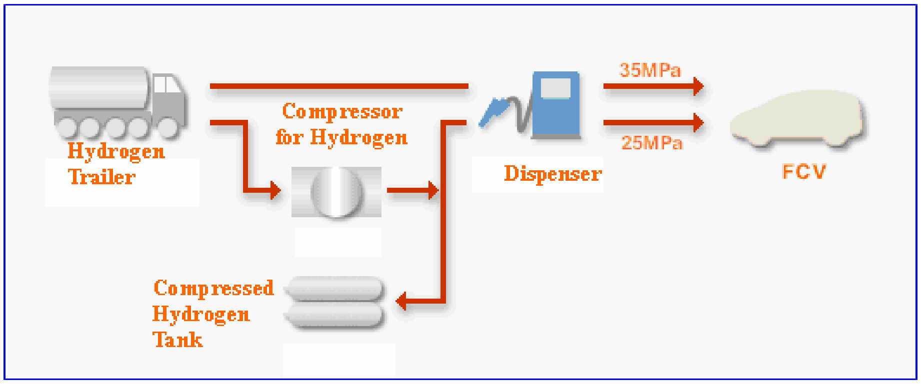
Figure 13.8: The Schematic for Yokohama-Daikoku Hydrogen Station

Yokohama-Tsurumi Hydrogen Station, an off-site type hydrogen station, operated by Tsurumi Soda Co., Ltd., and Iwatani International Corporation

Yokohama-Tsurumi Hydrogen Station is Japan's first off-site type hydrogen station. Hydrogen is used in various fields as industrial raw material and fuel, and this off-site type station, utilizing existing hydrogen stations and hydrogen trailers, is viewed as a promising system for the popularization of hydrogen stations. A main feature of this station is that it does not require reforming and refining processes, resulting in the simplicity of the facility. Here, hydrogen produced at Tsurumi Soda Co., Ltd., is dispensed into fuel cell vehicles through a trailer.

Material	Byproduct hydrogen (brine electrolysis)
Station Type	Off-site, using hydrogen trailer
Hydrogen Storage	Hydrogen trailer (2,030Nm^3, 19.6MPa)
Hydrogen purity	Over 99.99% (less than 1ppm of CO)
Filling capability	Five consecutive vehicles (5 minutes/vehicle) at 25MPa, 35Mpa
Features	--Japan's first off-site type hydrogen station --No hydrogen production facility, cutting space and construction costs --Does not require system start-up time

Table 13.6: Specifications of the Yokohama-Tsurumi Hydrogen Station



Adapted from the Japan Hydrogen & Fuel Cell Demonstration Project website

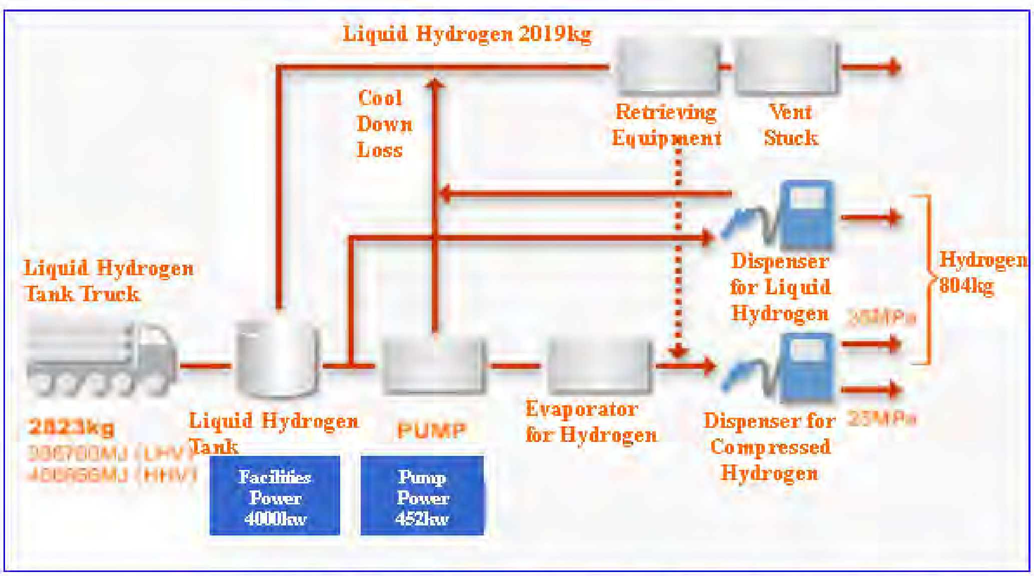
Figure 13.9: The Schematic for Yokohama-Tsurumi Hydrogen Station

Ariake Hydrogen Station, Liquid Hydrogen Storage Hydrogen Supply Facilities, operated by Showa Shell Sekiyu K.K. and Iwatani International Corporation

Ariake Hydrogen Station is an off-site liquid-hydrogen station which can supply both liquid hydrogen and compressed hydrogen gas. It is the only system for supplying liquid hydrogen in Japan. It does not have equipment for hydrogen production. For supplying liquid hydrogen and compressed hydrogen gas, its tank stores hydrogen transported from hydrogen production plants by truck. This tank can contain 130 truckloads of liquid hydrogen or 200 truckloads of compressed hydrogen gas.

Station Type	Off-site station which accepts liquid hydrogen trucks
Hydrogen Storage	10,000L
Hydrogen purity	99.99% or higher (The amount of CO, which adversely affects fuel cells, is 1 ppm or less.)
Filling capability	--Compressed hydrogen: 25/35MPaG, Filling time: 10minutes or less --140L of liquid hydrogen/vehicle, Filling time: 10minutes or less
Features	--Japan's first liquid hydrogen station --Capable of supplying both compressed hydrogen and liquid hydrogen. --Takes only a short time to set up.

Table 13.7: Specifications of the Ariake Hydrogen Station



Adapted from the Japan Hydrogen & Fuel Cell Demonstration Project website

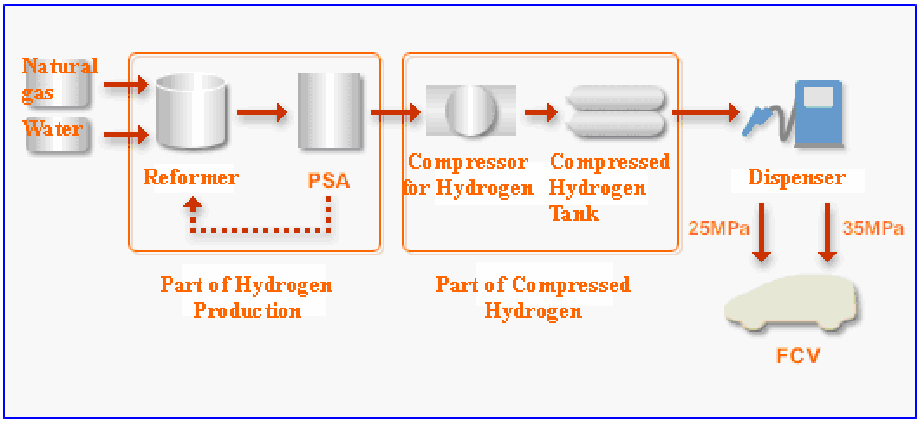
Figure 13.10: The Schematic for Ariake Hydrogen Station

Ome Hydrogen Station, a Natural Gas Reforming Hydrogen Supply Facilities, operated by Babcock-Hitachi K.K.

The Oume Hydrogen Station includes facilities for producing hydrogen by reforming natural gas (city gas). The production costs of this hydrogen production can be reduced because the infrastructure for natural gas is already well organized. Accordingly, natural gas is thought of as a promising fossil fuel for hydrogen production. Because all the facilities are vehicle-mountable, this station is expected to serve as a full-fledged mobile hydrogen station. It will cover these areas which do not have fixed hydrogen stations.

Material	Natural gas (city gas)
Hydrogen production method	Natural-gas reforming
Hydrogen production rate	30Nm^3/h
Hydrogen purity	99.99% or higher
Filling capability	Two consecutive passenger cars
Features	--This station can move to any where to supply hydrogen, because its hydrogen production device and fueling device are vehicle-mounted. --This kind of station is easily constructed and the cost of hydrogen production is low because the infrastructure for natural gas (city gas) is well organized. --This station can cover areas which do not have a fixed hydrogen stations, contributing to the widespread adoption of fuel cell vehicles. --If fuel cell vehicles are not yet disseminated in an area, this station can be used to investigate the demand for them before a fixed hydrogen station is deployed. It can also be used to temporarily back up a fixed hydrogen station.

Table 13.8: Specifications of the Ome Hydrogen Station



Adapted from the Japan Hydrogen & Fuel Cell Demonstration Project website

Figure 13.11: The Schematic for Ome Hydrogen Station

Hadano Hydrogen Station, a Kerosene-reform-type hydrogen fueling facility, operated by Idemitsu Kosan Co., Ltd.,

Kerosene, a liquid fuel low in volatility, has been considered a prospective fuel cell material for some time, being reasonably priced and with adequate infrastructure but it requires high level desulfurization and catalyst reforming technologies. Idemitsu Kosan Co., Ltd., through many years of research, has succeeded in producing hydrogen from kerosene by applying their desulfuring agent and catalyst reforming technology. The Hatano Hydrogen Station, built and operated by Idemitsu Kosan, is the world's first kerosene-reform-type hydrogen fueling facility, playing an important role in the popularization of fuel cell vehicles.

Material	Kerosene (JIS1)
Hydrogen production method	<desulfurization> adsorption desulfurization <hydrogen production> vapor reform <hydrogen refining> PSA
Hydrogen production rate	$50Nm^3/h$
Hydrogen purity	Over 99.99% (less than 1ppm of CO, harmful to fuel cells)
Filling capability	<Pressure> 25/35MPa < Consecutive Fueling Capability> Five consecutive passenger cars or one bus
Features	--The hydrogen source, kerosene, can easily be obtained nationwide --The world's first kerosene-reform-type hydrogen fueling facility, using originally-developed desulfurization technology --Compact, skid-mount system --Fully-automated operating control, with adequate safety measures --Located at the foot of the scenic Tanzawa mountain, with easy access to the Izu and Hakone areas

Table 13.9: Specifications of the Hadano Hydrogen Station

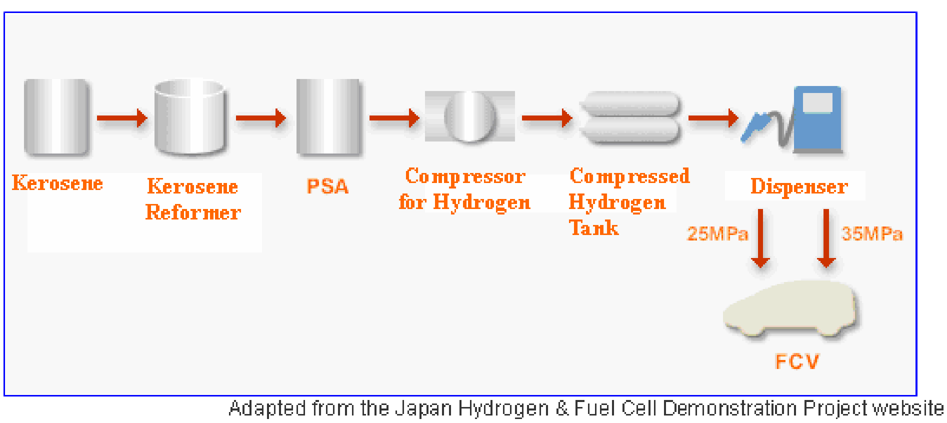


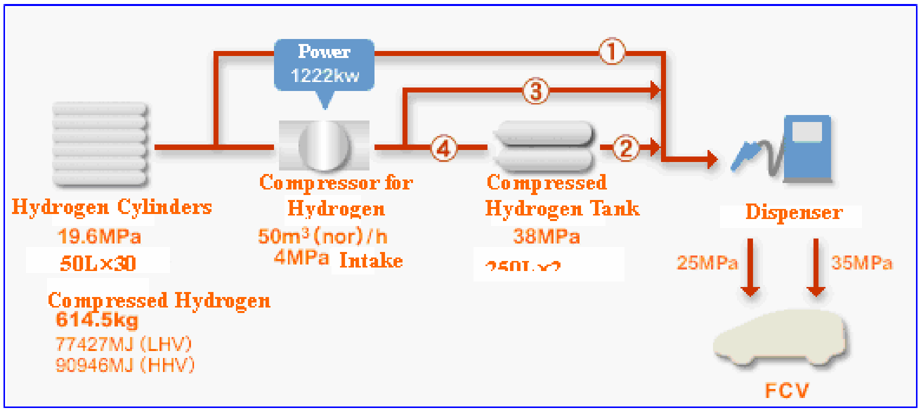
Figure 13.12: The Schematic for Hadano Hydrogen Station

Mobile Hydrogen Station, a High-Pressure Hydrogen Storage / Supply Facilities, operated by Nippon Sanso Corporation

A mobile hydrogen station can be found in the premises of the Ministry of Economy, Trade and Industry (METI) in Kasumigaseki, Chiyoda-ku, Tokyo. Each weekday morning, the components of this station are carried into the premises and assembled there; in the evening, they are moved off of the premises. All the devices used, such as the hydrogen cylinders and dispensers (fillers), are combined into a single unit for easy transportation. This mobile hydrogen station is expected to provide services outside the areas with fixed hydrogen stations. It is also expected to cover an area where installation of a fixed hydrogen station is difficult because of restrictions imposed by the Building Standard, High Pressure Gas Safety Law, and other current laws.

Material	Off-site hydrogen (curdled)
Gas storage facilities	250 L (40 MPa) x 2
Hydrogen production rate	50Nm^3/h
Hydrogen purity	99.99 % or higher (The amount of CO, which adversely affects fuel cells, is 1 ppm or less.)
Filling capability	Two consecutive passenger cars can be fueled.
Features	--Compact components which can be transported by truck --Ability to supply hydrogen to vehicles which are outside the area covered by fixed hydrogen stations --Ability to temporarily back up a fixed hydrogen station --Direct refueling by compressor --Easy-to perform operational control and adequate safeguards

Table 13.10: Specifications of the Mobile Hydrogen Station



Adapted from the Japan Hydrogen & Fuel Cell Demonstration Project website

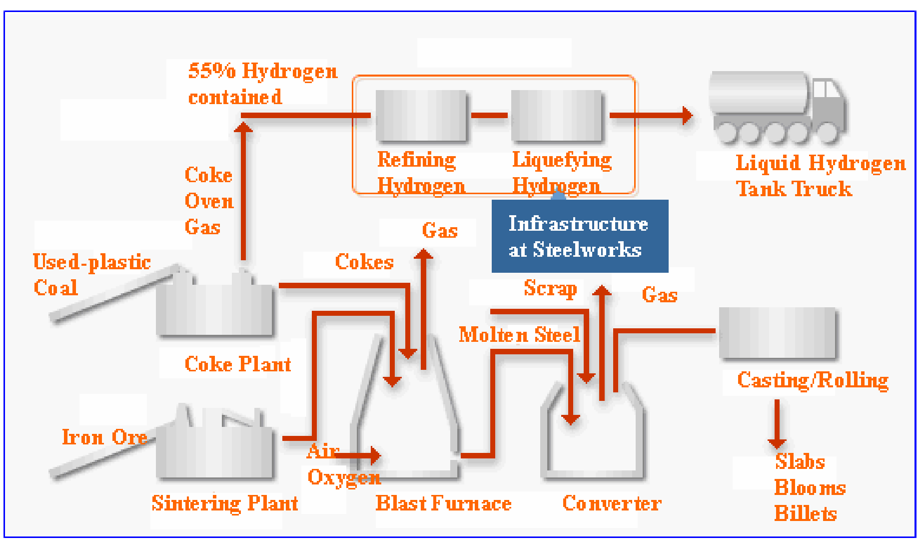
Figure 13.13: The Schematic for Mobile Hydrogen Station

Liquid Hydrogen Production Technology Development / Demonstration Facilities, a Facility for Manufacturing Liquid Hydrogen from Coke Oven Gas, operated by Nippon Steel Corporation

These facilities represent the world's first approach to mass-producing liquid hydrogen from by-product gas (coke oven gas: COG). They produce liquid hydrogen, which is efficiently transportable and storable, from large quantities of by-product gas generated in the steel making process. They can produce 0.2 ton of high-purity liquid hydrogen every day. In addition, they offer reduced cost of deployment by utilizing the existing steel making infrastructure. In the current JHFC Demonstration Project, an experiment is being conducted to investigate the full range of system operations, starting with the transportation of manufactured liquid hydrogen to the Ariake Hydrogen Station and ending with the supply of hydrogen to fuel cell vehicles.

Material	Coke oven gas (PSA-purified hydrogen)
Liquefaction method	Helium Brayton cycle
Liquid Hydrogen production rate	200 kg/day * (about 2,200Nm^3/day) * Equivalent to the amount of liquid hydrogen needed for 40 to 60 fuel cell vehicles/day.
Liquid Hydrogen Specifications	--Temperature: 20 K to 30 K (about -250°C to -25°C) --Pressure: 0.1 MPaG (1 kg/cm2G) --Purity: Hydrogen 99.999 vol.%
Main Components	--One liquidizing/cooling chamber (including an aluminum plate heat exchanger, an expansion turbine, etc.) --One circulation compressor (oil supply screw type) --One liquid nitrogen storage chamber (vacuum heat-insulating type) --One liquid hydrogen storage chamber (vacuum heat-insulating type)

Table 13.11: Specifications of the Liquid Hydrogen Production Facilities



Adapted from the Japan Hydrogen & Fuel Cell Demonstration Project website

Figure 13.14: The Schematic for Liquid Hydrogen Production Facilities

13.4 Construction Cost of Hydrogen Stations

The New Energy and Industrial Technology Development Organization (NEDO) established by the Japanese Government has played important roles in developing hydrogen energy technologies in the World Energy Network (WE-NET) in collaboration with industries, government, and universities.

"The WE-NET project is a long-range comprehensive plan, divided into three phases extending over a 28-year period from 1993 to 2020. Phase I started in 1993 with the aim of establishing a wide range of basic technologies related to hydrogen production, transportation, storage, and utilization. In Phase III, practical technology will be developed and pilot plants will be constructed on an international scale in order to deploy the system for actual use." (http://www.enaa.or.jp/WE-NET/suiso/suiso1_e.html, 2004)

The study of systems analysis in WE-NET in Phase 2 published in March 2004 includes the study on hydrogen station cost and hydrogen price for off-site station with by-product gas and for on-site station with steam methane reforming. As of today, this is the latest data released to the public on construction cost of hydrogen station.

13.4.1 Construction Cost of Hydrogen Station in Japan

The construction costs of hydrogen stations whose rates of hydrogen production are $100Nm^3/h$, $300Nm^3/h$, and $500Nm^3/h$ of both off-site and on-site are estimated from 2002 to 2020 by using a learning curve. 2002 is present at that time. 2006 is incubation period. 2010 is Beginning of Introduction. 2015 is Mid of Introduction. 2020 is mainstream acceptance period. Possibilities for reducing construction cost is taken into consideration in the sub-system level that consists of the reformer, the dispenser, hydrogen storage tank, the compressor, and so. Finally, the construction cost is adjusted by reflecting the reducing possibilities. Detailed calculation is not described in the paper. Revised construction cost of hydrogen station is as follows:

Year	Period
2002	Present
2006	Incubation Period
2010	Beginning of Introduction
2015	Mid of Introduction
2020	Mainstream acceptance Period

Table 13.12: Definition of Periods

(1 Million JPY)

Type \ Year	2002	2006	2010	2015	2020
100Nm3/h-off	163.5	124.1	110.2	101.6	93.2
300Nm3/h-off	267.5	212.8	192.3	167.7	151.3
500Nm3/h-off	399.1	324.1	276.9	248.5	221.4
100Nm3/h-on	280.6	187.4	156.4	138.1	121
300Nm3/h-on	498.4	370.4	285.3	253.5	216.8
500Nm3/h-on	708.9	536.1	430.5	368.7	311.7

Table 13.13: Construction Cost of Hydrogen Station (JPY)

The On means on-site station and the Off off-site station. Off-site stations supply hydrogen generated by using by-product gas. On-site is Steam methane reforming station. It seems that off-site type is most cost effective.

This study was done in terms of Japanese Yen (JPY), so we exchanged JPY into dollars (US$) with 1US$ = 131JPY because this rate was used to compare the cost difference in the US and Japan in this research paper.

($1,000)

Type \ Year	2002	2006	2010	2015	2020
100Nm3/h-off	1,248.1	947.3	841.2	775.6	711.5
300Nm3/h-off	2,042.0	1,624.4	1,467.9	1,280.2	1,155.0
500Nm3/h-off	3,046.6	2,474.0	2,113.7	1,896.9	1,690.1
100Nm3/h-on	2,142.0	1,430.5	1,193.9	1,054.2	923.7
300Nm3/h-on	3,804.6	2,827.5	2,177.9	1,935.1	1,655.0
500Nm3/h-on	5,411.5	4,092.4	3,286.3	2,814.5	2,379.4

Table 13.14: Construction Cost of Hydrogen Station (US$)

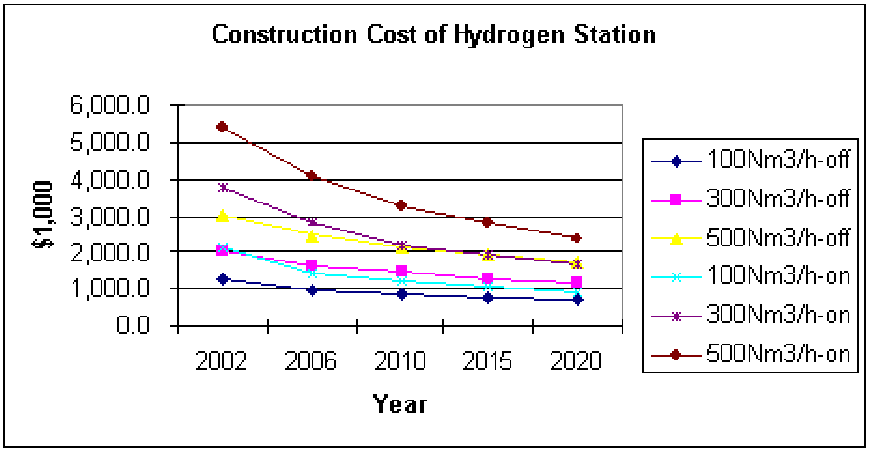


Figure 13.15: Construction Cost of Hydrogen Station

The Japan Hydrogen Fuel Cell Demonstration Project (JHFC) has constructed nine kinds of fixed hydrogen stations and a mobile hydrogen station so far. The construction costs of each station, however, are confidential so that the real cost data are not available at this point. Because the JHFC project is a government project, data of exact cost about the project might be released after the completion of the project.

13.4.2 The difference in construction costs of hydrogen stations in the US and Japan

Directed Technologies, Inc., analyzed the costs of hydrogen fueling stations in the US, according to the study of "Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances Task 2 Report" (April 2002). The assumptions of this study are as follows: the number of hydrogen stations constructed is 250/year; each hydrogen station supports 183 HFCVs (about one-eighth the size of the current average gasoline station); and the annual HFCV production rate is 50,000/year.

Each small hydrogen station consists of a small scale natural gas reformation unit producing hydrogen gas with a purity of 99.99%, a hydrogen compressor, on-site storage of the hydrogen, and a hydrogen dispenser to fuel hydrogen into the high pressure tank of a HFCV at 5,000 psi.

These hydrogen fueling appliance units are designed for a deliberately low hydrogen production rate, approximately 115 kg/day. In terms of the hourly production rate, 115kg/day is equal to 2,000 scfh ($54Nm^3/h$). The capacity of hydrogen production of the hydrogen stations in the Tokyo metropolitan area is 30 ~ 50Nm^3/h. The construction cost is about US$3 million.

This report examines multiple natural gas reformation chemical pathways (Steam Methane Reforming [SMR], Autothermal Reforming [ATR]) and multiple gas cleanup methods (Pressure Swing Adsorption [PSA], membrane separation, Preferential Oxidation [PrOx]) to determine the most cost effective approach. A Design of Manufacturing and Assembly (DFMA) costing approach is used to estimate cost. According to the research into 4 combinations of the above methods, the most cost effective combination is SMR + PSA.

The estimated initial construction cost of a hydrogen station whose hydrogen production ability: 115kg/day equal to 2,000 scfh (54Nm^3/h) is from $225,000 to $275,000 when the number of hydrogen stations constructed is 250/year and the annual HFCV production rate is 50,000/year. An annual investment of from $56.25 million to 68.75 million is required for constructing 250 hydrogen stations to support 50,000 HFCVs. This report also indicates that increasing the capacity of the hydrogen fuel appliances eight-fold (16000scf/h) will reduce the cost of the hydrogen by 45%.

"The study of systems analysis in WE-NET in Phase 2" (March 2004) shows comparison of construction cost of hydrogen station in the US and Japan in terms of the on-site hydrogen station with production ability of 300Nm^3/h.

The assumption of estimation of the construction cost by Directed Technologies, Inc., is that the number of hydrogen stations constructed is 250/year. This number of construction is close to that from at the end of Mid of Introduction to the mainstream acceptance period so that construction cost of 2020 in Japan is compared with the cost estimated by Directed Technologies, Inc.

	Directed Technologies, Inc., in the US				NEDO in Japan
	2000scf/h	16000scf/h	300Nm3/h		300Nm3/h
	($)	($)	($)	(1 MillionYen)	(1 MillionYen)
Reformer	105,470	367,300	296,400	38.8	62.4
PSA	18,075	130,300	92,800	12.2	
Compressor	20,780	98,800	75,600	9.9	12.0
Hydrogen Storage	43,583	314,200	223,800	29.3	10.4
Dispenser	20,700	58,500	49,000	6.4	8.7
Miscellaneous	21,404	91,800	71,500	9.4	123.3
10% Contingency	23,001	106,090	80,910	10.6	
Total	253,013	1,166,990	890,010	116.6	216.8

Table 13.15: Comparison of Construction Cost in the US and Japan

The cost of on-site 300Nm^3/h hydrogen station in the US is 116.6 million JPY (US$890,010) with exchange rate US$1=131JPY whereas that in Japan is 216.8 million JPY (US$1,654,961). The cost in Japan is as about 1.86 times as that in the US. One major factor of the cost difference is the cost of work such as installation and site operation, due to the high cost of wage in Japan. The other costs are not much different.

13.4.3 Estimated Construction Cost in the US from Japan's Cost

Japan's construction cost of hydrogen station in 2020 is 1.86 times higher than that in the US. This means that the cost in the US is 0.5378 times that in Japan. I estimate the hydrogen station cost from 2020 to 2002 by using the ratio of 0.5378. Table 13.15, Table 13.16, and Figure 13.16 show the construction cost in the US and Japan from 2002 to 2020.

1$= ¥131

Year / Type in Japan	2002	2006	2010	2015	2020
300Nm3/h-on (Million JPY)	498.4	370.4	285.3	253.5	216.8
300Nm3/h-on (1,000USD)	3,804.6	2,827.5	2,177.9	1,935.1	1,655.0

Table 13.16: Construction Cost of On-site 300Nm^3/h Hydrogen Station in Japan

Year / Type in the US	2002	2006	2010	2015	2020
300Nm3/h-on (1,000USD)	2,046.0	1,520.5	1,171.2	1,040.6	890.0
					0.537764

Table 13.17: Construction Cost of On-site 300Nm^3/h Hydrogen Station in the US

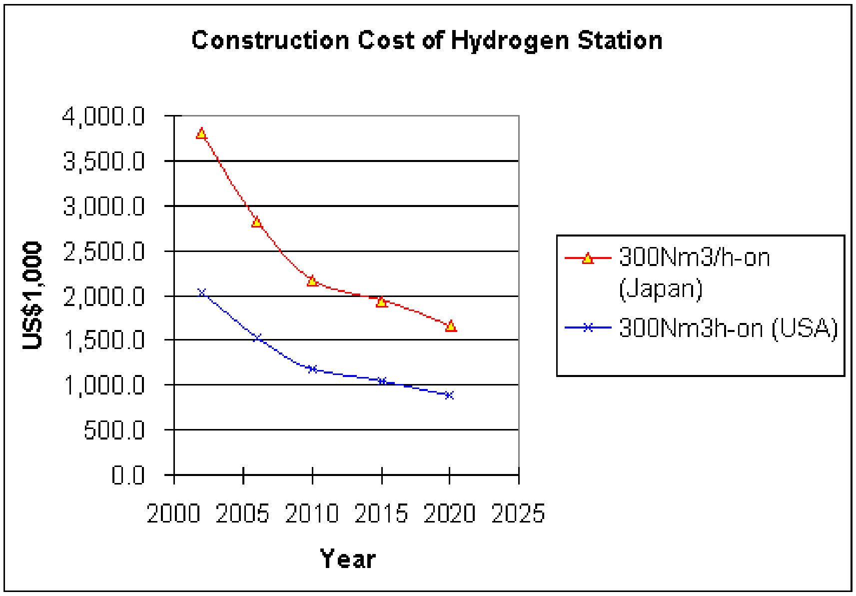


Figure 13.16: Construction Cost of On-site 300Nm^3/h Hydrogen Station in the US and Japan

By using above procedure, I estimate another five kinds of hydrogen station cost from 2020 to 2002 as well.

Japan (JPY)

Type \ Year	2002	2006	2010	2015	2020
100Nm3/h-off	163.5	124.1	110.2	101.6	93.2
300Nm3/h-off	267.5	212.8	192.3	167.7	151.3
500Nm3/h-off	399.1	324.1	276.9	248.5	221.4
100Nm3/h-on	280.6	187.4	156.4	138.1	121
300Nm3/h-on	498.4	370.4	285.3	253.5	216.8
500Nm3/h-on	708.9	536.1	430.5	368.7	311.7

Japan (US$1,000)

Type \ Year	2002	2006	2010	2015	2020
100Nm3/h-off	1,248.1	947.3	841.2	775.6	711.5
300Nm3/h-off	2,042.0	1,624.4	1,467.9	1,280.2	1,155.0
500Nm3/h-off	3,046.6	2,474.0	2,113.7	1,896.9	1,690.1
100Nm3/h-on	2,142.0	1,430.5	1,193.9	1,054.2	923.7
300Nm3/h-on	3,804.6	2,827.5	2,177.9	1,935.1	1,655.0
500Nm3/h-on	5,411.5	4,092.4	3,286.3	2,814.5	2,379.4

Table 13.18: Construction Cost of 6 Types of Hydrogen Station in Japan

Although exchange rate US$ versus JPY was US$1=131JPY, exchange rate has considerably changed to US$1= 105JPY in Jan. 2005. By multiplying 1.248 (131/105) to the above cost, I adjust the number for the accuracy based on the exchange rate factor as follows.

Type \ Year	2002	2006	2010	2015	2020
100Nm3/h-off	837.4	635.6	564.4	520.4	477.4
300Nm3/h-off	1,370.0	1,089.9	984.9	858.9	774.9
500Nm3/h-off	2,044.0	1,659.9	1,418.1	1,272.7	1,133.9
100Nm3/h-on	1,437.1	959.8	801.0	707.3	619.7
300Nm3/h-on	2,552.6	1,897.0	1,461.2	1,298.3	1,110.4
500Nm3/h-on	3,630.7	2,745.7	2,204.9	1,888.3	1,596.4

Table 13.19: Adjusted Construction Cost of Hydrogen Station with Exchange Rate Factor

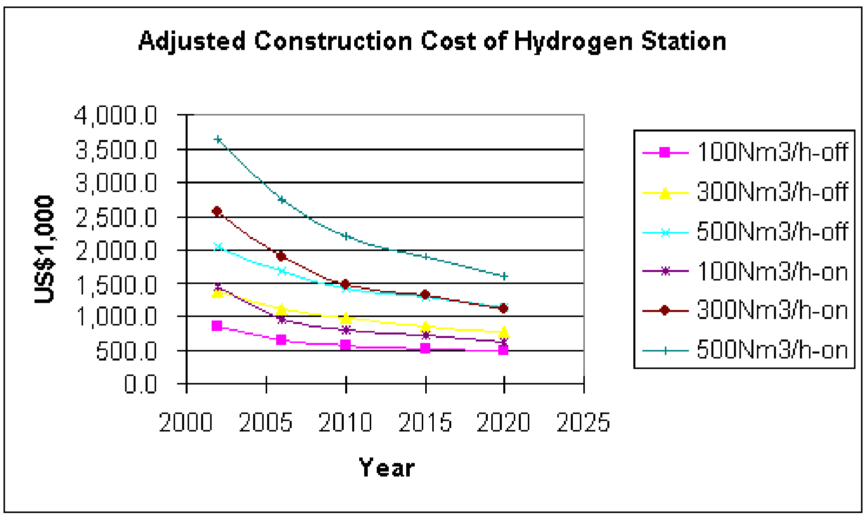


Figure 13.17: Adjusted Construction Cost of Hydrogen Station with Exchange Rate Factor

Another possible scenario results in the penetration of HFCVs starting in 2020. Cost reduction should be taken into consideration on the construction cost. We can expect technological advance leading to decrease the production cost of equipment such as dispensers, hydrogen storage tanks, and compressors. Technological advance and mass production in the whole world will help cost decrease. We anticipate that the cost in 2020 can be reduced by 10 percent of that in 2002, the cost in 2025 can be reduced by 5 percent of 2006, the cost in 2030 may be consistent with 2010, the cost in 2035 may be comparable with 2015, and the cost in 2040 may be equal to that in 2020. We also predict construction cost in 2050 and 2060. Finally, we assume that the cost in 2050 could be reduced by 10 percent of that in 2040 and the cost in 2060 could be decreased by 5 percent of that in 2050. Because mass construction of hydrogen station would be started around this period, large cost reduction cannot be expected before them. The predicted construction cost of hydrogen station and approximate curves for each station are as follows.

Type \ Year	2020	2025	2030	2035	2040	2050	2060
100Nm3/h-off	753.7	603.8	564.4	520.4	477.4	429.7	408.2
300Nm3/h-off	1,233.0	1,035.4	984.9	858.9	774.9	697.4	662.5
500Nm3/h-off	1,839.6	1,576.9	1,418.1	1,272.7	1,133.9	1,020.5	969.5
100Nm3/h-on	1,293.4	911.8	801.0	707.3	619.7	557.7	529.8
300Nm3/h-on	2,297.3	1,802.2	1,461.2	1,298.3	1,110.4	999.4	949.4
500Nm3/h-on	3,267.6	2,608.4	2,204.9	1,888.3	1,596.4	1,436.8	1,364.9

Table 13.20: The Predicted Construction Cost of Hydrogen Station from 2020 to 2060

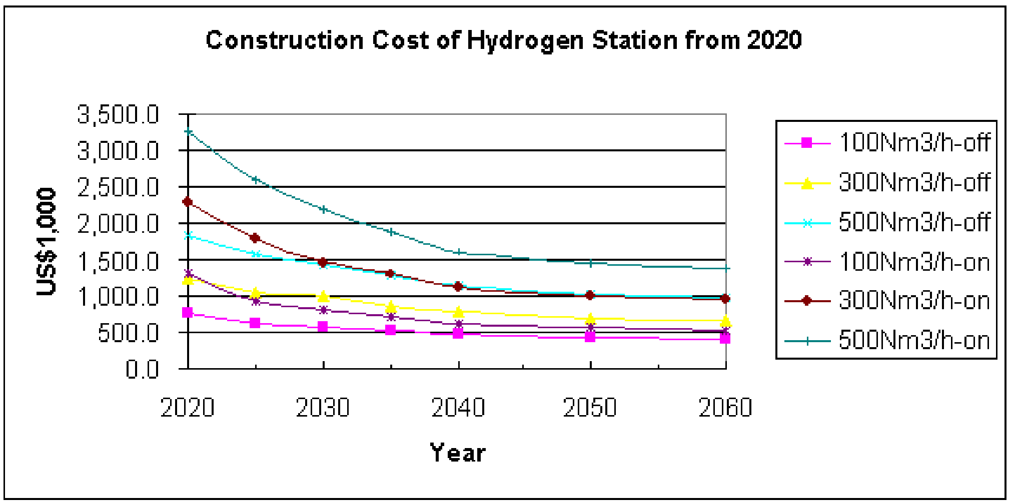


Figure 13.18: The Predicted Construction Cost of Hydrogen Station from 2020 to 2060

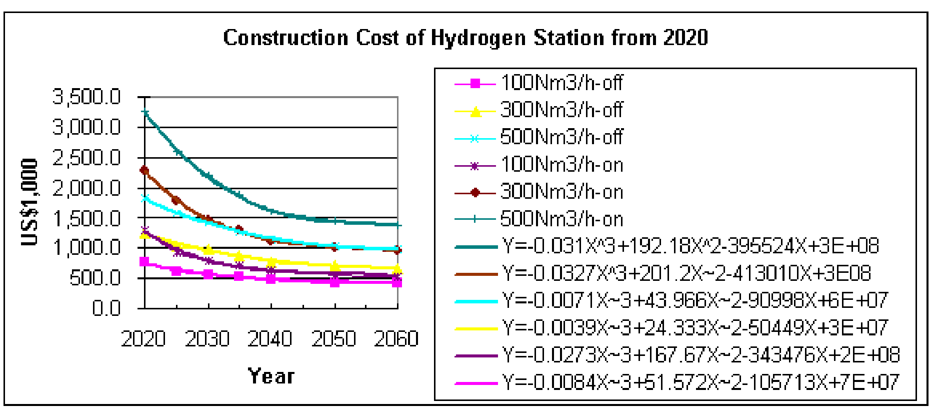


Figure 13.19: The Approximate Curves for the Construction Cost

13.4.4 Economic Analysis for the Investment of Hydrogen Infrastructure

In this economic analysis, we estimate the minimum selling price of hydrogen in order to offset the investment cost of the hydrogen infrastructure. To accomplish this, we used a nonlinear optimization model using Solver in Excel. The objective was to set net present value (NPV) equal to zero.

A key assumption of this economic analysis is that the penetration of HFCV starts in 2020. In this first phase, we will construct 11 hydrogen stations in Washington, DC. Due to the cost effectiveness, 500Nm^3 hydrogen supply facilities are constructed at existent gasoline stations. As the number of HFCV increase, demand of hydrogen will also increase. Just before the demand for hydrogen exceeds the capacity of the initial stations, new 500Nm^3 hydrogen supply facilities will be added in among the 11 hydrogen stations. The hydrogen-selling price is decreased by 5 % annually to promote new users of HFCV.

This analysis covers 16 years of operation because the lifetime of a facility is estimated to be 15 years for large hydrogen production facilities (Directed Technologies, pg. 122 [204]). Therefore, a 15 year life cycle is analyzed for recovery of the investment just after the completion of initial construction. Parameters for the cost analysis are as follows.

Number of HFCVs

The number of HFCV is predicted by our research. The result is as follows:

Year	2020	2025	2030	2035	2040	2045	2050
No. of HFCV	5,288	13,082	40,076	80,263	149,813	209,813	284,442

Table 13.21: The Number of HFCV

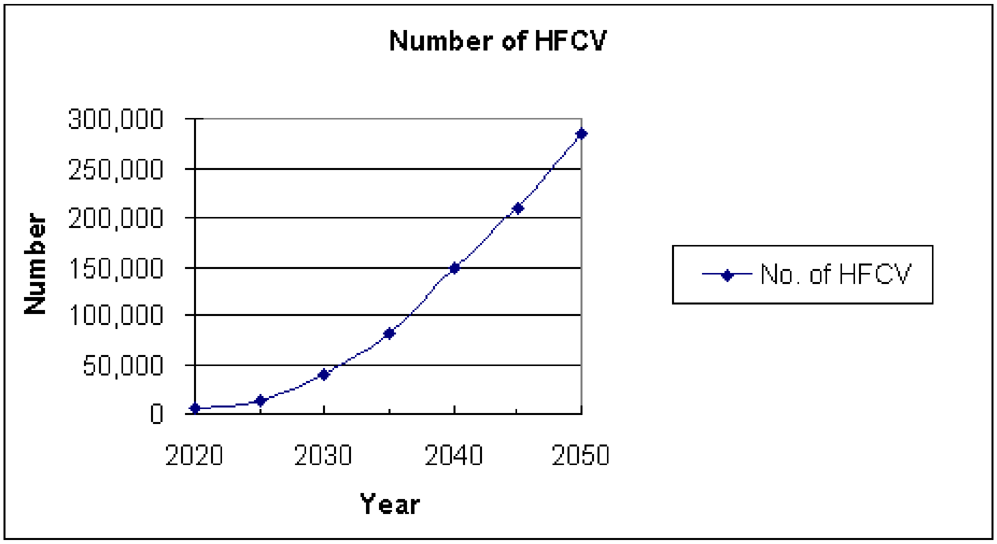


Figure 13.20: The Number of HFCV

Average Mileage/Year

On the basis of "Transportation Energy Data Book: Edition 22" (2002 (pg. 7-2)), the number of registrations of passenger vehicle is $133,621 * 10^3$ and vehicle miles traveled is $1,601,914 * 10^3$. Therefore, average mileage/year in a vehicle is 11,989 mile/year.

Fuel Economy

According to the specification of HONDA FCX (Honda Motor Co., Ltd, 2004 [205]), maximum trip is 430km (268.75mile) with amount of hydrogen of 42 Nm^3 (3.75kg). Therefore, fuel economy 0.014kg/mile is acquired. "Transportation Energy Data Book: Edition 22" (2002, pg. 7-2 [206]) indicates that average annual percentage change of fuel economy for 19702000 is 1.6% and 19902000 is 0.9%. In this economic analysis, we will use fuel economy 0.014kg/mile with annual 1% improvement at the beginning of penetration period of HFCV. The rate of improvement of fuel economy, however, might slow down after the level of technology for HFCVs reaches a steady state.

The Number of Hydrogen Stations

In the first phase, we plan to construct 11 hydrogen stations. Table 13.10 shows how many $500Nm^3$ hydrogen supply facilities are required in eleven hydrogen stations. Availability of hydrogen supply from 2020 to 2028 is obviously more than demand. However, at the beginning of this stage we need to construct enough stations to increase the number of HFCV. Fifteen 500Nm^3 hydrogen facilities will be needed in 2029. Therefore, we will add four 500Nm^3 hydrogen supply facilities in 2028. Based on this policy, we add 500Nm^3 hydrogen supply facilities to satisfy demand of hydrogen.

Year	No. of FCV	Av. Mileage/ year	H2 Kg/mile	H2 Kg/Year	Required production ability(kg/h)/ station	Required production ability(Nm3/h) /station	Required Number of 500Nm3/h station	Number of Construction	Construction Cost
2019								11	20,235,600
2020	5,228	11,988	0.0140	877,426	9.11	102	3	0	0
2021	5,300	11,988	0.0139	880,615	9.14	102	3	0	0
2022	6,000	11,988	0.0137	986,953	10.24	115	3	0	0
2023	8,000	11,988	0.0136	1,302,778	13.52	151	4	0	0
2024	10,000	11,988	0.0134	1,612,187	16.73	187	5	0	0
2025	13,082	11,988	0.0133	2,087,973	21.67	243	6	0	0
2026	15,000	11,988	0.0132	2,370,157	24.60	275	7	0	0
2027	20,000	11,988	0.0130	3,128,608	32.47	364	8	0	0
2028	25,000	11,988	0.0129	3,871,652	40.18	450	10	3	4,365,000
2029	35,000	11,988	0.0128	5,366,110	55.69	624	14	2	2,860,000
2030	40,076	11,988	0.0127	6,082,906	63.13	707	16	3	4,254,300
2031	48,000	11,988	0.0125	7,212,788	74.85	838	19	4	5,600,000
2032	60,000	11,988	0.0124	8,925,825	92.63	1,037	23	4	5,400,000
2033	70,000	11,988	0.0123	10,309,328	106.99	1,198	27	3	3,900,000
2034	80,000	11,988	0.0122	11,664,268	121.05	1,356	30	0	0
2035	80,263	11,988	0.0120	11,585,588	120.23	1,346	30		

Table 13.22: Required number of 500Nm3 Hydrogen Supply Facilities

The Purchase Price of Hydrogen

We have decided to apply off-site hydrogen station due to the cost efficiency so that purchase price of hydrogen must be included into the hydrogen-selling price. “The study of systems analysis in WE-NET in Phase 2” (March 2004, pg. 54 [207]) includes the analysis of hydrogen selling price. On the basis of this analysis, the purchase price of hydrogen generated from by-product gas is 21.6JPY/Nm^3 in 2020 whereas hydrogen-selling price to HFCV in 500Nm^3 /h off-site station is 70.8 JPY/Nm^3: Purchase price of hydrogen account for 30 percent of selling price. This rate is considered in our economic analysis.

The Maintenance Cost and Insurance & Tax

“The study of systems analysis in WE-NET in Phase 2 NEDO Japan" (March 2004) shows comparison of construction cost of hydrogen station in the US and Japan in terms of the on-site hydrogen station with production ability of 300Nm^3/h. The construction cost in the US is derived from “Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances Task 2 Report”

(Directed Technologies, Inc., April 2002 [204]). According to Table-1.2.5-7 on p.81 in "The study of systems analysis in WE-NET in Phase 2 (March 2004 [207])", the maintenance cost calculated by Directed Technologies, Inc., USA is 5 percent of the facility cost while the maintenance cost analyzed by NEDO is 7 percent of the facility cost. 5 percent of the facility cost is considered as a maintenance cost in our economic analysis.

Insurance cost and tax refer to annual property taxes at 1.5% of capital investment and annual insurance premiums at 1% capital investment (p-3) in "Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances Task 2 Report April 2002 Directed Technologies, Inc.," Therefore 2.5% construction cost is considered as the insurance and tax in our research.

Miscellaneous

Some cost factors cannot be estimated so that 10% of sales of hydrogen are taken into consideration as miscellaneous cost for coping with unknown costs and contingency costs.

The result of this analysis

Based on the above all factor, I acquired NPV = 0 US$ when hydrogen selling price is US$3.44/kg in 2020 and US$1.68/kg in 2034.

Objective Function		
NPV	0	US$

Variable			
Hydrogen Selling Price/kg in 2020	3.44	US$/kg	(5% decrease/Year)

Parameters			
Discount rate	7%		
% H2 purchase Price in Selling Pri	30%		
Starting Year	2020		
Avarage Mileage/year	11,988	mile/year	
Fuel Economy in 2020	0.014	Kg/mile	(1% Improvement/Year)
H2 1 m3	0.0893	Kg	

Year	No. of FCV	Av. Mileage/year	H2 Kg/mile	H2 Kg/Year	H2 $/kg	H2 Sales	Initial Construction Cost	H2 Purchase	Maintenance Cost 5%	Insurance 2.5%	Miscellaneous 10%	Total Revenue
2019							-20,235,600					-20,235,600
2020	5,228	11,988	0.0140	877,426	3.44	3,019,217		-905,765	-1,011,780	-505,890	-301,922	595,762
2021	5,300	11,988	0.0139	880,615	3.27	2,878,680		-863,604	-1,011,780	-505,890	-287,868	497,406
2022	6,000	11,988	0.0137	986,953	3.11	3,064,979		-919,494	-1,011,780	-505,890	-306,498	627,816
2023	8,000	11,988	0.0136	1,302,778	2.95	3,843,484		-1,153,045	-1,011,780	-505,890	-384,348	1,172,769
2024	10,000	11,988	0.0134	1,612,187	2.80	4,518,496		-1,355,549	-1,011,780	-505,890	-451,850	1,645,277
2025	13,082	11,988	0.0133	2,087,973	2.66	5,559,386		-1,667,816	-1,011,780	-505,890	-555,939	2,373,900
2026	15,000	11,988	0.0132	2,370,157	2.53	5,995,187		-1,798,556	-1,011,780	-505,890	-599,519	2,678,961
2027	20,000	11,988	0.0130	3,128,608	2.40	7,517,965		-2,255,389	-1,011,780	-505,890	-751,796	3,744,905
2028	25,000	11,988	0.0129	3,871,652	2.28	8,838,308	-4,365,000	-2,651,492	-1,011,780	-505,890	-883,831	304,145
2029	35,000	11,988	0.0128	5,366,110	2.17	11,637,400	-2,860,000	-3,491,220	-1,230,030	-615,015	-1,163,740	3,441,135
2030	40,076	11,988	0.0127	6,082,906	2.06	12,532,308	-4,254,300	-3,759,692	-1,373,030	-686,515	-1,253,231	2,458,771
2031	48,000	11,988	0.0125	7,212,788	1.96	14,117,140	-5,600,000	-4,235,142	-1,585,745	-792,873	-1,411,714	1,903,381
2032	60,000	11,988	0.0124	8,925,825	1.86	16,596,463	-5,400,000	-4,978,939	-1,865,745	-932,873	-1,659,646	3,418,907
2033	70,000	11,988	0.0123	10,309,328	1.77	18,210,469	-3,900,000	-5,463,141	-2,135,745	-1,067,873	-1,821,047	5,643,711
2034	80,000	11,988	0.0122	11,664,268	1.68	19,573,653		-5,872,096	-2,330,745	-1,165,373	-1,957,365	10,205,440

Figure 13.21: Non-linear Optimization Model for NPV calculation

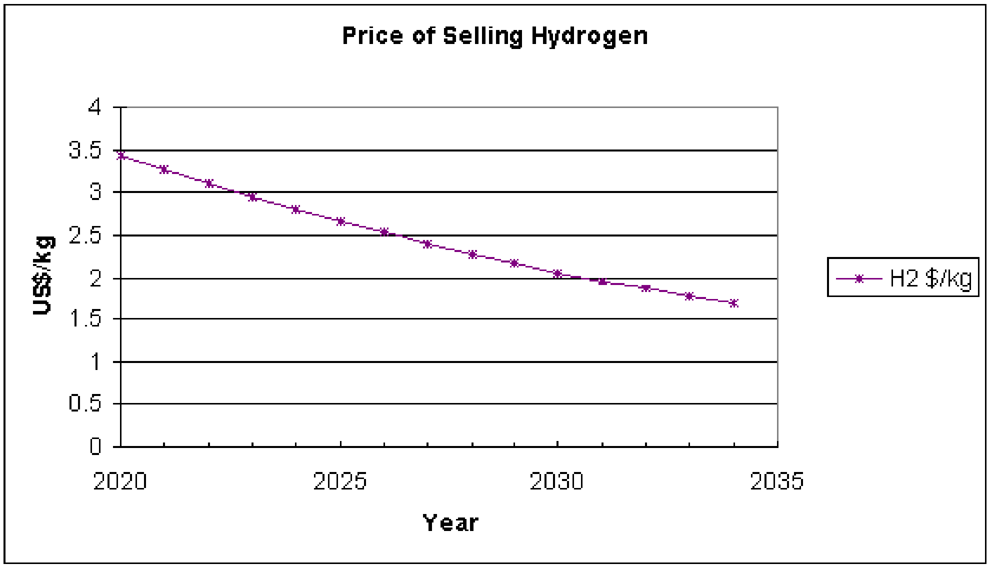


Figure 13.22: Price of Selling Hydrogen

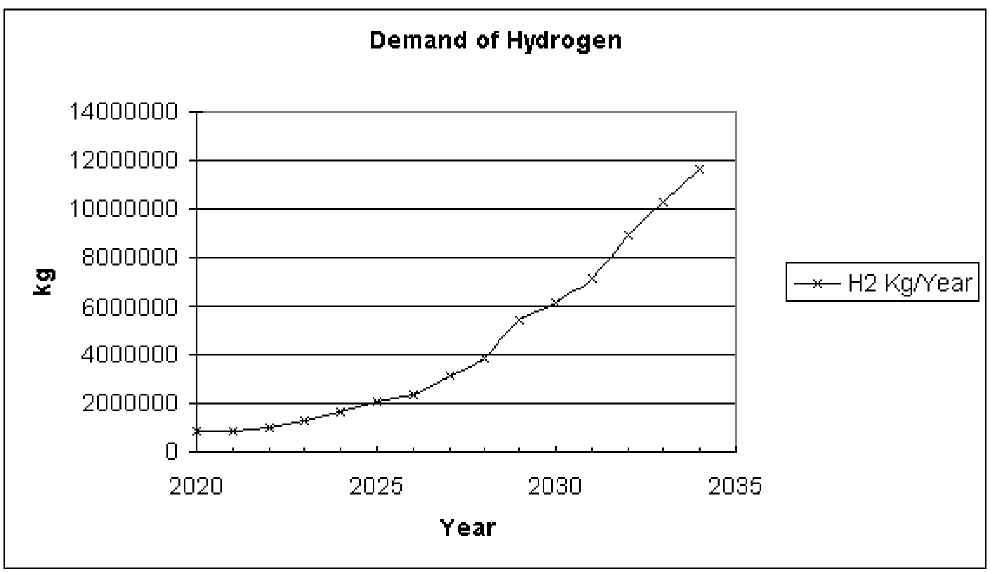


Figure 13.23: Demand of Hydrogen

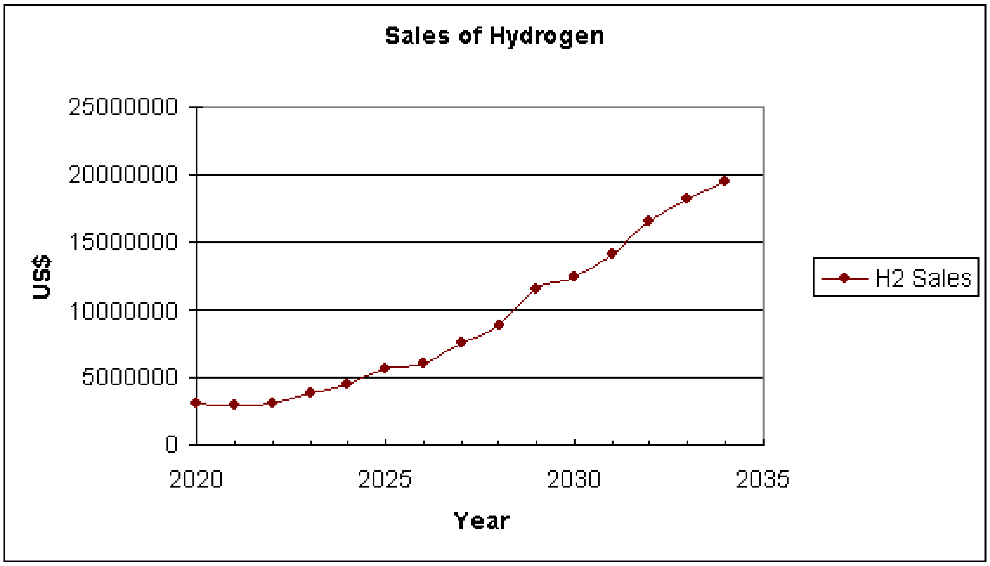


Figure 13.24: Sales of Hydrogen

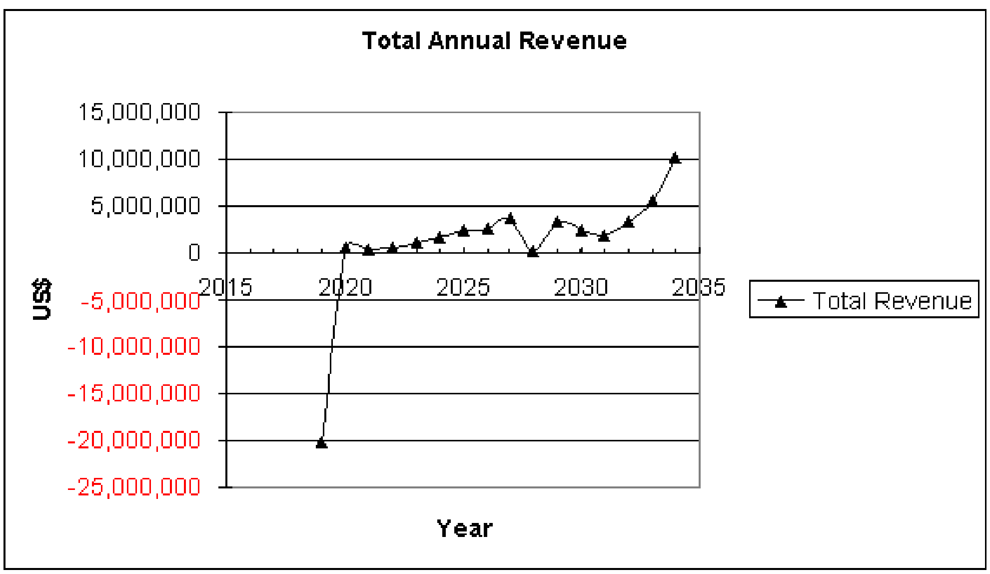


Figure 13.25: The Annual Revenue

Chapter 14

Design of Network

14.1 Design of Network

14.1.1 Sufficient Number for Initial Stage

According to Melaina (2003) [208], the criteria of the initial hydrogen stations are as follows:

- Located in close proximity to higher traffic volumes.
- Located in high profile areas to increase public awareness.
- Accessible to potential first FCV buyers.
- Located to provide fuel to vehicles during long distance trips.

The research also provides 3 approaches for estimating a sufficient number of early hydrogen stations.

Approach 1, Percentage of existing stations

Transforming a certain percent of existing gasoline stations into hydrogen stations is suggested because of customer expectation, habit and affinity. The research suggested 5% for the initial first stage for metropolitan stations to provide an alternative fuel penetration and 15% of all stations for the second stage. However, we will focus on the stations managed by major oil companies since they are more likely to support the conversion to hydrogen. Since we are looking at the Greater

DC area as a whole, we will not distinguish between metropolitan and urban areas. Thus, we divide the initial stage into two phases with approximate 10% and 20% of stations for a gradual penetration. This corroborates the research cited earlier in this report by Sperling (1987) [199] that 10-15% of the existing network would be necessary to begin significant market penetration.

Approach 2, Metropolitan land area

Assigning a certain amount of metropolitan land area to the hydrogen stations in the beginning is an analytical measure to check if the number is sufficient for a metropolitan area. However, since we already have good estimates for how many stations we need, and we felt this method had limited value. It seemed to be a method with very little value other than providing a general estimate, and its general benefit was implicitly included in our own algorithm.

Approach 3, Principal arterial roads

It is a good idea to identify the major urban arterials since they are part of a structured urban network. As Marc Melaina mentioned in this approach, most urban residents do a significant amount of routine driving on major arterial roads. This means that the locations related to arterial roads account for a significant volume of vehicle miles traveled. Furthermore, in this project we take major interstate roads into consideration due to a large amount of commuters from Virginia and Maryland.

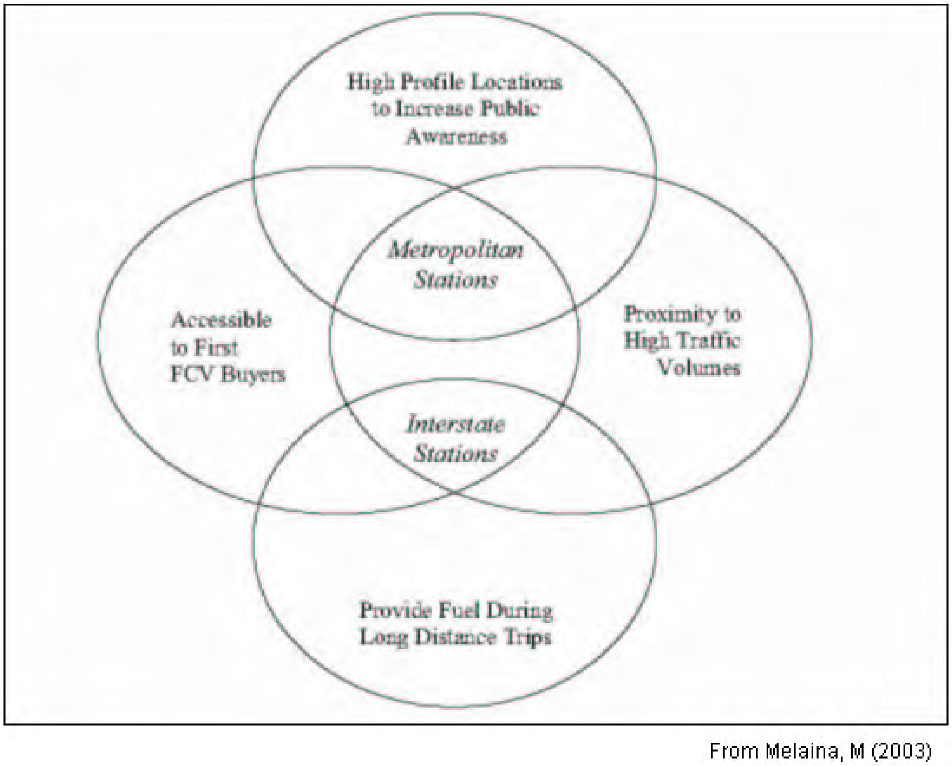


Figure 14.1: General criteria for identifying effective locations for initial hydrogen stations.

14.1.2 The Procedure of Initial Hydrogen Network

Screen of existing gasoline infrastructure

Presumably, the existing gasoline stations have already projected the demand pattern of the D.C. area, and the total size and structure of a station will not change significantly after transition. Thus, we will filter the existing stations and pick an appropriate number of stations to use as a base for a hydrogen network.

According to economic census by U.S. Census Bureau, the number of gasoline stations (with and without convenient store) in D.C was 112 in 1997 and this is the most recent official number available. By using yellow pages in Yahoo, we can find 140 gas stations in D.C. and many of them are named under the heading of convenience store. In the beginning, we assume that only big companies' can afford the investment of hydrogen transition. Using this assumption, we pick the four largest oil companies gasoline stations in D.C. The names of these companies and the number of stations they operate in the D.C. area is shown in the following table.

Company Name	Gasoline Stations in D.C.
BP-Amoco www.bp.com	20
Chevron Texaco www.chevrontexaco.com	10
Exxon Mobil www.exxonmobil.com	36
Shell www.shell.com	17
Total	83

Table 14.1: Major oil companies' infrastructure in D.C.

The number of gasoline stations is obtained from officieal website of the companies and superpage website www.superpages.com. By comparing and elimination the repeating records, we obtained the most precise data we can have.

Thus, we decide 10 stations out of these 83 stations for the first phase of the initial transition stage. In addition, there is an existing hydrogen station operated by Shell on Benning Road in D.C. We included this existing station so that in the first phase of the initial transition, eleven stations will be evaluated. After the first phase, nine additional stations will be added to meet increasing demand.

Distribution Major roads and Zip Codes

To select the stations while following Melaina's approach, we will need to develop some sort of algorithm. Since we have the addresses of the 83 candidate stations, we can categorize the stations by a sorted identity number zip code. Using the data of Zip code tabulation areas for Census 2000, we can divide D.C. into several regions. (www.census.gov/geo/www/tiger/glossary.html#zcta, 2000 [209])

The zip codes in D.C. range from 20000-20599 but most of them can not be represented graphically. According to the tabulation and GIS data the US census offered, the most important and useful zip codes we can apply are shown on the next page. To simplify the trivial zip code areas without any stations in them and expedite the analysis, we combined several zip code areas as follows:

Zone 20032 contains 20336, 20332 and 20315

Zone 20024 contains 20024 and 20319

Zone 20036 contains 20004, 20005 and 20006

The divided regions with zip code are in the graph on the following page. Please note that

Phase I is in **bold** and Phase II is in *italics.*

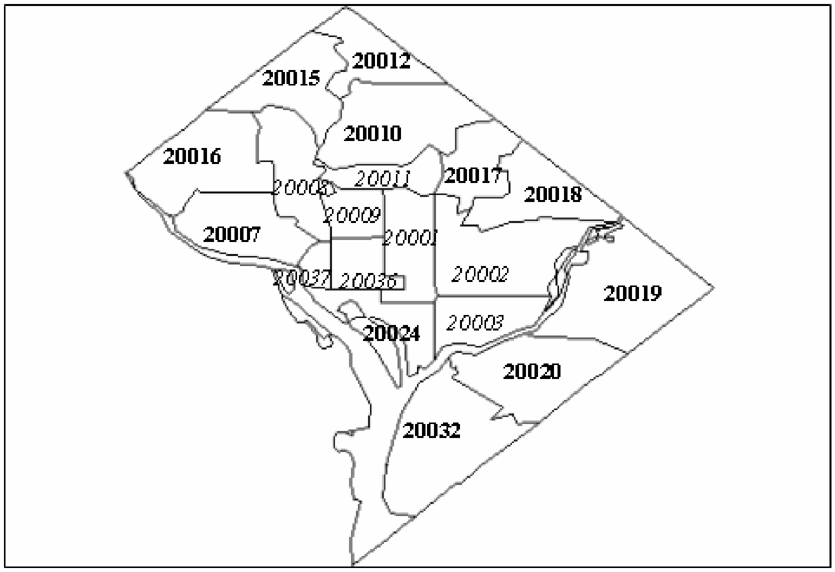


Figure 14.2: Zip code tabulation area of the District of Columbia

Another reason we decide to classify by zip code is because it offers the approximate granularity we need. It is also easy to categorize the existing stations instead of using arbitrary grids. The steps for zip code with road analysis are as follows:

- Generate list of station in each zip code.
- If there are no stations in a specific zip code, we assume that there is no demand in this neighborhood so we discard this zip code.
- If there is only one station in a zip code, pick the only one because even though there is not much demand, it may still have strategic value
- If there is more than one station in the zip code region, use the following multiple criteria to pick one station.
  - Close to major arterials, because it is easy to access
  - Not close to border of D.C., because the other side of the border is not well represented.
  - Centrally located in zip code region

The following page contains a demonstration of this algorithm.

Take zip code 20007 as an example. There are four candidate stations in this zip code area.

Station Name	Address	Quadrant	State	Zip code
Key Bridge Exxon	3607 M street	NW	D.C.	20007
Parker's Exxon	4812 Macarthur Boulevard	NW	D.C.	20007
Georgetown Amoco	2715 Pennsylvania Avenue	NW	D.C.	20007
Mid Atlantic Petroleum	2450 Wisconsin Avenue	NW	D.C	20007

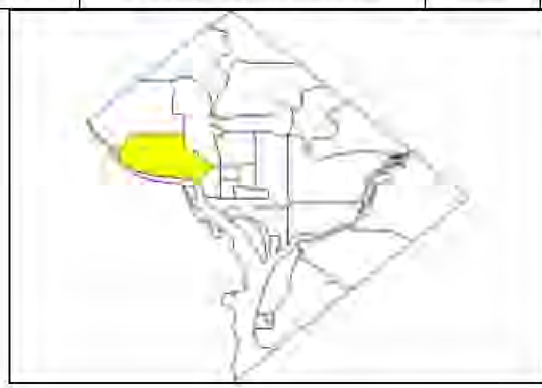


Figure 14.3: Stations in 2007

We pick Mid Atlantic Petroleum as the representative this area because it is located on Wisconsin Ave. near the intersection of two major arterials. While this is not owned by a major oil company, this location is much better than the other three stations.

Figure 14.4: Mid Atlantic Petroleum on Wisconsin Avenue

Following this procedure, 11 primary choices were selected, with 9 secondary choices. These two sets make up the first and second phases of our project, respectively. The stations are listed in the table that appears in Section 14.1.3. Also, detailed maps of the location of each station can be found in the Appendix.

Decision to avoid downtown area

The downtown D.C. area is mostly occupied by government agencies and bureaus. Furthermore, high security landmarks and monuments like the White House are in this area. Even though hydrogen technology is proven stable, this alone may not be convincing enough to locate hydrogen stations in these high security areas. In addition, most areas in this central D.C. area are not zoned for refueling stations, leaving few options.

Another reason to set the stations away from downtown is because of the impact on traffic. Setting hydrogen stations in the downtown area will make it harder for drivers to refuel their cars, especially in a congested area. According to the research mentioned before, drivers tend to refuel near their house rather than their work place. Thus, it is reasonable to set the initial stations away from downtown and more towards the suburbs where commuters reside. Moreover, if we apply off-site hydrogen stations, the refueling fleets for stations will have difficulty reaching them, and may even cause problems themselves. If the stations need to be refueled twice a day, it is inevitable to refuel in the daytime and cause traffic jams, even during non peak hours.

Another reason to avoid the downtown area is the Metro. The Metro subway system in D.C. covers all of the downtown area. Assuming that most workers have easy access to the Metro at the home end of the commute, public transportation might be a much more reliable way to get to the office in a timely manner in this area. Because of this, many would take advantage of the system. Thus, we assume that the demand for refueling here is not as great as in residential areas. Finally, from a psychological standpoint, if the downtown area is the first thought for drivers to refuel, any station there may quickly become overcrowded. It is better to introduce them to the alternative options so that the fluency of traffic and service rates at individual stations can be maintained.

A detailed description of the downtown area appears on the following page.

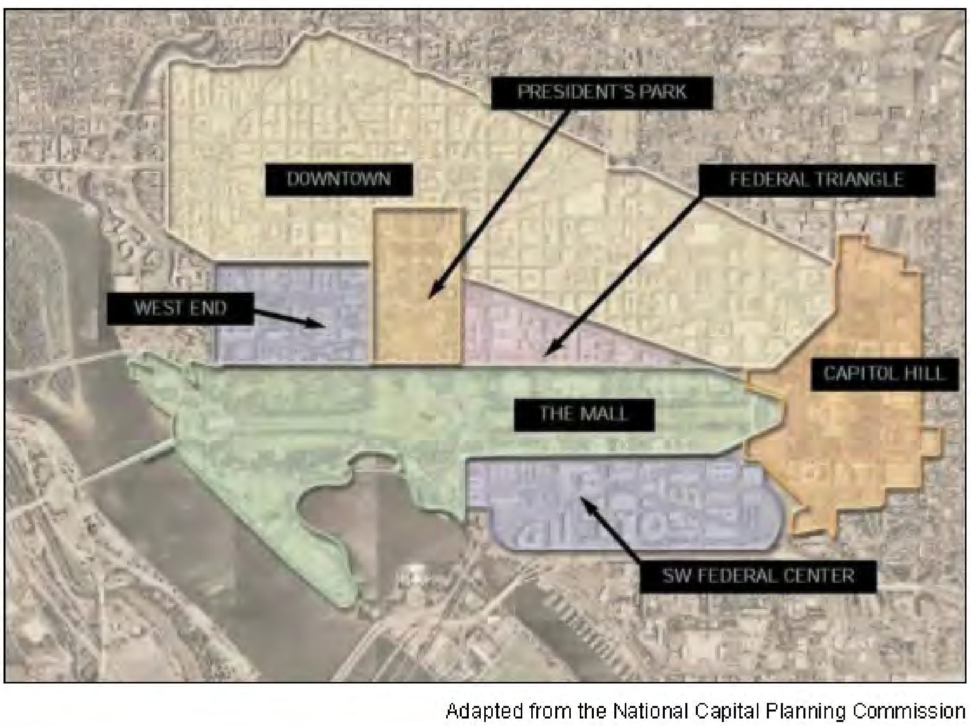


Figure 14.5: The downtown area of D.C.

The downtown area of D.C. is defined and shown as above. The downtown area is roughly bounded by Pennsylvania Avenue on the south, Massachusetts Avenue on the north, and runs from approximately 3^{rd} street, NW to 25^{th} Street, NW. According the National Capital Planning Commission's designing principle, especially for security reasons, the uses, business interests, pedestrian circulation, and traffic and parking requirement must be considered carefully. Any measure taken in this zone has to avoid any negative impact. Thus, the establishment of hydrogen facilities has to be evaluated and the impact to the traffic as well. The central part of D.C. is therefore not recommended as the initial location of hydrogen stations.

14.1.3 Final Design of Hydrogen Network

The suggested stations for phase 1 and phase 2 are in following table.

Phase 1		
Station Name	Address	Zip Code
Mid Atlantic Petroleum	2450 Wisconsin Ave.	20007
J & K Amoco	3426 Georgia Ave.	20010
J and K Shell	6419 Georgia Ave.	20012
KM Inc	5521 Connecticut Ave.	20015
Spring Valley Exxon	4861 Massachusetts Ave.	20016
South Dakota BP	4925 South Dakota Ave.	20017
Shell	1830 Rhode Island Ave.	20018
Benning Road Shell	3355 Benning Rd. NE	20019
Shell	2501 Penn Ave.	20020
Georgia Avenue Shell	30 L St.	20024
M. L. King Jr. Ave. Texaco	3011 Martin Luther King Jr. Ave.	20032
Phase 2		
Station Name	Address	Zip Code
Sun Amoco	306 Rhode Island Ave.	20001
Shell	1765 New York Ave.	20002
Distad's Amoco	823 Pennsylvania Ave.	20003
Shell	4500 Connecticut Ave.	20008
Rock Creek Exxon	1827 Adams Mill Rd.	20009
Miller Brothers Exxon	264 Missouri Ave.	20011
Sonny's Amoco	5207 Nannie Helen Burr Ave.	20019
Johnny's Half Shell	2002 P St.	20036
K & M Exxon	2150 M St.	20037

Notice that zip code 20019 appears in both Phase 1 and Phase 2 because Benning Road Shell is an existing hydrogen station and will undoubtedly serve for Phase 1.

14.1.4 Background on Implementation Decisions

The path of fuel transition from gasoline to hydrogen will affect the impact of the new technology. For instance, if we decide to use a station as part of the beginning phase of the transition, there are three ways to transform it from a traditional gasoline service station to an innovative pioneer. We could either add a new hydrogen pump, convert an existing gasoline pump into a hydrogen one, or expand the gasoline station to include a separate hydrogen facility.

Changing or adding one or several pumps in the gasoline stations we picked is a gradual and more conservative method, especially for the stations not located in early-adapter communities. This kind of transition is also similar to the diesel-gasoline transition because in the beginning of that transition, the consumers could access two fuel sources. It can also avoid customer discontent from the routine patronage if they have not changed their vehicles. Moreover, it may raise the curiosity of those drivers that have not made the switch and decrease the unfamiliarity and uncomfortable feelings.

Totally converting a traditional station into a new one might be a risky method. From the market point of view, if the routine patronage and community were not previously notified, this will cause not only complaints from people but also affect the growth and adaptation of potential customers. However, the switching cost might be more economical if there is no significant drop in facility expense. For a more detailed discussion of construction costs and the effect of multiple station production, see Section 13.4, Construction Cost of Hydrogen Stations.

Expanding the existing structure is limited by not only the space available but also restricted by the zoning regulation. As we mentioned before, zoning regulations determine the borders and the purpose of each region so that the expansion of a current station may not be allowed if extends beyond the zone border. Also, we should still need to take into consideration if there is any discrepancy in the zoning code between traditional gasoline stations and hydrogen stations, especially due to the legislation which is from public animosity.

From another viewpoint, the switch for the eleven stations we chose can be gradual or rapid. Gradual transition means that we switch these eleven stations gradually. Assuming that the duration for system switch is similar for each station, gradual transition will not allow the transformation for any two of them begin at the same time. In other words, the overlap of the stations reconstruction should not be long. For stations that are completely switched over to hydrogen, this can reduce inconvenience at a certain level because even though customers could not get fuel at the converted station, another station would still be available. As such, the impact felt by an area such as D.C. could be alleviated.

A rapid transition, by contrast, means that the switch of these eleven stations will begin at approximately the same time and would be complete all at once. In a small area, it will definitely cause an impact because eleven gasoline stations would suddenly not be in service. For the hydrogen transition in D.C. area, the impact might be less serious because these eleven stations are distributed far enough apart that drivers still have another option to refuel. However, the impact on traffic due to construction at so many crucial points of major roads or the heavy load of short-term budget would be an issue.

An expansion transition also means that the initial location will not be limited to current stations. In our project, we use the existing stations for the beginning stage because we consider the validation in zoning, familiarity of the patronage and community, and the economical issues. However, if these there criteria can be met, choosing a new location for a hydrogen station for the first stage can be discussed further.

Chapter 15

Network Analysis

To analyze the DC network, we first needed to decide what performance measures we wanted to use. Due to the limited amount of data available about a network that only exists on paper and describes a future time, the best projections and estimates in conjunction with modeling techniques had to be used to come up with these measures.

One performance measure is related to the chicken and egg problem previously discussed. The underlying question is the seemingly contradictory problem of needing hydrogen refueling stations on the road to support hydrogen cars, while simultaneously needing hydrogen cars to justify building the refueling stations. While it is difficult to quantify this performance measure, the consequences of a network that scores poorly on this measure are fairly obvious. If there are too few stations, owners of hydrogen cars will become frustrated as they have to contort their schedules to refuel in a sparse network or have to deal with long queues at the stations available. In fact, research suggests that potential customers may simply opt out of buying hydrogen vehicles if their impression is that the network is insufficient (Sperling & Kurani, 1987 [199]).

At the other extreme, a large and redundant network would make consumers very happy, but would be difficult on those who are financing the development. Hydrogen fuel sellers would be unwilling to sink the necessary funds into a network if they would not see some return on investment fairly soon. In the event that the development is heavily subsidized by the government, the taxpayer burden would be needlessly high if a large, inefficient network was built. The measure can thus be defined as minimizing initial investment costs while maximizing the service level.

Moreover, service level is a difficult thing to define as well. From a transportation engineering point of view, level of service (LOS) is defined by wait time (Papacostas, 2001 [210]). Certainly, time is a design factor in this network in that customers would not want to spend a lot of it queuing up to refuel at a station. Also, a satisfied customer would not want to travel too much out of their way (which takes time) to get to a station, so a geographically diverse network is also preferable. Since this is a new technology, there are other less quantifiable measures that need to be taken into account like acceptance of a new technology, and ease of use.

What makes this even more difficult is the lack of concrete data. To evaluate the performance of a network of stations that has already been built would be a complex but straightforward matter. The fact that this network does not yet exist complicates the problem. Furthermore, a demand does not yet exist for the network, forcing us to rely on projections well into the future for all of the analyses. The uncertainty factors require that analysis procedures be carefully thought out and documented. It also requires a certain robustness of design, since the variability of the input data could be quite large.

15.1 Estimate Load on Network

The following method was used to estimate the load on the network through 2050. The method is derived from the Urban Transportation Planning (UTP) Process of trip generation, trip distribution, mode split, and trip assignment (Papacostas, 2001 [210]). First, population projections for the cities of Washington and Alexandria, and the counties of Arlington, Fairfax, Montgomery and Prince George were obtained. Next, current data on commuter flows and trends were incorporated. In addition, current preferences and trends in commuter behavior were incorporated. Finally, the estimated demand was loaded onto the network.

15.1.1 Population Projections (Trip Generation)

The Metropolitan Washington Council of Governments (COG) is a regional organization of Washington area local governments. COG is composed of 19 local governments surrounding the District of Columbia, plus area members of the Maryland and Virginia legislatures, the U.S. Senate, and the U.S. House of Representatives. The COG website gives the following map to illustrate its jurisdiction:

Figure 15.1: Map of the Jurisdiction of the MWCOG (MWCOG, 2004 [213]

The area encompasses the counties of Arlington, Fairfax, Frederick, Loudoun, Montgomery, Prince George, and Prince William, and the cities of Alexandria and Washington. This area is a subset of the Washington, DC-MD-VA-WV Primary Metropolitan Statistical Area, as determined by the U.S. Census Bureau and outlined on that entitys website (2004) [209]. For our network analysis purposes, the counties of Frederick, Loudoun, and Prince William are neglected. This decision was made based on their distance from the District of Columbia. Since the first phase of the network will not extend outside DC, it seems reasonable that only those in close proximity would be willing to purchase a hydrogen-powered vehicle. While it is possible that some residents of the more distant counties might opt to purchase an FCV, their effect is assumed to be negligible (MWCOG, 2004 [213]).

COG provides a focus for action and develops sound regional responses to such issues as the environment, affordable housing, economic development, health and family concerns, human services, population growth, public safety, and transportation. Its mission is to facilitate smart planning decisions for the region surrounding the District of Columbia so that the entire region can coordinate efforts to solve problems in a way that benefits the region, not just one or two specific areas. As such, they have a wealth of statistical data about the area for use in planning purposes. Included among this data are population predictions for the region in five year increments through 2030.

Used for both short- and long-range planning, these data are the only official planning forecasts accepted by those who make government policy decisions for the region (Farina, 2004 [213]).

Since the nature of this research requires estimates through 2050, estimates were constructed for the years 2040 and 2050 using a simple regression on the data. The following graph shows the data and trends.

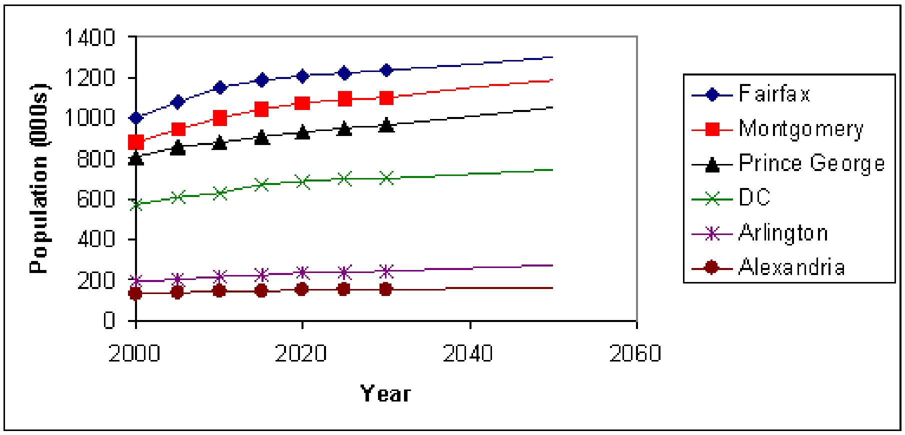


Figure 15.2: Population of Greater DC regions over time

It should be noted that populations in each of the regions considered is expected to increase through 2050. It should also be noted that while there has historically been a trend of population diffusion out of the city into the suburbs of this region, this trend has showed signs of tapering off. The following graph illustrates: ments for the Washington, DC area as well.

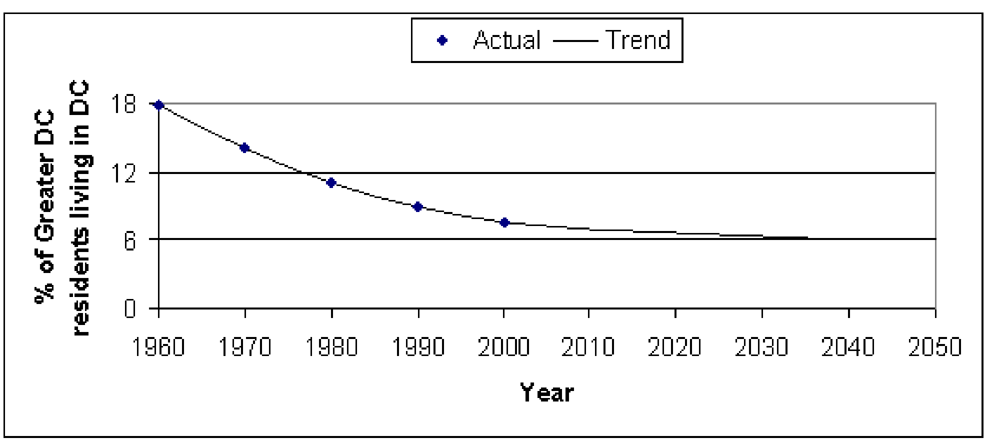


Figure 15.3: Trend over time of Greater DC urban sprawl

Two facts are assumed here. First, that the COG's estimates take into account the trend through 2030. Second, that over the period 2030-2050 the effect is negligible as it approaches an asymptote of approximately 6%. Now that we have estimated the population through 2050, we have essentially completed the trip generation phase of the UTP process.

15.1.2 Users

The next step in the UTP process is trip distribution, which essentially means once we have an idea of how many trips there are, we must determine where they are going. It quickly became apparent that there are two distinct classes of users, those serviced directly by the network and those that must travel to the network.

Residential users (Trip Distribution)

For those users that reside in the area where the network is located, in this case the District of Columbia, the following estimation was used. First, a resident need not work in DC (or work at all). He or she simply needs to own a car. For this reason, the vehicle per capita rate was calculated from census data using the method in the following table.

	DC		
Households	# of vehicles/HH		Vehicles
91699	x	0	0
108151	x	1	108151
38395	x	2	76790
10093	x	3	30279
	Total Vehicles		215220

Total Vehicles/Total People = Veh./cap
215220 / 572059 = 0.376

Table 15.1: Calculation of Vehicles/capita

Assuming the rate of vehicle ownership would not change substantially over the analysis period, future vehicle population was estimated using the projected population numbers already determined. This seems reasonable considering that, if anything, vehicle ownership is declining in the District of Columbia, possibly because more citizens are taking advantage of the metro subway system. Since we are creating this network based on capacity, any overestimation of the vehicles in the system only serves to make the model more conservative.

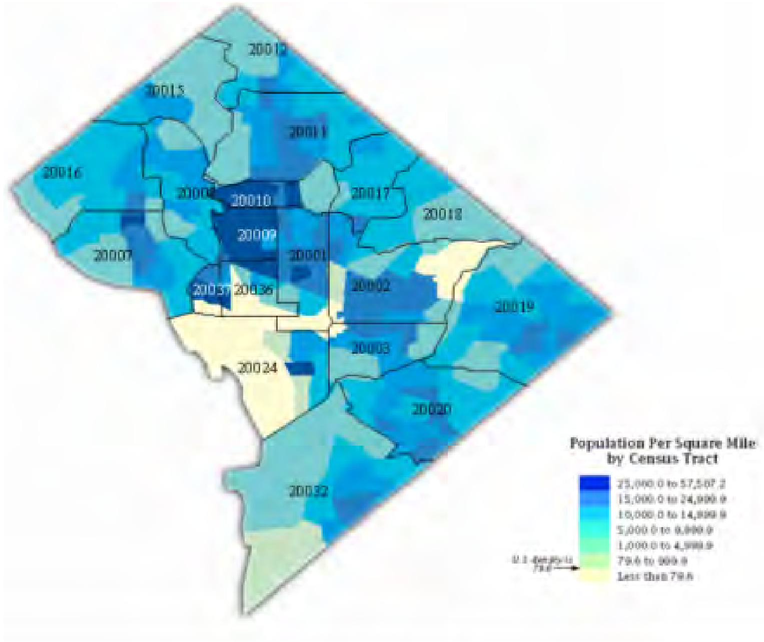
The District of Columbia presented a unique challenge in that since it is a county, city, and state, there are not any easily usable subdivisions. This would normally mean that DC would be counted as a single unit with a single set of census statistics like mean income, population density, and educational level. This level of detail would not have been sufficient since we are interested in studying the performance of each part of the network, which is entirely self-contained in DC. Specifically, we wanted to assign factors for each subregion of DC according to its population density and socioeconomic status.

Population density

From US Census Tract, the population density of DC can be obtained. To estimate the population distribution in each zip code region, we have to match the population density graph by superimposing the zip code boundaries. After necessary adjustment in matching, ignoring the area of water, we assume each color presents the mean of the density range.

Density Range	Mean	Level
25,000.0 to 57,507.2	41,253.6	1
15,000.0 to 24,999.9	20,000.0	2
10,000.0 to 14,999.9	12,500.0	3
5,000.0 to 9,999.9	7,500.0	4
1,000.0 to 4,999.9	3,000.0	5
78.6 to 999.9	539.8	6
Less than 79.9	39.8	7

Table 15.2: Population density ranges represented on map below



(US Census website, 2000)

Figure 15.4: Population distribution in Washington D.C

By calculating of the area and density of each region, we can obtain the estimated population of each zip code area as follows:

Zip code	Area (mile^2)	Population %	Population	Phase	Remark
20032	6.47	4.55%	26,049	1	
20020	5.05	8.04%	45,976	1	
20019	6.84	9.85%	56,356	1	Existing
20018	3.50	2.74%	15,696	1	
20017	2.59	3.07%	17,541	1	
20012	2.80	2.70%	15,417	1	
20015	3.71	3.01%	17,203	1	
20016	5.05	5.64%	32,266	1	
20007	3.80	5.47%	31,280	1	
20024	2.92	1.41%	8,058	1	
20010	1.75	7.48%	42,780	1	

Table 15.3: Population in different zip codes

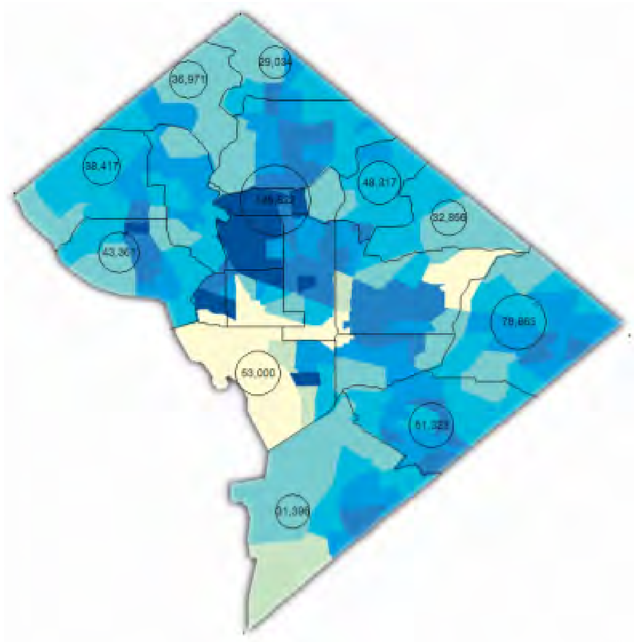


Figure 15.5: Population estimation in Washington D.C

Socioeconomic factors

Another concern was that socioeconomic factors might play a role in how quickly a group of individuals would adopt a new technology like hydrogen fuel cell vehicles.

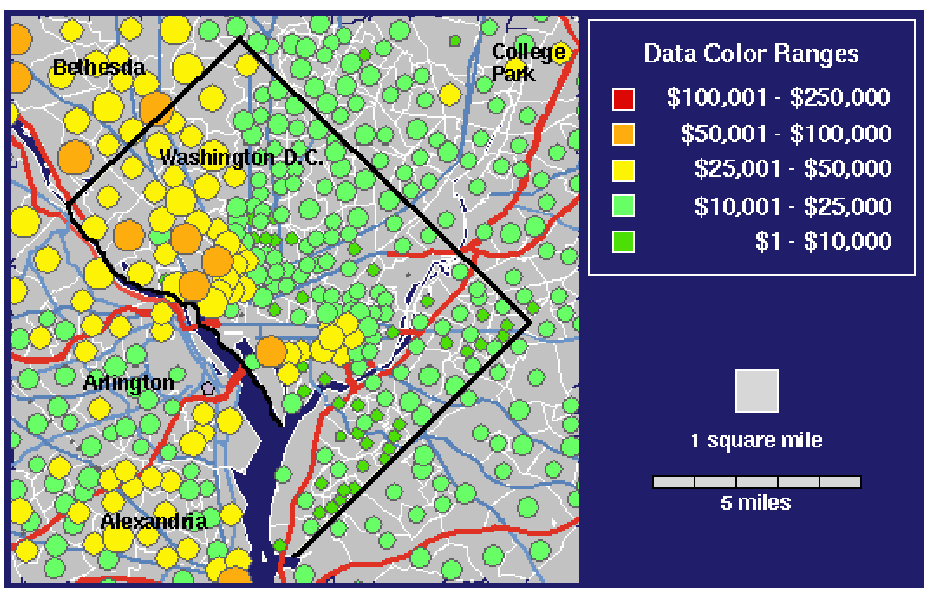


Figure 15.6: Per capita income of census tracts in DC area (Bowen, 2004)

This graphical representation is based on census tract data and gives enough information to make some statements about the socioeconomic status of different areas of DC. A method similar to the one used above for population density was used to make some generalizations about the socioeconomic status of the areas of DC. Based on the dominant color of a region, a scaling factor was multiplied to the total in each of the subregions. For areas where the dominant color was yellow or orange, this factor was simply 1.0, indicating that users in this area would follow the penetration curve exactly. A similar method was used to multiply factors of 0.7, 0.4, or 0.2 to each of the remaining regions. For example, in regions classified by a 0.2 scaling factor such as the southeastern areas of DC, it was determined that acceptance of the new technology in this region would only be 20% of the acceptance in the more affluent areas of DC. This is due to average incomes being very low in this area, but perhaps with some pockets of higher income interspersed throughout.

Once population density and socioeconomic coefficients were taken into account, the remaining number of cars was multiplied by a penetration factor. The urban penetration curve is the same as the scenario hypothesized in the discussion of HEV vehicles previously. This yielded a total of resident cars that would utilize each station in our network. The second curve for suburban users is explained and utilized in the discussion of transient users below.

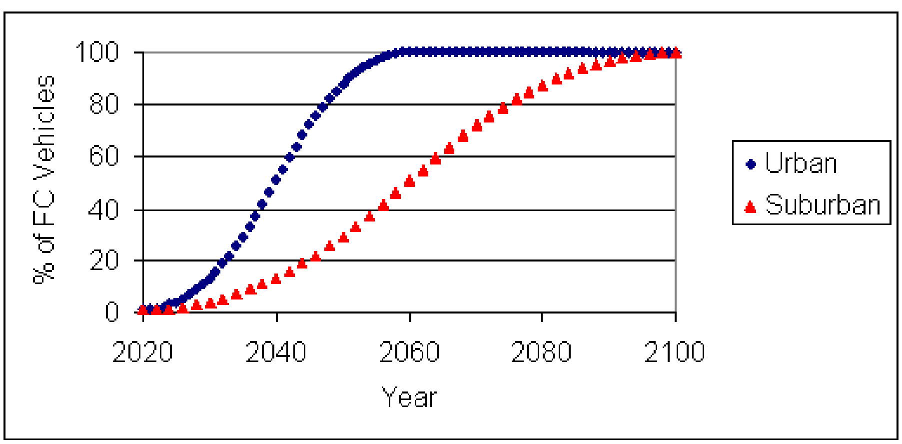


Figure 15.7: Penetration curves of FCVs over time

Transient users (Trip Distribution and Mode Split)

The transient population was treated quite differently, although the basic principles remain the same. First, the population estimates for the surrounding counties of Arlington, Fairfax, Montgomery, and Prince George and the city of Alexandria were taken into account.

Next, a simple origin-destination (O-D) matrix was constructed using data from the U.S. Census' Journey to Work data. In essence, this data accurately reports the geographical distribution of commuters. Specifically, it reports the total number of commuters who live in one county, and work in another county. It was assumed that those commuters who work in DC were the most likely to first adopt hydrogen fuel cell technology since they would have ample opportunity to refuel at the stations located in DC. The percentages of commuters coming from the surrounding counties was then calculated and used in conjunction with the population estimates to predict future trends. The assumption was made that while the numbers may change, the general patterns would remain consistent. For example, if 19% of the commuters currently come from Prince George County into DC to work, then roughly that percentage will come from Prince George County throughout the analysis period (Census website, 2004 [209]).

Then, the most recent estimates of car-based commuters (versus public transportation, etc.) were utilized to determine what fraction of commuters were actually using their cars to commute. This is the part of the UTP process known as mode split, when travelers are divided up according to the mode of transportation they use. The most recent data available from the census indicates that approximately 91% of the area commuters use their cars to commute to work (Reschovsky, 2004 [211]).

Finally, a penetration curve was used again to determine what fraction of this subset of vehicles was likely to be made up of hydrogen vehicles in a particular year. The suburban curve is simply the urban curve stretched over the time axis by a factor of two. It was thought that this might more accurately predict the behavior of suburban users in the first stages of the urban transition. It is expected that after 2050, the market would respond to the demand of FCV users who live in the suburbs and begin building refueling stations within the suburbs, facilitating greater penetration among this population. This, however, would occur after the scope of our analysis, and as such is not included. Until then, however, the suburban users would undoubtedly be hindered by the lack of hydrogen stations available in their area. Thus, it would take them longer to make the switch.

By adding this value to the one obtained in the residential users section, we get the total load on the network.

The following graph illustrates the growth in FCV vehicles over time in the urban and suburban areas of Greater DC. It is assumed that there are no effects by HEVs on the market for FCVs.

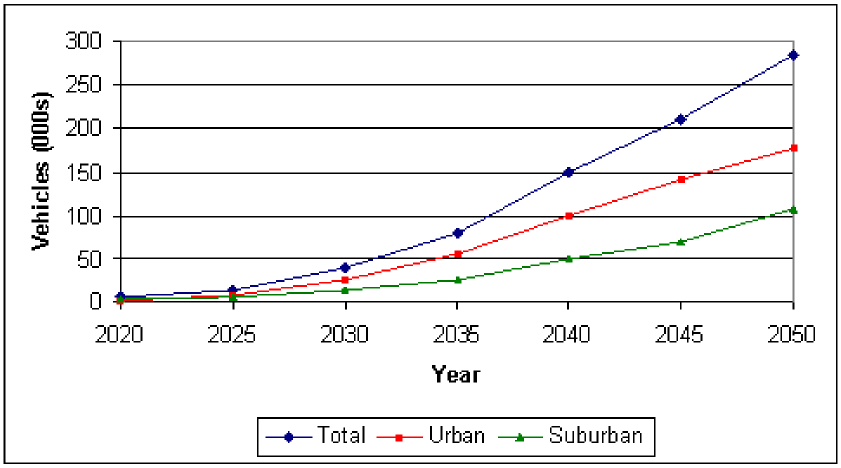


Figure 15.8: Growth of FCV users over time

It is important to note that while the suburban curve grows at a slower rate than the urban one, there is greater potential in the suburban area since there is a significantly larger vehicle population. As such, it is expected that the urban and suburban curves will eventually crossover further ahead in time and suburban forces would then dominate the total. This would most likely be hastened with the construction of hydrogen fueling stations in the suburban counties themselves.

15.1.3 Loading the Network (Trip Assignment)

The final step in this model is to take all the data about commuters and flows in the network, and assign them to specific stations in the network. In the UTP process, this is referred to as Trip Assignment. For the residential users, this is a simple process. Geographic location alone determines which station serves a customer. If a customer falls within that station's region (in this study, its zip code), it is assigned to that station. Also, in the case where there is no station located within a customer's zip code, it has been assigned to one of the neighboring stations.

For transient users, station choice is based mainly on which stations are closest. For example, customers in Montgomery County are assigned to the three zip code areas that fall along the border between DC and Montgomery County (20012, 20015, and 20016). If there is more than one station available, the commuters are evenly divided among the stations available to them. It does not seem necessary to assign commuters to more than one station, since they traditionally stick with the one they are used to. Also, the commute distances are not longer than the range of the vehicles, so one station along their travel route should suffice (Kuby, 2004 [212]).

The following graph illustrates how the load on the network might proceed over time. It was constructed under the assumption that there is no significant impact due to HEVs that delays the introduction of FCVs in 2020. It also assumes a range of 250 miles between refills, as well as the other assumptions present in the NPV analysis of Section 13.4 of this report.

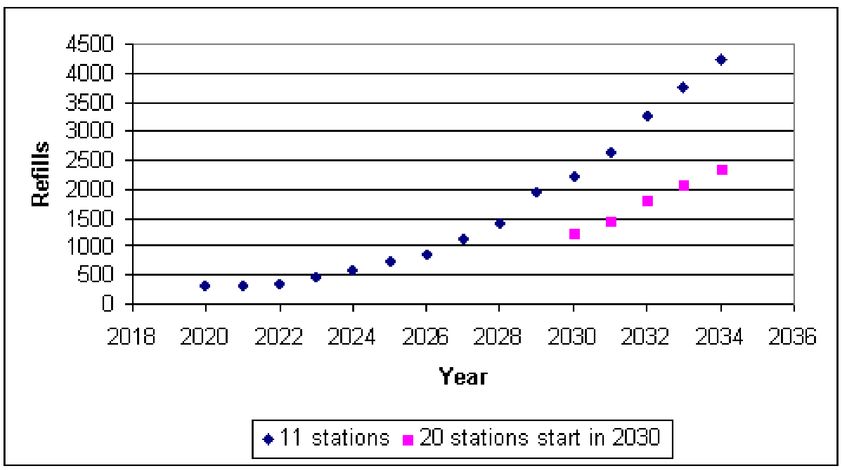


Figure 15.9: Average refills per year at a station in the network

It is worthwhile to note that in the year 2034 (the highest represented on this graph), even under the scenario where only 11 stations are operational in the network, the volume/day is about 12 refills. This is fairly low compared to what an average gasoline stations sees on an average day.

15.2 Simulation

Now that we have a static model for loads in the network, it would be useful to see how those loads really behave in the network. Specifically, are any of the nodes overloaded, or does behavior at them even occasionally blow up? The best way to answer this is with a discrete-event simulation. Although no such simulation was completed for this report, the following represents a skeleton version that could be created and modified for further study.

First, a profile of use throughout the day needs to be constructed. The material from Papacostas & Prevedouros, previously modified in the Contest part of this report, should serve as a good approximation. This following version of the graph just shows the percentage of total demand throughout the day, thus allowing it to be scaled to whichever station is being studied.

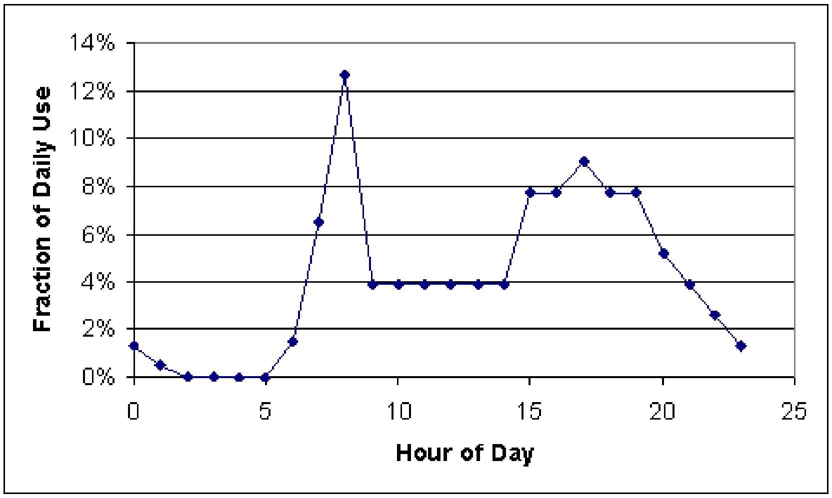


Figure 15.10: Approx. hourly usage of a gasoline station (derived from Papacostas, 2001 [210])

Presumably, our primary concern would be during the morning peak hour, since that time experiences the largest load in a short period of time. A simple queuing model that models the arrival and service times of customers at a station would provide information as to how close to capacity this node in the network is. The standard way of processing arrival times for this sort of problem is to treat it as a Poisson process. This simply means that the time between arrivals is exponentially distributed around the arrival rate. To model the service time, we would use a uniform distribution over the interval 5-10 minutes. This should accurately represent the prediction that refueling time will be designed with the current system in mind to ease the transition. The pumps would be modeled as a 2-server queue, again with the consideration that a single pump would probably be double-sided, as the ones today are.

It is hoped that the results of this simulation could be used to predict the appropriate time to expand the network. Specifically, when a station begins to experience long queues, we would want to plan to expand capacity in that part of the network so that the additional pumps come online before the problem becomes too much of a concern.

15.3 Chickens and Eggs: How will the system grow?

The main result of the simulation model is the determination of the threshold year. Specifically, the year that growth in FCV use is so great that the network approaches capacity. At this point, or most likely before, the network will need to be expanded to support the growing demand. In addition to long lines, there is the concern that some customers may be turned away at a hydrogen station because the stations inventory runs too low. Again, discrete-event simulation would be useful in determining how likely a station is to bottom out their inventory. Another way to look at this problem is from an economic standpoint, as was touched upon in Section 13.4. There, the variable of 11 beginning stations was fixed, but it could just as easily be unrestricted. In this scenario, the NPV would be used to determine maximum profitability in expanding the network. While special care would need to be taken to ensure that the feasibility assumptions are satisfied, the optimum number of stations could be found that would maximized profit and growth while minimizing upfront and selling prices.

In any case, certain main tenets appear to be unshakeable. The chicken and egg problem must be solved by an influx of stations that drives the demand for hydrogen cars. Logistically, this makes the most sense because you only need to control (or entice) a few key players such as the major oil/hydrogen companies and the government. To take the other side, and instead force consumers to buy the cars to drive the demand would be extremely difficult and not make much sense. There is good evidence to suggest that with even a small infrastructure in place of 10-15% of the existing gasoline supply network, a shift in consumer behavior could result. Once that transition in the users is initiated, market forces should be enough to sustain it. For instance, we have shown that in the DC area, a network of stations that is confined to the District of Columbia itself still results in growth in FCV ownership in the surrounding counties. Once those early adopters get onboard, a market for hydrogen begins to grow in the suburban counties. This would be an incentive for a hydrogen-selling company to begin building stations in the suburbs, which would then lead to yet more growth. All that remains is for continued management to monitor behavior and anticipate growth from the level of interest and market penetration. If this data is collected and reported, the suppliers of the hydrogen should see the benefits and continue the growth.

The following pages illustrate a suggestion for the next phase of expansion in the hydrogen network. All of the Phase 2 stations were determined in the initial design phase as meeting the requirements of the algorithm. There were simply too many of them to be feasible. However, when demand sufficiently grows, it would be wise to use these stations first to augment the DC network. The resulting relative loads are shown.

Zip code	Area (mile^2)	Population %	Population	Phase	Remark
20032	6.47	4.55%	26,049	1	
20020	5.05	8.04%	45,976	1	
20019	6.84	9.85%	56,356	1	Existing
20018	3.50	2.74%	15,696	1	
20017	2.59	3.07%	17,541	1	
20012	2.80	2.70%	15,417	1	
20015	3.71	3.01%	17,203	1	
20016	5.05	5.64%	32,266	1	
20007	3.80	5.47%	31,280	1	
20024	2.92	1.41%	8,058	1	
20010	1.75	7.48%	42,780	1	
20019	6.84			2	Additional
20011	5.59	9.52%	54,467	2	
20008	3.42	4.30%	24,606	2	
20037	0.67	2.07%	11,859	2	
20036	1.54	2.75%	15,725	2	
20009	1.50	8.40%	48,034	2	
20001	2.92	6.27%	35,878	2	
20002	5.67	9.00%	51,478	2	
20003	2.55	3.74%	21,390	2	
SUM	68.34	100.00%	572,059		

Table 15.4: Phase II

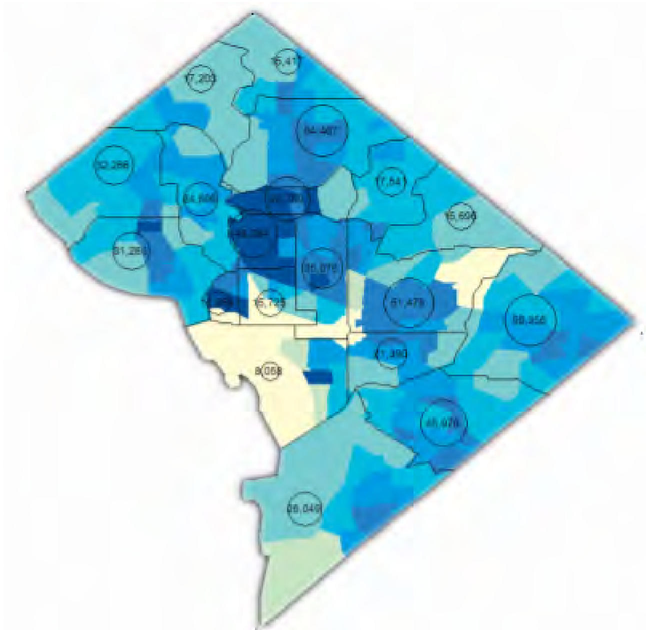
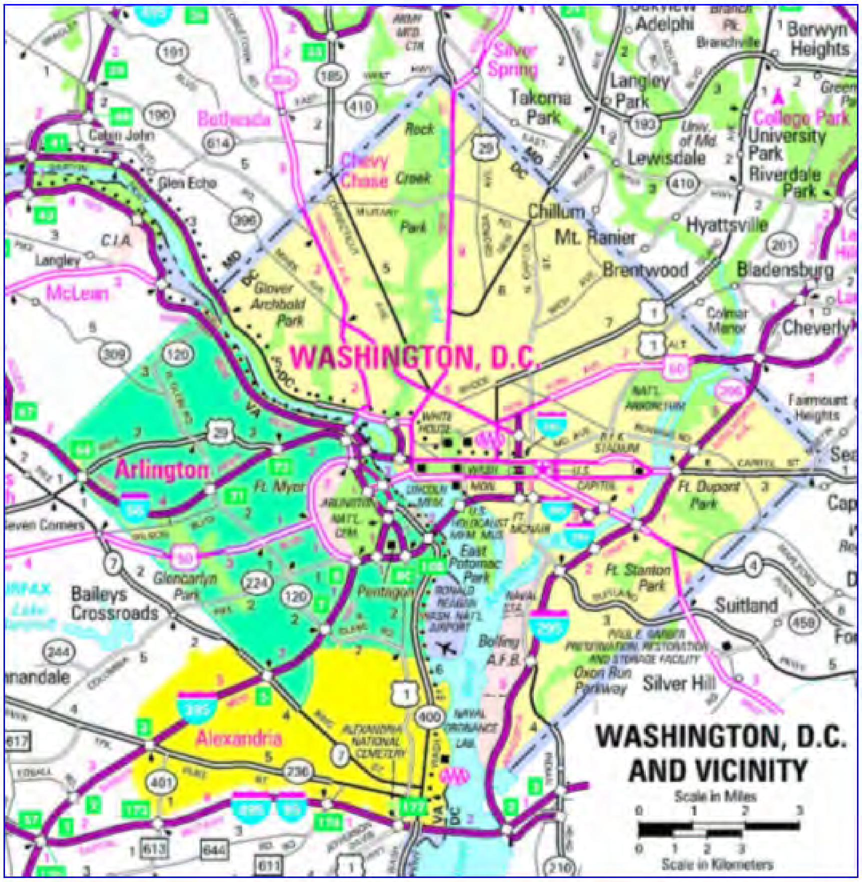


Figure 15.11: Phase II

15.3.1 Arlington, Alexandria City and Pentagon

Since the initial network is only designed for the District of Columbia, there are several great business opportunities that are overlooked. The Pentagon is just across the Potomac River and is essentially a very large office complex. In addition, Arlington and Alexandria are home to many residents that work in the DC area, as well as many employers. Thus, it makes sense to consider adding support to these two areas, either in the first phase or soon after.



Adapted from AAA website, 2005

Figure 15.12: Arlington, Alexandria City and Pentagon

Assuming we pick 11 stations for the initial requirement in D.C. area, it is reasonable to pick 6 stations for North Virginia (Arlington county and Alexandria city) based on the population ratio of D.C. in the first phase. Alexandria city and Arlington Country have similar populations, so we assumed each of them would house 3 hydrogen stations. Because of the large amount of employees in the Pentagon (approx. 23,000), it is reasonable to put one station in Pentagon City even though some portion of these workers use the Metro subway system to commute.

Because the D.C. area is the focus of our topics, we will not go into great detail about where these 6 additional stations should be located. However, the following maps suggest possible prime locations. Notice that although these areas are primarily residential areas, the stations are near major roads. Also, we are not concerned with avoiding those areas that are served by the Metro system. It should also be noted that it is beneficial to the main D.C. network to add support to these areas as it would reduce the strain on sections of the D.C. network. Currently, if FCV owners in the Alexandria or southern Fairfax areas want to refill, their preferred station is just across the river in the 20024 zip code area. Because of this, that station carries the highest load compared to the others in the network. Diverting some of its demand to other areas would thus increase the robustness of the DC network.

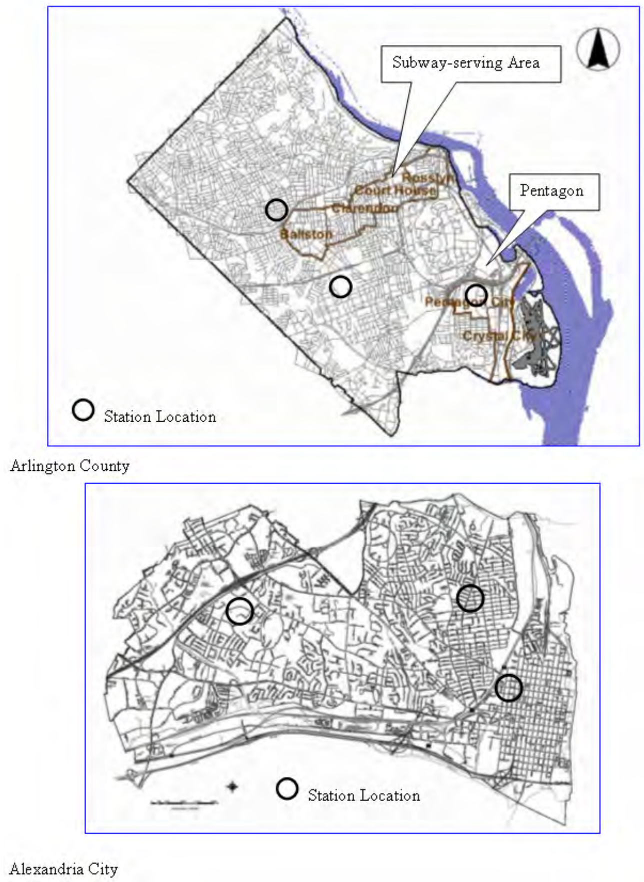


Figure 15.13: Station Locations in Arlington, Alexandria City

15.4 Conclusion

To implement a fully functional and efficient network, much information and consideration will have to go into the planning. Sources like census data and surveys of public opinion will be a necessity to ensure success. Like any complex system, the network will not operate unless the users desires and behavior are taken into account. At a minimum, accurate demand projections and cooperation with automakers will be a necessity. To maximize acceptance, the interface must be simple and as convenient as possible. A good benchmark will be the most current gasoline technologies. Any sharp increase in the time or complexity of the refueling process will only hinder public acceptance.

Studies suggest that the infancy of the hydrogen transition will take place within the current gasoline infrastructure. Many of the major oil companies have already begun to anticipate this switch and have conducted extensive research into the process of converting the industry from oil and natural gas to hydrogen. To begin with, a percentage of gasoline stations will have hydrogen pumps added to them. It is believed that this will enable customers to easily see the availability of hydrogen, as well as reduce construction costs. Research suggests that an appropriate threshold would be 10% of the gasoline stations in service. For the city of Washington, this is about 11 stations.

Cost of this program is widely dependent on the capacity and design of the new stations. Larger capacity and on-site production stations will in general cost more than their off site and smaller companions. It will also depend on when the first stations are constructed, and the development of hydrogen technologies at that time. This study has determined that an off site production station with a capacity of 500 Nm^3/h in the year 2020 will cost between \$1.2 million and \$1.8 million, depending on the number being constructed and the current level of technology. At this level of investment, a selling price of \$3.44/kg of H_2 will result in a successful business model over a 15 year life cycle.

Overall success of the network will be determined by how well it balances the two objectives of reducing cost yet increasing support for hydrogen fuel cell vehicle owners in the beginning. Over time, a successful network will allow users to easily locate stations at which they can quickly refuel. It will also have management of its growth so that the network grows with demand in a seamless way.

Without question, management is especially crucial in this phase of the hydrogen transition. Market forces alone can not be expected to facilitate the implementation of an effective network. It also seems fairly certain that one company can not be expected to manage the transition alone. The process will require the cooperation of many companies, and most likely the council of governments for the Washington, DC area as well.

Part IV

Gen H Power Park Design

Chapter 16

Technical Design

As the world's demand for gasoline steadily increases, the amount of the world's fossil fuels show a steady decrease to levels that require a new solution. This crisis necessitates a new paradigm in energy generation – the hydrogen generation.

The design of the hydrogen support infrastructure represents one critical obstacle to successful implementation. How will the next generation get their hydrogen? Gen H Power Park demonstrates that the solution to the infrastructure obstacle may be just around the block.

Gen H eschews short-sighted answers that involve further mining of limited fossil fuels, for more long-term solutions that integrate environmental concern with technical and economic feasibility. Accordingly, Gen H Power Park's HMax derives its fuel from an inexhaustible source of hydrogen and produces eMax via clean electricity production methods.

Gen H Power Park is a beacon of progress for the next generation. What better place to locate such a beacon than in the nation's capital? Not only will the location serve to better show the country and the world that the solution to the hydrogen infrastructure challenge has been found, but it will also expedite the development of the relationship between government and the hydrogen community, a necessary element in making the hydrogen economy a reality.

16.1 Park Location

Gen H Power Park is designed to serve the Washington D.C.-Maryland-Virginia-West Virginia Primary Metropolitan Statistical Area (PMSA, as referred to by the U.S. Census Bureau). As of the year 2000, the area had a population of 4,923,153. The following 25 counties and cities make

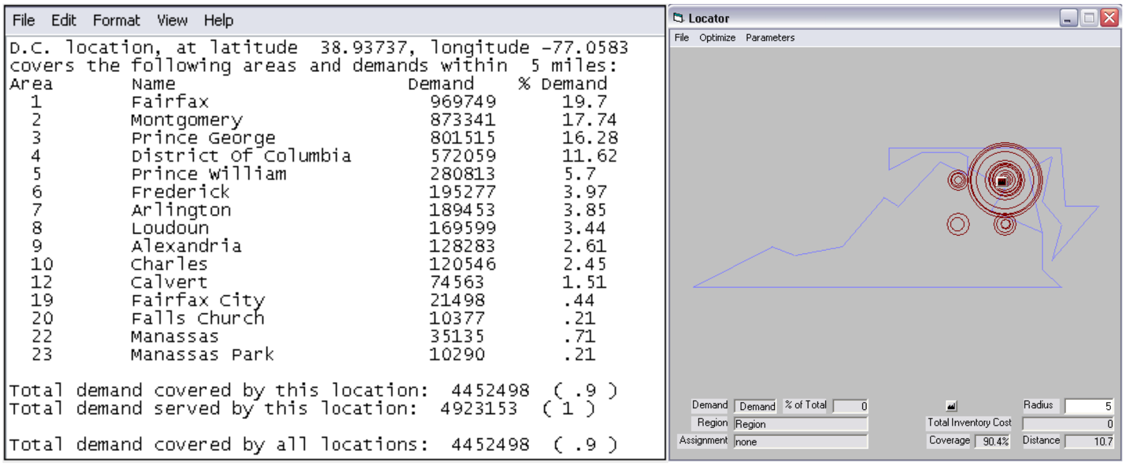


Figure 16.1: Numerical and Graphical Output of Location Analysis

up this target market:

- *District of Columbia*
- *Virginia (17)*: Fairfax County, Prince William County, Arlington County, Loudoun County, Alexandria City, Stafford County, Fauquier County, Clarke County, Culpeper County, King George County, Spotsylvania County, Warren County, Fairfax City, Falls Church City, Fredericksburg City, Manassas City, Manassas Park City
- *Maryland (5)*: Montgomery County, Prince Georges County, Frederick County, Charles County, Calvert County
- *West Virginia (2)*: Berkeley County, Jefferson County

For the purpose of placing the park within this target market, Gen H's development team created a demand model in *Locator Software* by Dr. Mark Turnquist of Cornell University.

This piece of software takes as input a file which contains the name, population, and geographic location of the demographic centroid (latitude, longitude) of each of the 25 counties and cities in the target market. The model then optimizes the location of a possible number of facilities that would serve the targeted area.

Based on the optimization of minimizing the average distance from each served area to the proposed facility, the location analysis of the power park yields the results shown in figure 16.1. The software indicates that the best location for Gen H lies on (38.93737, -77.0583), at the intersection

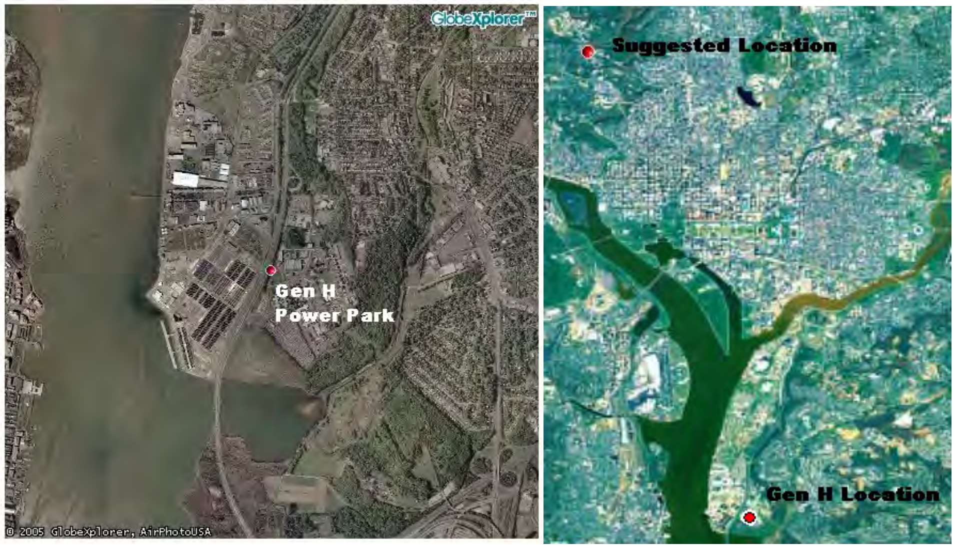


Figure 16.2: Gen H Location

of Connecticut Avenue SW and Ordway Street SW, in D.C. Placed here, the facility covers 90.4% of the overall demand, with an average distance of 10.7 miles to the population centers. Unfortunately, local zoning laws do not allow for the placement of a power plant there.

The nearest available zone classified as "M" (suitable for manufacturing) lies near the Blue Plains Advanced Wastewater Treatment Plant (AWTP), only 7 miles away from the optimal solution suggested by the model. The Blue Plains AWTP is the largest advanced wastewater treatment facility of its type in the United States [241], providing Gen H Power Park with its inexhaustible source of hydrogen. This alternative location also minimizes the cost of the material transport pipeline. Therefore, Gen H Power Park is located at the southernmost tip of Shepherd Parkway, S.W, east of I-295, just across the street from its source of hydrogen.

16.2 Hydrogen Source

Wastewater collected from the District of Columbia and the Maryland and Virginia suburbs is delivered to the Blue Plains AWTP, which maintains a rated average capacity of 370 million gallons per day [242]. The existing wastewater treatment processes at the Blue Plains AWTP consists of preliminary treatment, secondary treatment, nitrification/denitrification, effluent filtration, chlorination, dechlorination, and post aeration. Presently, Blue Plains AWTP does not digest their biosolids, creating unusable waste that must be disposed of in environmentally harmful ways.

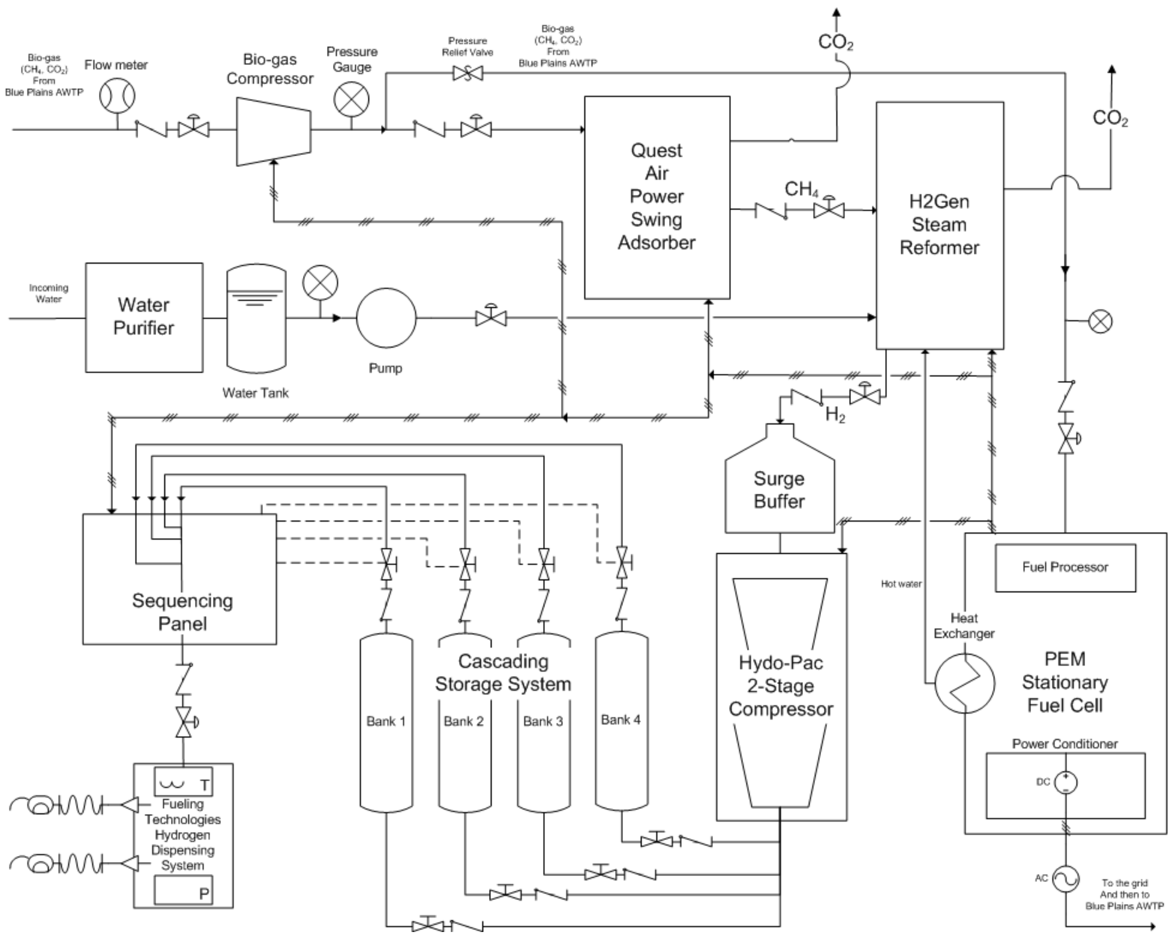


Figure 16.3: Schematic

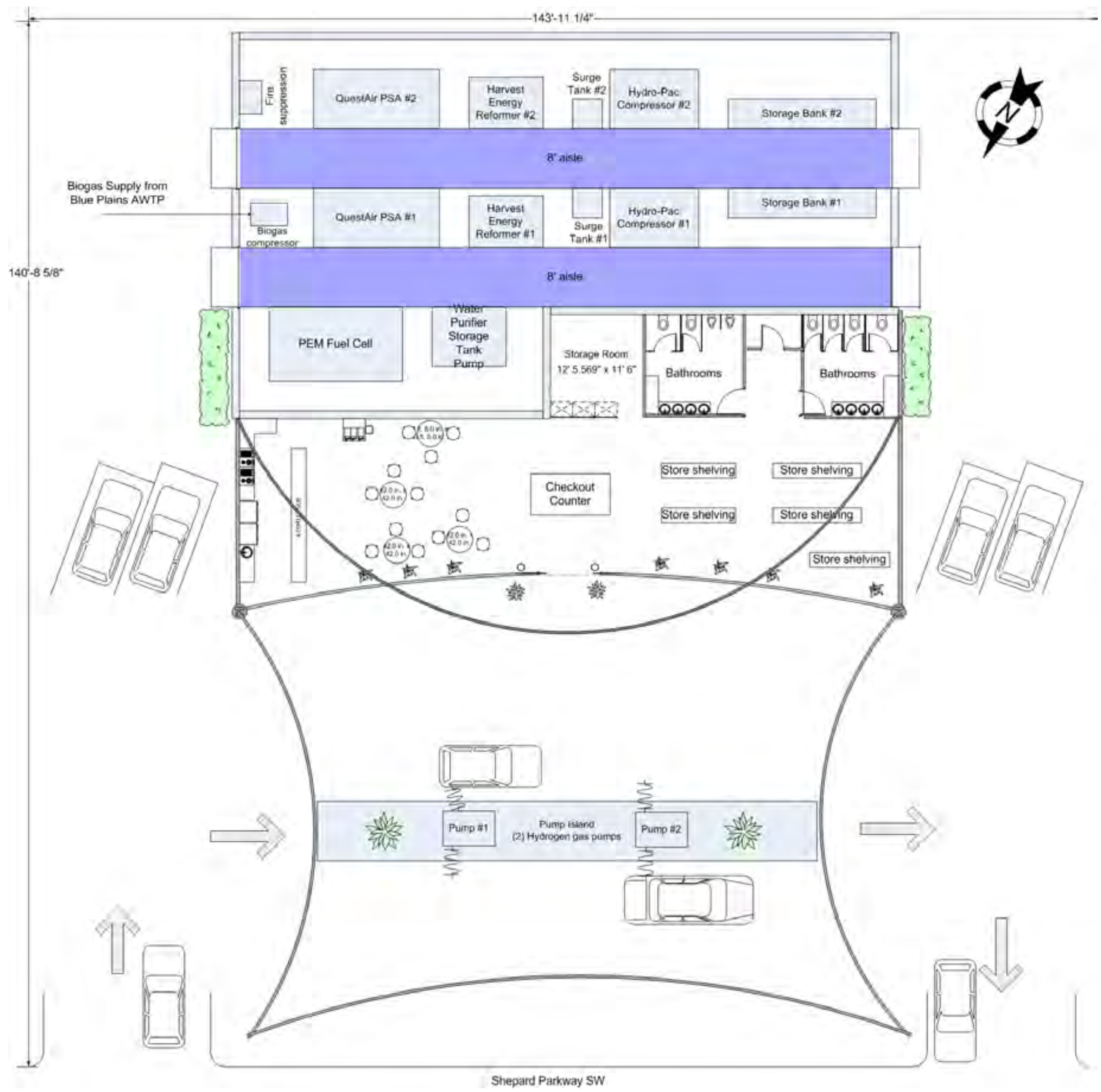


Figure 16.4: Plan View

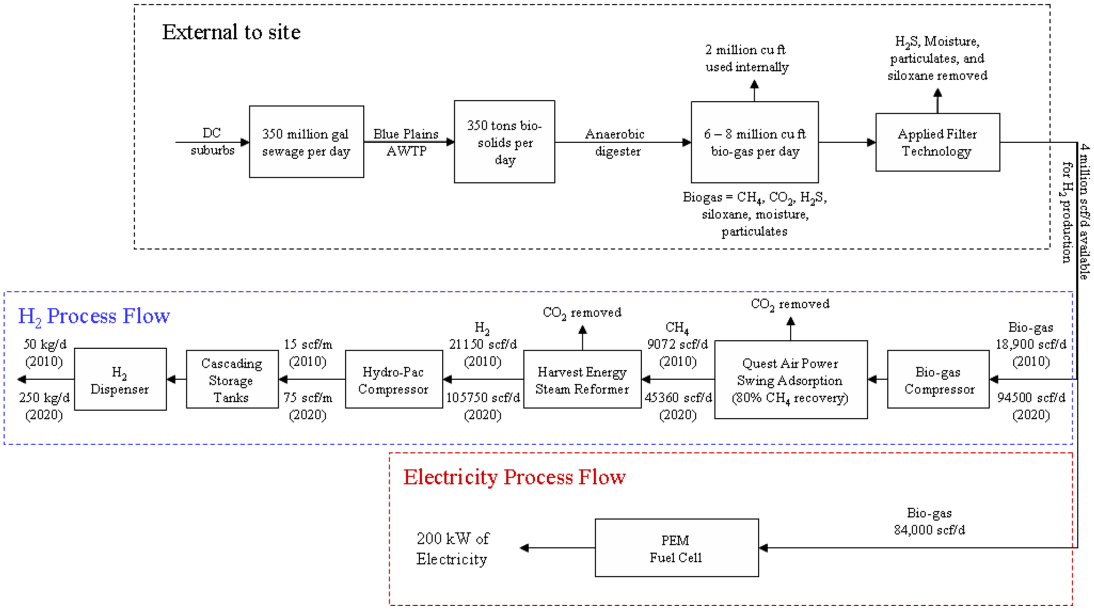


Figure 16.5: Process Flow

Starting in 2010, new egg shaped anaerobic digesters will be online, allowing Gen H to turn waste into the next generation of energy [243]. These egg-shaped digesters will produce 6 to 8 million ft^3 of biogas per day from the anaerobic digestion of biosolids.

Gen H Power Park plans to purchase this biogas from Blue Plains AWTP, then reform it into hydrogen. The biogas is primarily composed of CH_4 and CO_2, with a small amount of particulates, namely siloxane, and H_2S. The H_2S, particulates, siloxane, and moisture will be removed at the Blue Plains AWTP through an Applied Technologies filter system [244]. The cleaned biogas, composed of 60% CH_4 and ~ 40% CO_2, will be subsequently transferred to Gen H Power Park for the hydrogen production process.

The cleaned biogas provides Gen H Power Park with its feedstock for hydrogen production. While hydrogen can be created through burning coal, electrolysis, or natural gas reformation, all of these processes require the use of fossil fuels – a demand on our environment unsuitable for the next generation in which exhaustable fuel volumes are approaching their nadir. On the other hand, Gen H focuses on real solutions to the problems of the hydrogen generation.

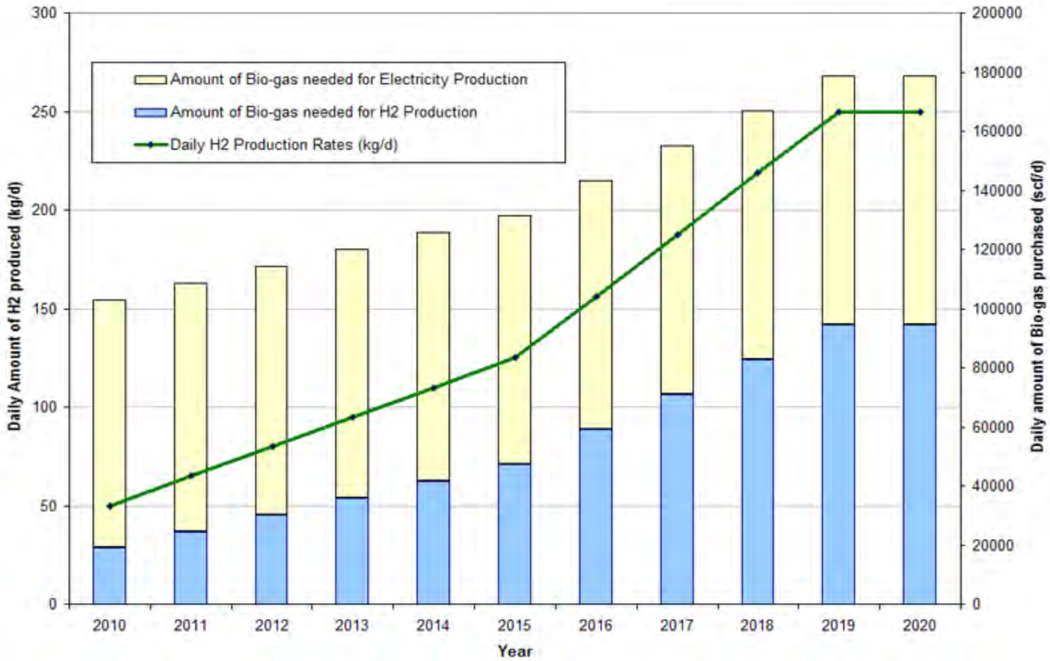


Figure 16.6: Daily Demand and Bio-Gas Purchased

16.3 Hydrogen Production

Figure 16.5 shows how biogas, given in scf/d, creates hydrogen, given in kg/d. According to Gen H's design, 378 scf/d of biogas will produce 1 kg of hydrogen per day.

Two requirements – centering on the amount of hydrogen that must be available for dispensing in a given day – dictate the production rate of hydrogen. Proceeding chronologically, the first requirement is the production of 50 kg/d of hydrogen at the start of the project, in the year 2010. The second requirement states that 250 kg/d of hydrogen must be available for dispensing in 2020.

To ensure that the design includes the capability of the increasing amounts of HMax needed per day, the HMax production components have been sized to produce, compress, store, and dispense the required amount of hydrogen in two phases, as seen in figure 16.6. Phase one covers the first five years; phase two includes the final five years of the project life-cycle. During phase one, the amount of HMax produced increases linearly from 50 kg/d in 2010 to to half of the total required in the year 2020 – namely 125 kg/d – in 2015. Consequently, the component set included in the hydrogen production, compressing, storage, and dispensing have been sized to handle a 125 kg/d production rate. As a result, first four years' equipment will run at lower than maximum capacity to achieve the required amount.[1]

In 2015, a second set of components will be purchased and installed. Starting in 2016, both sets of components will run at a production rate that will linear increase the amount of HMax produced at rate so that 250 kg/d will be generated by 2019. The design ensures that the 250 kg/d requirement will be met achieving the maximum capacity one year in advance. This allows for additional capacity to be added if unforeseen circumstances make the maximum capacity unachievable in 2019.

In order to size the total biogas requirement purchased from Blue Plains AWTP, Gen H considered both both hydrogen production and electricity generation. While the above paragraphs justify the amount of biogas necessary to support Gen H's hydrogen requirements, electricity production components run completely independently (see the distinct branch for electricity production in figure 16.5).

The electricity production is constant for the life cyle of the project; therefore, the amount of biogas purchased for the electricity production is constant. Figure 16.6 depicts the total amount of hydrogen produced and the subsequent amount of biogas purchased from the AWTP.

16.3.1 Hydrogen Production Process

Gen H's strategic location enables pipeline to be laid between the power park and Blue Plains AWTP, providing for the ready supply of the necessary biogas.

Before the methane can be converted into hydrogen, it must be separated from the carbon-dioxide in the cleaned biogas. To create pure methane from the gas stream, the design of the Gen H Power Park has included a QuestAir M-3200 Power Swing Adsorption system (PSA). The M-3200 PSA is a compact, economical, and reliable gas purification system designed for the removal of CO_2 from CH_4 [245]. The PSA process is based on physical adsorption of gases onto specialized beds of adsorbents. The M-3200 system employs six adsorber beds used in parallel to ensure a constant flow of product gas. Since the reformer requires a methane rich gas stream at 150 psig, the PSA has been designed to deliver a pure stream of gas at 150 psig. This required boosting the incoming biogas to the PSA to around 175 psig, and hence requiring the addition of a compressor

[1]The component manufacturer suggested that the two phase approach would be the most cost efficient solution to the increasing demand set forth by the Gen H design.

in the design.

The power park design includes a GrimmerSchmidt Industrial Air Compressor to boost the incoming modified bio-gas to 175 psig. The compressor would need modifications in order to handle a combustible gas, at a cost of $60,000 [246]. The compressor would be able to handle the required flow rate when the power park is producing 250 kg of HMax per day, or 94,500 scf of bio-gas per day.

While there are several different ways to produce hydrogen from methane (or natural gas), the most cost-effective option is to utilize a steam methane reforming (SMR) process with subsequent pressure swing adsorption [247]. For Gen H's design a hydrogen generator from Harvest Energy Technology, Inc. (HET) has been incorporated [248] . The HET reformer generates hydrogen from a pure stream of methane and input water through the following two chemical reactions.

$$CH_4 + H_2O \dashrightarrow 3H_2 + CO$$

$$CO + H_2O \dashrightarrow H_2 + CO_2$$

The first reaction combines methane with steam to create hydrogen gas and carbon-monoxide. The second reaction combines the carbon monoxide with the water to produce more hydrogen and carbon dioxide. The HET SMR System collects the hydrogen gas, cools it, and purifies it with an internal PSA – effectively producing 99.9998% pure hydrogen. As a result, HMax is reliably and predictably produced to the production rate requirements.

16.4 Hydrogen Distribution Process

Gen H Power Park was designed to accommodate a mature fuel cell vehicle market even though the rate of production and required dispensing rate for the first few years reflects a smaller, less mature fleet. For large stations, the price difference between a booster compression and a cascading storage system is negligible [249]. Coupled with the fact that the most common approach for hydrogen refueling is a cascading storage system [250], Gen H's design includes a cascading storage system that employs a high-pressure compressor, a four bank storage system, and two dispensers. Each bank can independently be filled via the compressor or discharged via the dispenser. The term "bank" describes a total amount of hydrogen available at a certain pressure. A sequencing panel controls the banks for priority filling. Each phase of the cascading system is described below. The analysis described below uses a hydrogen fuel cell vehicle that stores 5 kg of hydrogen at 5000 psig. Each bank will store the required amount of hydrogen at 6500 psig. The refueling components were designed with the use of the CASCADE software [251]. The CASCADE software allows the user to size the compressor and storage banks to meet a demand entered by the user. A full description of the software and how it aided the design is included in appendix D.1 on page 302.

16.4.1 Hydrogen Compression

The cascading storage system requires storing the hydrogen at a pressure greater than the pressure needed in the fuel cell vehicle. The Gen H Power Park employs a Hydro-PacTM LX Series Gas Compressor, model # C07-60-140-200LX/SS [252]. The design requires a compressor capable of compressing the hydrogen from 150 psig to 6500 psig, with a flow equal to the production flow rate. Because hydrogen production proceeds in two phases with two sets of equipment, Gen H Power Park sized the compressor to meet a 125 kg/d flow rate and will purchase two compressors, one at the beginning of the project and another in the midway point. The production and compression of the hydrogen will run at a constant rate throughout the day. A 125 kg/d production rate requires a compressor size of approximately 37 scf/m [253]. The Hydro-PacTM LX Series Gas Compressor is a two-stage, electro-hydraulically driven, nonlubricated unit that includes an electric motor, hydraulic pump, hydraulic oil reserve, high-pressure gas intensifier and intensifier shifting mechanism. Each unit consumes approximately 32 kW of power.

16.4.2 Hydrogen Storage

Gen H will purchase and install its storage system in two phases, similar to the compression and production equipment. The total size of the cascading storage tanks was calculated using a 250 kg/d requirement and then divided in half to create the required volume for each set of storage tanks. The size of the storage was calculated using the following formula taken from Thomas and Reardon [254].

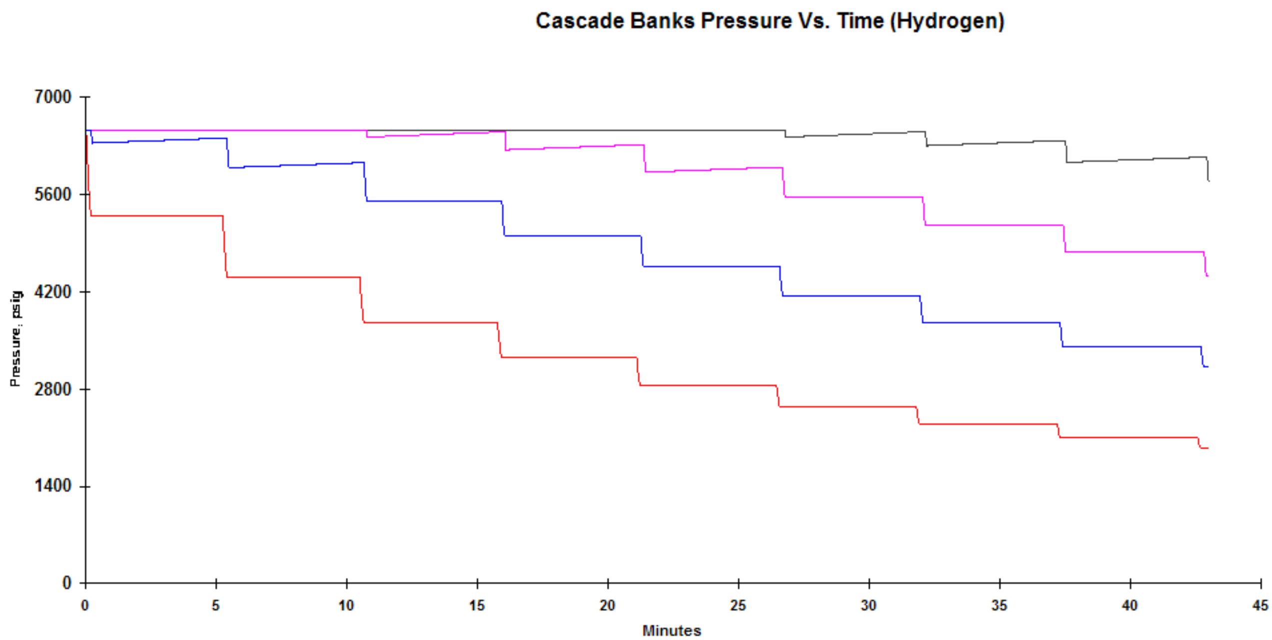


Figure 16.7: Cascade Banks Pressure vs Time

$$M_{cascade} = \frac{M_{dispensed} - M_{produced}}{U_H CF}$$

The formula considers the utilization efficiency, U_H, of a four bank cascading storage system [255]. The formula also takes into account the capacity factor of the station, CF, which accounts for daily, seasonal, and statistical fluctuations. The cascading system's design handles the 17 hour period from 6am until 10pm. During this time, 90% of the daily demand, or 240 kg, is dispensed, while only 177 kg of HMax is produced. Using 0.54 as the utilization efficiency and 0.69 as the capacity factor, the total mass of the cascading storage system should be 168 kg. Dividing this in half, the total mass of each set of storage tanks becomes 84 kg. With a four bank system, each bank must store 21 kg of HMax at 6500 psig. Using the real gas van der Waals equation and a compressibility factor of 1.3 (hydrogen at 6500 psig, 60°F), the volume of each tank needs should be 26 ft3. Each tank has a fixed diameter of 16 in., so each tank should be 18.6 ft. long. Gen H Power Park will use ASME approved steel Seamless Pressure Vessels from CP Industries. Each tank costs approximately $17,500 [256].

16.4.3 Hydrogen Dispensing

The final component in the refueling station is a hydrogen dispenser. Gen H's design includes a Fueling TechnologiesTM hydrogen dispenser. Gen H will purchase and install one dispenser in 2010 and another in 2015, each at $100,000 [257]. Each dispenser has two hoses to allow for dual refueling. The dispenser is rated to 6480 psig, with a maximum flow rate of 22 kg/min. According the software, each fill is approximately 3.6 kg. This flow rate easily allows for fast-fills of 3 to 5 minutes.

16.5 Hydrogen Refueling Capability

Gen H Power Park is designed according to two main requirements. The first, as mentioned before, is the daily amount of hydrogen needed per day. The second states the single peak vehicle fueling period of 30 kg in 1 hour. The CASCADE software was run with a daily production rate of 15 scf/m of hydrogen (equivalent to 50 kg/d) and each bank with a volume of 26 ft^3. If each fill takes 5 minutes, the output of the software shows that the cascading storage system can handle 9 fills in 43 minutes before the system reaches a point where not enough hydrogen at high enough pressure is available to fill a vehicle to the required amount. Each fill is 3.58 kg, so 9 fills in 43 minutes yields 32 kg. The software shows that the power park can meet the requirement even in when the system is producing and compressing the least of amount hydrogen and has the smallest amount of storage.

To show that the power park satisfies the daily demand requirement, a daily refueling profile was created. The daily load profile was built from the average distribution of personal trips per hour in the U.S [258]. The profile was built using the assumption that the time of day that a customer would refuel his or her vehicle would be the same time that the individual is taking a personal trip. If this assumption holds true, the total number of personal trips per hour would be the total number of refuels per hour. The number of refuels per hour was weighted according to the total number of refuels per day. The total number of refuels Gen H Power Park would see in 2020 is the total amount of HMax dispensed divided by the average amount per fill, or 250 kg divided by 3.58 kg/fill, which yields 70 refuels per day. Figure 16.8 shows the amount of hydrogen dispensed per hour, the total cascading storage volume, and the amount of hydrogen available for dispensing

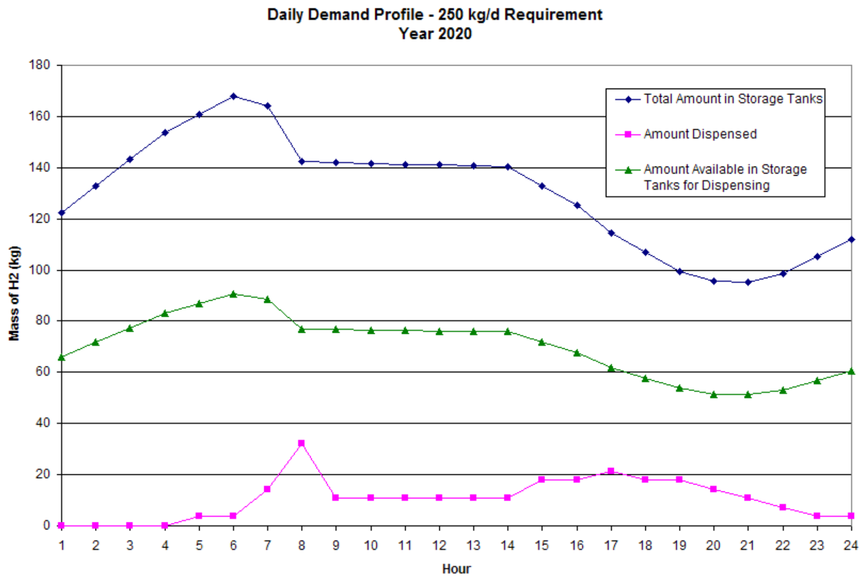


Figure 16.8: Hydrogen Dispensing Simulation

in 2020. The amount available for dispensing is the total production amount multiplied by the utilization efficiency. The figure shows that enough HMax will always remain for dispensing during the day. Appendix D.1 explains how the CASCADE software was used to ensure that hydrogen always remained at high enough pressure to meet the hourly distribution of refueling trips.

16.6 Fuel Cell

Gen H Power Park uses a Proton Exchange Membrane (PEM) fuel cell[2] for its electricity, known as eMax. The PEM fuel cell's total cost ranks among cheaper fuel cells when installation, maintenance, and operating costs are included. The main strength of the PEM fuel cell is the commercial and technical viability. Companies such as Ballard, GM, Plug Power, and UTC have invested a high degree of research into this particular technology. Thus, to ensure that Gen H Power Park will produce electricity from a green source in 2010, a PEM fuel cell was chosen as the production component. While there are other forms of producing electricity, Gen H Power Park is designed not only to provide the consumer with electricity, but to do so without harming the environment. This was a key concern when researching and choosing the different methods of production.

[2]The PEM fuel cell manufacturer requested their name be left out of the report due to the proprietary nature of this emerging technology. All data, including cost, is consistent with present literature (Shipley, et al. [262])

Other viable fuel cell options include phosphoric acid fuel cells (PAFC), solid oxide fuel cells (SOFC), and molten carbonate fuel cells (MCFC). The difference among these fuel cells lies in the type of electrolyte used in the interior of the fuel cell. PEM fuel cells and PAFCs use hydrogen ions as the medium to transfer the electrons through the electrolyte, where as SOFC use oxide ions and MCFC use carbonate ions. The sole manufacture of PAFCs has stopped developing this technology and has decided to concentrate on PEM fuel cell technology (Shipley, et al. [262]). SOFCs and MCFCs have shown promise, but are still in the pre-commercial stage of development. Neither technology is commercially or technically viable in the next five years. Therefore, the only possible choice for Gen H's fuel cell was a PEM fuel cell.

16.6.1 The PEM Fuel Cell

The PEM fuel cell operates in the same way as the other fuel cell designs. It is comprised of an anode, a cathode, and an electrolyte in between. In this case, the proton exchange membrane serves as the electrolyte. The membrane is only porous to protons. Since electrons cannot travel through the electrolyte, they instead must travel around the anode to cathode through an external circuit. The current that results in this circuit produces the electricity that Gen H sells to the local grid uses internally to run the hydrogen production and dispensing processes.

The PEM fuel cell that Gen H Power Park will use has its own hydrogen reformer, fuel cell, heat exchanger, and electric conditioner. The fuel cell will accept the cleaned biogas from the AWTP and reform it into hydrogen. The hydrogen will then pass through the fuel cell, creating electricity. The electricity created by the fuel cell is in direct current, DC, and must be converted into alternating current, AC. The fuel cell employs it own electric conditioner capable of converting the DC current to AC current. The fuel cell can produce 200 kW of power with a fuel flow of 3500 scf/h of biogas. The fuel cell also employs its own heat exchanger, with a capacity of 300,000 btu/h at rated power up to 250 °F.

16.6.2 PEM Fuel Cell Operational Characteristics

Gen H plans to produce a constant rate of 200 kW, 24 hours a day. The power park will use 100 kW internall. A rough calculation of the power needed to run the power park indicates that 100 kW is sufficient. In fact, for the first five years, the facility will be running at a power rate much lower than 100 kW. This additional electricity not needed by Gen H Power Park could be added to the 100 kW of electricity being sold to the grid, increasing profit margins. While this will most likely be the case, the added benefit was not included in the economic analysis, keeping the economic analysis conservative.

The other 100 kW will be sold to the local electric grid, at the present green electric rate of $0.0865/kWh at a constant rate throughout the life cycle of this project. The documented efficiency of the PEM fuel cell is 40%, but the actual efficiency of the PEM fuel cell in 2010 is difficult to establish due to the technological advancements that will take place between now and when this fuel cell becomes operational.[3] The efficiency of the fuel would degrade if run at a lower power output, but Gen H Power Park does not plan on this operation, as the grid provides an infinite sink.

[3]This information was to given to us from the fuel cell manufacturer.

Chapter 17

Safety Analysis

Gen H considers safety to be of the foremost importance as a determining factor in the success of Gen H Power Park. Today's general public still harbors the misconception that hydrogen is unsafe, particularly when compared with petroleum. In order to convince them that the hydrogen economy is safe and has great potential, Gen H Power Park must convey a sense that the customers and workers of Gen H Power Park can enjoy an accident-free environment. All production components must operate safely at all times and storage tanks must be guarded and inspected regularly. Accordingly, Gen H Power Park is created in such a way as to meet the standards and codes established by widely-recognized organizations, such as ASME, NFPA, CGA, SAE, and ISO. The relevant codes are listed in the appendix for reference.

Gen H employs Failure Modes and Effects Analysis (FMEA) to identify possible failure modes and their consequences [259]. This method is comprehensive and allows for the ranking of failure modes in order of significance. The results are then used to generate mitigation plans and improved safety controls. Subsequently, performing Fault Tree analysis provides sensitivity analysis on system performance before and after the mitigation and contingency plans are in place. All of these efforts go towards making Gen H Power Park far safer for its workers and customers.

17.1 Failure Modes and Effects Analysis

Using FMEA effectively obtains a comprehensive list of failures for all components with relative significance. In the analysis, the causes and effects of the failure modes are tracked along with the probabilities and severity of the consequences. Since the effects of system failures on human

Item No.	Component	Failure Mode	Failure Effects	SEV	Causes	OCC	Current Controls	DET	RPN
31	**Power Conditioner**	Power leakage	Electric shock	4	Humid atmosphere / mishandling	4	Component shutdown	4	64
38	**Storage System**	Tank Rupture	Catastrophe due to explosion	5	Collision by hard obj & Ignition	2	Fire Fighting	5	50
45	**Hydrogen Pipes**	Pipe Breakage	Catastrophe due to explosion	5	Collision by hard obj & Ignition	2	Fire Fighting	5	50
52	**Hydrogen Dispensing Hose**	Hose Rupture	Catastrophe due to explosion	5	Collision by hard obj & Ignition	2	Fire Fighting	5	50

Table 17.1: FMEA of Top Four Failure Modes by RPN

beings and community are of primary concern, only failure modes that could cause injuries or catastrophes are considered. For Gen H Power Park, the failure modes include component rupture, cable breakage, gas and liquid leakage, pressure build-up, and irritation.

In the analysis, there failure modes are given three ratings: severity (SEV), occurrence probability (OCC) and difficulty of detection (DET). SEV and OCC are the relative severity and the probability of occurring of the failure modes respectively. DET is the difficulty to detect the failures and to implement contingency plans. The aggregate rating called the Risk Priority Number (RPN) is calculated by multiplying the prior three ratings together. RPNs are used to rank the failure modes from highly urgent to less urgent and are calculated as the products of the three ratings above. Further methodology describing the ratings can be found in appendix D.2.2 on page 305.

In total, for Gen H Power Park, 54 failure modes are considered, ranging from extreme heat and noise to component rupture and breakage. An excerpt of FMEA before safety enhancement of Gen H Power Park is illustrated in table 17.1, showing the failure modes with high RPN.

Table 17.1 indicates that FMEA indentifies four major failure modes in need of immediate risk mitigation. These failure modes all have an RPN of 50 or above indicating that they are high-risk items.

17.2 Risk Mitigation

17.2.1 Power Conditioner

The main failure mode for power conditioner is power leakage. It occurs when the worker does not follow the standard procedures or operates it with wet hands. When power leaks, the control process requires the component to shut down completely. This causes downtime in production, potential loss of customers as well as possible additional injuries to other workers. In order to mitigate such risks and to reduce the significance of effects, the following controls are employed.

- Lockout / tagout procedures.
- The workers are required to wear insulating boots which prevent them from being grounded. Plastic guards are placed on the power conditioner to prevent workers from touching the conducting parts.
- In the event of power leakage, technicians will be deployed immediately to fix the components in order to prevent further damage to the conditioner and to the workers.
- Safety procedures are enforced and the workers will need to take qualification exams to become certified power conditioner operators or technicians.

With the above controls and preventive procedures, the OCC rating lowers to 3 and the DET rating to 2.

17.2.2 Storage System

In the event of vandalism or a terrorist attack, the storage tanks could rupture and catch on fire or explode if the tanks are hit hard enough and ignition occurs. It is important then to ensure that preventative measures are in place such that the storage tanks can be protected from such attacks. Otherwise, in the event of an attack, the sheer amount of hydrogen stored in tank could create a massive explosion. The following preventive systems and procedures are used to improve the safety of the tanks.

- Fire suppression systems are employed to prevent fire from spreading into the production area (see the plan view on on page 210).

- No Smoking, Highly Flammable, and Explosion Hazard signs are placed visibly in the storage area and within Gen H Power Park.
- Ventilation to prevent buildup of hydrogen gas.
- Concrete walls surround the storage tanks to prevent non-workers from accessing the storage tanks.
- In the event of unauthorized entry to the storage area and breakage due to vandalism or terrorism, an alarm system will go off, notifying the police department automatically.
- All equipment should be Ex rated[1] or intrinsically safe for explosion protection and spark free operation [260].

With the above controls and preventive procedures, the OCC rating lowers to 1 and the DET rating to 2.

17.2.3 Hydrogen Pipes and Dispensing Hoses

Hydrogen pipes and dispensing hoses are exposed to similar risks as the storage system. In addition to those risks mentioned in section 17.2.2, additional accidents could occur, breaking the pipes. The following approaches are taken to improve safety.

- Pipes are built underground to minimize exposure.
- The monitoring system is equipped with pressure gauges, shutting off valves to prevent further leakage in the event of breakage or rupture.
- The dispensing system is equipped with an alarm directly connected to the police department to stop vandalism.

Both OCCs are lowered to 1 and DETs to 2. After the new safety system is employed, the FMEA is updated with new data (table 17.2).

[1] Based on the safety rating in the Automotive handbook.

Item No.	Component	Failure Mode	Failure Effects	SEV	OCC	DET	RPN
31	**Power Conditioner**	Power leakage	Electric shock	4	3	2	24
38	**Storage System**	Tank Rupture	Catastrophe due to explosion	5	1	2	10
45	**Hydrogen Pipes**	Pipe Breakage	Catastrophe due to explosion	5	1	2	10
52	**Hydrogen Dispensing Hose**	Hose Rupture	Catastrophe due to explosion	5	1	2	10

Table 17.2: FMEA of Top Four Failure Modes by RPN

17.3 Fault Tree Analysis

From the previous analysis, the OCCs of all four failure modes drop dramatically after the safety improvements. However we are still concerned with the effectiveness of such control processes.

One way to verify the effectiveness of the new safety control is to use Fault Tree to find the overall probability of failure [261]. Due to the rarity of actual probabilities, this fault tree is by no means a scientific measure but provides a way to compare the overall performance of the system before and after the safety controls are put in place. In order to compare the overall probabilities, a scale to convert OCC to probabilities is used. In the fault tree, the operation of each day is assumed to be an independent event. For example, according to the OCC scale, a failure that would happen once in a year has a probability of 1/365 or 0.002739. The conversion scale and a sample fault tree can be found in the appendix.

In conclusion, it is found that the probability of failure per day before the new safety controls is 0.067 and after is 0.063. At the first glance, these two numbers may seem high. However, the analysis takes many non-life-threatening failure modes into account such as irritating noise from mishandling such that a small failure happens often is reasonable. Also, although the probability of failure does not drop dramatically, the DETs in the FMEA drop drastically. The drop in DETs indicates that it would be easier to implement contingency plans in the event of failure that

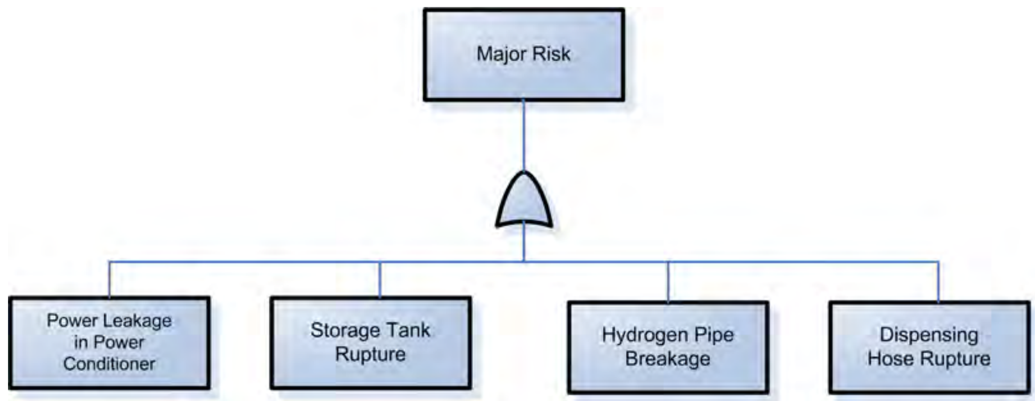


Figure 17.1: Sample Fault Tree of the 4 major risks

previously calculated. If only the 4 major failure modes are considered in the Fault Tree analysis, the probability for Gen H Power Park to experience any one of the failures drops dramatically from 0.00356 to 0.000712. Thus it is worth the investment to implement those controls above. The Fault Tree for the 4 major failure modes is shown in figure 17.1.

Such improvement does not only make Gen H Power Park a safer place but also conveys a sense to the public that the workers are professional and security is strong.

Chapter 18

Economic Analysis

A primary goal of Gen H Power Park is to demonstrate the economic feasibility of a key component of the hydrogen infrastructure. Since hydrogen production for vehicular use is at initial development stage, capital costs of equipments represent a major concern in the economic model. Costs are minimized wherever possible by comparing devices from different vendors and revenue is maximized by adding a convenience store to improve the business profitability. All costs are quoted directly from vendors to give the most accurate data. The references for all the costs are included in the appendix. Various costs and economic analyses are discussed in the following section.

18.1 Cost Structure

18.1.1 Capital Cost

Cost is split into capital cost and operating expenditure. All pieces of equipment are installed before the inauguration of Gen H Power Park so that there is no capital cost incurred in 2010. In order to expand Gen H Power Park to meet capacity, more components are purchased in early 2015, at the midway point of the power park's expected life cycle. The components added in 2015 include a reformer, a PSA, a dispensing system, a hydrogen compressor, four hydrogen storage tanks, as well as the core of the fuel cell. Incremental purchase lowers the front-loaded capital cost before inauguration, while still meeting the expected demand.

Description	Cost as of 12/31/09	Cost in 2015
Safety Equipment	274.8	0
Reformer	300	300
PSA	100	100
Dispenser	100	100
Hydrogen Compressor	87	87
Biogas Compressor	60	0
Gas Treatment	97.45	0
Cost of Tanks	70	70
Fuel Cell	1,000	380
Total	2,606.25	1,037

Table 18.1: Capital Equipment Costs (x $1000)

Description	Cost
Land Cost	100
Construction	417
Total	517

Table 18.2: Land and Construction Costs (x $1000)

Description	Cost
Construction	300
Pipeline Cost	50
Convenience Store	67
Total	417

Table 18.3: Construction Cost Spread (x $1000)

Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Safety Equipment	5	5	5	5	5	5	5	5	5	5
Reformer	10	10	10	10	10	10	10	10	10	10
PSA	4	4	4	4	4	8	8	8	8	8
Gas Treatment	12.3	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
Total	31.3	26.6	26.6	26.6	26.6	30.6	30.6	30.6	30.6	30.6

Table 18.4: Maintenance Costs (x $1000)

Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Admin Cost	10	10	10	10	10	10	10	10	10	10
Marketing Cost	63	59	50	48.8	46.6	51.4	45.2	45	42.8	47.6
Total	73	69	60	59	57	61	55	55	53	58

Table 18.5: Administration Costs (x $1000)

18.1.2 Running Expenses

The cost to operate the hydrogen power park includes both maintenance and administration costs. Although it is difficult to calculate the exact maintenance cost, Gen H discussed with equipment suppliers to reach the final estimates. These values are summarized in table 18.4.

The other major running expenses derive from marketing and administration. These values appear in table 18.5.

Gen H requires biogas as input to the fuel cell for producing electricity and hydrogen. The calculation of hydrogen and biogas requirement is already detailed in the Technical Design, section 16.3 on page 212. The detailed requirement of biogas is detailed in table 18.6.

18.1.3 Biogas Cost

Gen H sells its electricity to the grid at the current avoided cost rate of $0.04/kWh. This information is obtained from D.C. Wastewater And Sewer Authority (DC WASA). The DC WASA would purchase electricity from the local utility company at $0.04/kWh. This calculation is based at the high end such that the price for HMax could be lowered in order to promote the hydrogen economy. The calculation for the biogas cost is as follows.

1 scf of biogas=600 btu *0.0002931 kWh/btu *30% efficiency =0.052758 kWh

Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
For Fuel Cell										
Biogas (x 1000 scf/day)	84	84	84	84	84	84	84	84	84	84
Biogas Cost (x $1000)	64.7	64.7	64.7	64.7	64.7	64.7	64.7	64.7	64.7	64.7
For Vehicles										
Hydrogen (kg/day)	50	65	80	95	110	125	156	188	219	250
Biogas (x 1000 scf/day)	18.90	24.57	30.24	35.91	41.58	47.25	59.06	70.88	82.69	94.50
Biogas Cost (x $1000)	0.61	0.79	0.97	1.15	1.33	1.52	1.90	2.27	2.65	3.03
Total Cost (x $1000)	14.6	18.9	23.3	27.7	32.0	36.4	45.5	54.6	63.7	72.8

Table 18.6: Biogas Costs

$$\text{1 scf of biogas} = 0.052758 \frac{\text{kWh}}{\text{scf of biogas}} * \$0.04/\text{kWh} = \$0.00211$$

18.2 Revenue

Gen H's three major revenue streams are electric power, hydrogen for vehicles, and the on-site convenience store.

Gen H Power Park maintains 100kWh of electricity in excess after taking into account internal electrical requirements. As required by the National Hydrogen Association, the electricity is sold to the local electric company, Pepco. According to Pepco, renewable energy such as eMax could be sold to customers at $0.0865/kWh [263].

The additional revenue stream of the convenience store is added to keep Gen H Power Park profitable. The average profit of a convenience store in the United States is $30,000 per year. Since Gen H Power Park will become a full-fledged fueling station by 2020, its convenience store should have a profit comparable to the national average. Therefore, the present value of the profit of the convenience store yields $30,000 at 2020. Then, the initial profit of $6000 in 2010 is obtained by scaling down proportionally according to the demand of HMax which is 50kg/day. Based on the multiple revenue streams, hydrogen is priced economically at $8.31/kg while making net present value (NPV) equal to zero at the internal rate of return of 10%. Assuming the demand does not change, Gen H Power Park could raise profit by raising the selling price of hydrogen.

Description	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Electricity										
Available for sale (x 1000 kWh/yr)	876	876	876	876	876	876	876	876	876	876
Electricity Revenue (x $1000)	75.8	75.8	75.8	75.8	75.8	75.8	75.8	75.8	75.8	75.8
Hydrogen										
Requirement (kg/day)	50	65	80	95	110	125	156	188	219	250
Hydrogen Revenue (x $1000)	110.8	144.0	177.2	210.5	243.7	276.9	346.2	415.4	484.6	553.9
Convenience Store										
Profit (x $1000)	6	9	11	14	17	19	22	25	27	30
Total Revenue (x $1000)	216.5	249.8	283.0	316.2	349.5	382.7	451.9	521.2	590.4	659.7

Table 18.7: Revenue

18.3 Cash Flow

Operating cash flow is determined by deducting variable cost from revenue. Taxable income is determined by deducting depreciation from the operating cash flow and corporate tax is determined using the current corporate tax structure of the United States. Present value of the total cash flow is found by using the discount rate of 10%, which gives the enterprise value.

Now, NPV = enterprise value – current value of total capital cost. Using Excel's Solver with the given 10% IRR, the hydrogen price for which NPV becomes zero is determined. The calculation illustrates the price of hydrogen as $8.31/kg as indicated in the previous section. A detailed cash flow table for Gen H Power Park can be found in the appendix D.4 on page 310.

18.3.1 Depreciation Calculations

Equipment is depreciated using the straight-line depreciation method. Based on the information from vendors and various equipment suppliers, the salvage value of Gen H equipment at year 10 is nearly zero. However, if Gen H Power Park were to remain in service beyond 10 years, some equipment could still be in service and used to keep the power park profitable. At last, land value is assumed to appreciate at 10% per year with a terminal value of \$259,374.

18.4 Conclusions

With HMax and eMax priced at \$8.31/kg and \$0.0865/kWh, Gen H maintains high profitability while still meeting the production requirement set by National Hydrogen Association. Gen H has great potential to keep its business beyond 2020 and remain profitable. Therefore, with Gen H Power Park, the transition to the hydrogen economy shows great promise.

Chapter 19

Environmental Analysis

Production methods represent a determining factor in the success of hydrogen as an energy transmission medium. Using fossil fuels such as natural gas or coal as feedstocks does not alleviate the global warming effects and consumption of exhaustible reserves of carbon based energy. Gen H Power Park produces hydrogen from products that would otherwise remain unused as waste, preventing the entry of methane into the atmosphere, and reducing global warming effects.

A strength of Gen H's design is its high environmental performance. Because the hydrogen source is biosolids, no net CO_2 is actually produced. Presently, Blue Plains AWTP creates waste that must be disposed of in landfills. Gen H will work with Blue Plains AWTP so that the waste will become valuable fertilizer and energy. While this will result in limited carbon dioxide emissions, the net result will be much less than the amount produced by combustion of fossil fuels. The sewage sludge processed by Blue Plains is highly suitable for fertilizer, as the anaerobic digestion process serves to sterilize the product and concentrates nutrients, creating a closed loop cycle of biomass usage.

19.1 Hydrogen Production Emissions

A major concern of Gen H Power Park is its carbon dioxide emissions. Carbon dioxide results from two seperate stages in the hydrogen production process, as illustrated by figure 19.1. First, the Power Swing Adsorber takes the biogas, composed of 40% CO_2 and 60% CH_4, and separates the carbon dioxide from the usable methane. For every kilogram of hydrogen produced, 7.96 grams of CO_2 is extracted from the biogas. However, because the biogas is not a fossil fuel but instead

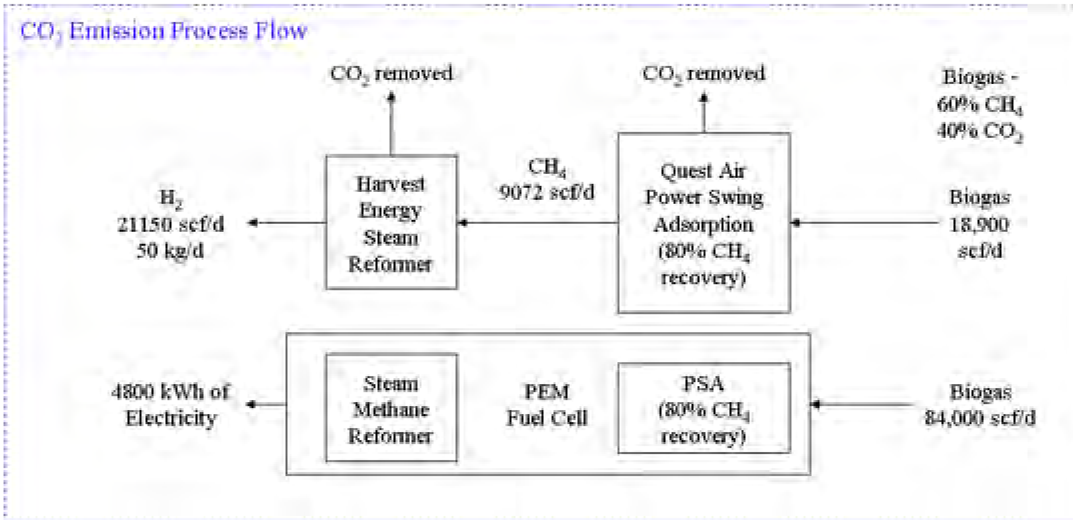


Figure 19.1: Production Pathway: Above– Hydrogen, Below– Electricity

Source	Carbon Dioxide emitted (kg of CO_2/ kg of H_2)
Power Swing Adsorber	7.96
Steam Reformer	9.56

Table 19.1: Carbon dioxide emissions during hydrogen production.

a waste energy source, Gen H does not consider that the 7.96 kg of CO_2 adds to the net CO_2 resulting from the power park (see D.3.1 on page 309 for the calculations).

Subsequently, the methane is processed by the steam reformer to produce hydrogen. This procedure requires the ingression of water, which combines with the methane to produce carbon monoxide. When this is followed by the Water Gas shift reaction, carbon dioxide forms alongside the hydrogen that results. (The chemical reaction is spelled out on page 214.) Specifically, 9.56 kg of CO_2 result per kilogram of hydrogen produced (see D.3.2 on page 309 for the calculations). These values are summarized in table 19.1.

19.2 Electricity Production Emissions

The electricity production process consists of sending biogas directly into the PEM fuel cell. Essentially, the fuel cell operates by producing hydrogen in the same way as Gen H Power Park, albeit on a smaller scale and within the fuel cell itself; accordingly, the analysis is analogous.

84,000scf of biogas enters the fuel cell per day. Similar to the hydrogen production pathway,

Source within Fuel Cell	Carbon Dioxide Emitted (kg of CO_2 / kWh)
Power Swing Adsorber	0.37
Steam Reformer	0.44

Table 19.2: Carbon dioxide emissions during electricity production

40%of the biogas is CO_2. This enters the PSA. As a consequence, 0.37 kg of CO_2per kWh is emitted from the 200 kW fuel cell from the Swing Adsorption process that takes place within the fuel cell. Correspondingly, the fuel cell-internal steam reformation process gives 0.44 kg per kWh. Table 19.2 summarizes these values, which are consistent with present day literature [262].

19.3 Total Carbon Dioxide Emissions

On a typical day, Gen H Power Park is unlikely to require electricity from the local power grid because of the electricity produced in-house via the fuel cell. However, should Gen H Power Park require external electricity sources, it will do so through Pepco Energy Services, a major provider in the Washington DC area. In particularly, Gen H Power Park will subscribe to their 100% Green Electricity as another instance of the park's support of renewable energy and the environment. This particular electricity source uses captured methane whose byproduct of carbon dioxide is a mere 0.75 kg of CO_2 per kilowatthour [263]. However, since Gen H will only use this electricity in emergency situations, this figure will not be included in the total emissions calculation as it is considered to be negligible.

Gen H's total daily carbon dioxide emissions is the sum of the per day values in table 19.1 and table 19.2. Of course, this value will vary with the amount of hydrogen produced. Starting in 2010 when 50 kg of hydrogen is produced per day, $3.19 * 10^5$ kg of carbon dioxide result from hydrogen production and $1.42 * 10^6$ kg of carbon dioxide result from electricity production. Total, this yields $1.74 * 10^6$kg of carbon dioxide for the year 2010. As production ramps up, the carbon dioxide resulting from hydrogen production increases accordingly, while carbon dioxide from electricity production stays constant because Gen H's production is 200 kW throughout. The total carbon dioxide emissions are summarized in figure 19.2.

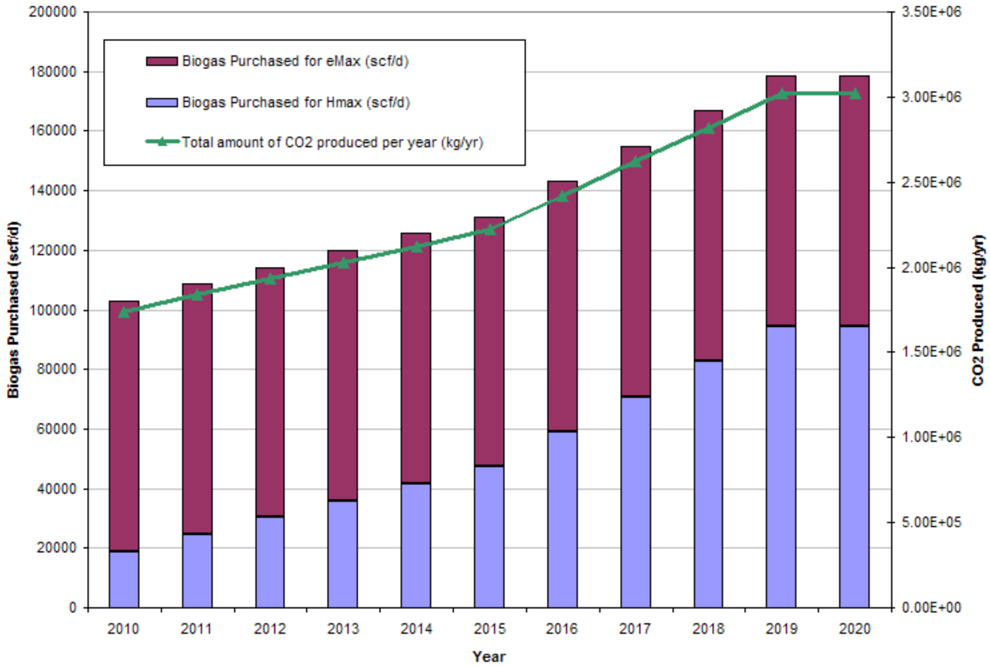


Figure 19.2: Total Carbon Dioxide Emissions

19.4 Net Carbon Dioxide Emissions

Gen H Power Park is carbon neutral. All of the carbon dioxide emitted by the power park is from a fuel that is already in the waste stream, whose carbon content originally came from the atmosphere, and not fossil fuels. So while the power park does give off CO_2, this does not add carbon dioxide to the atmosphere whose presence has not already been accounted for because the biogas comes from anerobically digested wastewater. Because there are no net carbon dioxide emissions to the atmosphere, Gen H Power Park compares favorably with its competitors, particularly those who use fossil fuels.

The hydrogen generation demands thinking about problems in new ways as part of a world in which it will no longer be possible to sweep the waste underneath the rug. Gen H does more than look for different ways to hide its dirty business – Gen H puts it to good use. Starting in 2010, one man's trash will become another man's clean energy.

Chapter 20

Marketing and Education

Due to the pioneering nature of hydrogen energy-generating technologies, Gen Hs marketing and education plan aims to educate the public on the promise of hydrogen as the solution to many of todays environmental and energy issues. Gen H considers the planets health as merely indistinguishable from its power parks purpose, thus forming a natural marketing tie – Gen H: Energy for the Hydrogen Generation. This slogan incorporates hydrogen as the parks product but also as its purpose: to usher in a new generation dedicated to preserving the earths resources.

Unfortunately, a high percentage of the population does not possess familiarity with the basic concepts of hydrogen technologies. In order to ease this transition into an effective and accepted implementation of the power park, the Gen H team has formulated an awareness, marketing and education plan. This plan outlines the key focus areas and measures to build support, allay fears, reduce resistance, and raise awareness of hydrogen in the D.C. area that will echo throughout the nation. The plan includes two sections: Education and Public Awareness, and Marketing.

20.1 Education and Public Awareness

20.1.1 General Public

The Gen H team will contact Neighborhood Watch programs. Together, they can help to endorse the hydrogen transition by holding regular meetings and open discussions for communities interested in learning more about hydrogen. Representatives from national agencies, such as the NHA can visit them and guide their efforts. The Gen H team will financially support these visits. The power park will hold town meetings with the local D.C. authorities and host open forums, where citizens can express their concerns and voice their questions. This will help educate and reassure the population that HMax and eMAx are a safe choice. T*otal 10 year budget: $86,400.*

20.1.2 Academic Outreach

College Level

Gen H will advocate for universities to offer more advertised, encouraged, and even required seminars and classes, i.e. "Alternative Energy Sources". These will hold an open enrollment, and can be taken for a letter grade or for the mere learning experience. This flexibility encourages exploration and awareness among the students. Variable credit options can also be offered, with the opportunity of independent projects and research papers. The existence of student and professional organizations will aid with the implementation of this plan. Many non-profit organizations, such as Engineers for a Sustainable World (ESW), can further transmit Gen H's message in a structured manner. With the cooperation of faculty and students, the Gen H team will form committees and sponsor competitions dedicated solely to the hydrogen transition. *Total 10 year budget: $42,000.*

High School Level

Gen H will help institutions offer various elective modules focusing on hydrogen as an upcoming energy source. Focused career path programs can be created for those interested in hydrogen from a relatively early age in order to guide their educational efforts. A proactive setting and educational environment will facilitate this support through hands-on activities, field trips, and semester-long projects. These events will culminate in an end of the year science fair, where the students can showcase their independent or group projects. Each respective school may apply for funds from Gen H to reward those students who participate. Gen H will also provide them with special recognition and certificates. Gen H will extend an invitation to professional organizations to take part in the science fair. By being present at high schools, these organizations can begin recruiting future members early and convincingly. *Total 10 year budget: $42,000.*

Junior High School Level

Due to the brevity but high importance of this educational stage, Gen H's programs will focus on having on-site activities and plant tours that will help the kids become better acquainted with the hydrogen technology and processes. The teenage years prove critical in developing young peoples minds. By conveying a message of safety, reliability, and convenience, Gen H Power Park and the hydrogen industry will benefit greatly. *Total 10 year budget: $39,000.*

Elementary School Level

At an early age, children must be stimulated and challenged to think creatively. Gen H will sponsor annual coloring contests for children in grades 1st – 3rd and essay contests for children in grades 4th – 6th to ignite this creativity. By providing the younger kids with drawings of hydrogen-related scenes and their significance, they will become more familiar and comfortable with Gen H and hydrogen use. The essays will serve the same function, as well as push for further thoughts and curiosity among the childrens parents. *Total 10 year budget: $50,000.*

20.2 Marketing

- The production of GREEN Hydrogen will serve as the main point of Gen H's marketing campaign.

- Gen H will produce promotional videos. These will be offered for free or at a discount to qualifying organizations such as ESW, Neighborhood Watch boards, and academic institutions.

- Educational, appealing ads will appear in magazines, newspapers, and local TV stations.

- Most radio stations offer free public service announcements for non-profit organizations. These will prove useful when promoting Gen H after forming partnerships with entities such as the NHA. *Total 10 year budget for the above: $100,000.*

- Gen H will present proposals for toy lines to selected manufacturers, including Fisher Price. These can be especially marketed at stores throughout the nation: *Total budget: $20,000.*

Figure 20.1: H:can:2, HydroRanger

- Ages 3-10: HydroCities, the building block toy line, will be marketed towards this age group. Different components such as trucks, stations, little people, and cars will be produced and sold separately. Since all the components will be directly related to hydrogen, collecting the different styles in order to build cities will promote the idea of self-sufficient communities relying on hydrogen-generated energy. This will set the young kids mindset of approval at an early stage. City-building contests will be held locally, sponsored by Gen H, and winners will advance to a national showdown in Washington D.C. Gen H will request dual sponsorship from the NHA for this event.
- Ages 10-15: Small scale models of robots, fuel cells, and other more technologically advanced components will be offered for this age group. This will increase the childrens familiarity and awareness with hydrogen technologies, and serves as a continuing toy line following HydroCities.
- Gen H has developed a logo for the toy line, H:can:2, as well as a character, HydroRanger. (see figure 20.1)

• Gen H will submit a proposal to Lego Inc., requesting that they add a small hydrogen module to their existing amusement park in San Diego, CA. This will make parents and youngsters aware of the reliability, promise, and future of H2. *Total budget: $7,500.*

• Various proposals will be written to different video game manufacturers (i.e. Nintendo, Sony Playstation, and Microsoft X-Box) to request for the development of new titles that include sustainability and hydrogen energy as a theme. The extensive and diverse market of video games will further extend the reach of Gen H's marketing campaign. *Total budget: $7,500.*

• The H2 challenge: *Total budget: $105,000.*

  - Gen H will invite the general public to the power park on a given day every month.

  - Some fuel cell vehicles will be on-site, and Gen H will help the visitors to become more familiar and comfortable with them. This includes the opportunity to fuel the vehicles themselves.
  - Gen H will encourage the participants to drive the cars. Do they feel and perform the same? Of course!
  - Gen H will award prizes, including free fuel and discounts, to participants of the H2 challenge, especially to those who consider converting to hydrogen fuel and electricity.
  - Gen H will hold a closing ceremony at one of the parks offices.
  - FFM (Free Fuel for a Month) for owners of hydrogen-powered vehicles in the area.

- *Total Plan Cost: $499,400*

Part V

Conclusions

Chapter 21

Recommendations for Shell Gas & Power

Before the beginning of this project, the advisor of this project, Francis Vanek, approached the Shell Hydrogen Washington D.C. project to generate a list of questions that were of interest to Shell as part of the hydrogen transition. The four questions that were agreed upon are:

1. What are all the possible ways to generate hydrogen?
2. What can Non-Governmental Organizations (NGOs) do to support the transition?
3. What can be done to overcome the public's concern about hydrogen?
4. Are government incentives really necessary?

In the course of this project we have stressed to examine each of these questions in detail. While we have compiled the answers to the questions in this part, additional information about the specific research and analysis can be found in various chapters through this report.

21.1 Various Ways to Generate Hydrogen

There are a number of methods to produce hydrogen using a variety of sources. As part of the Japan Hydrogen Fuel Cell Demonstration Project (JHFC), the Japanese government has investigated many different types of hydrogen production methods and considers the following to be the most feasible. The JHFC has implemented stations that use naphtha reforming, LPG reforming, methanol reforming, electrolysis, de-sulfurized gasoline reforming, high-pressure hydrogen storage liquid-hydrogen storage, natural gas reforming, and petroleum reforming. A mobile station and a facility for mass-producing liquid hydrogen from by-product gas (coke oven gas: COG) has also been constructed.

In the naphtha reforming method, high-purity hydrogen gas is produced from naphtha with steam reforming and pressure swing adsorption (PSA). This hydrogen gas is supplied to fuel cell vehicles as high-pressure gas. In the petroleum industry, companies are mass-producing hydrogen from petroleum product such as naphtha, removing sulfur and other impurities during the refining process.

LPG reforming involves the use of LPG (mixed butane and propane (7:3) gas, odorized) to produce hydrogen by steam reforming with PSA refinement. The hydrogen production equipment for the station is based on field-proven industrial technology for on-site hydrogen production by LP gas reforming. This equipment uses a small-size 6-tower PSA for reduced size and improved efficiency. The dispenser for the station is easy-to-use precision equipment utilizing Nippon Sanso's gas control technology.

Methanol reforming is appealing because Methanol is the safest of all the materials available for hydrogen production. Another benefit is that the reforming reaction for methanol can be carried out at a relatively low temperature of 250 to 300°C, compared with 600 to 700°C for natural gas, and a smaller amount of energy is required to heart it and to hold it at that temperature. Stations implementing Methanol reforming evaporate methanol and water, then cause them to react with each other through catalysts. After generation, hydrogen is separated and compressed to provide fuel cell vehicles with the high-pressure hydrogen.

Currently, the most cost-effective method for hydrogen production involves reforming natural gas. The production costs of this hydrogen production can be reduced because the infrastructure for natural gas is already well organized. Accordingly, natural gas is thought of as a promising fossil fuel for hydrogen production. Because all the facilities are vehicle-mountable, this station is expected to serve as a full-fledged mobile hydrogen station. It will cover these areas which do not have fixed hydrogen stations.

Kerosene, a liquid fuel low in volatility, has been considered a prospective fuel cell material for some time, being reasonably priced and with adequate infrastructure but it requires high level desulphurization and catalyst reforming technologies. Idemitsu Kosan Co., Ltd., through long years of research, has succeeded in producing hydrogen from kerosene by applying their desulphuring agent and catalyst reforming technology. The method of desulphurization is an adsorption desulphurization. Hydrogen is produced with vapor reform with PSA. The Hadano Hydrogen Station, built and operated by Idemitsu Kosan, is the world's first kerosene-reform-type hydrogen fueling facility, playing an important role in the popularization of fuel cell vehicles.

A mobile hydrogen station can be found in the premises of the Ministry of Economy, Trade and Industry (METI) in Kasumigaseki, Chiyoda-ku, Tokyo. Each weekday morning, the components of this station are carried into the premises and assembled there; in the evening, they are moved off of the premises. All the devices used, such as the hydrogen cylinders and dispensers (fillers), are combined into a single unit for easy transportation. This mobile hydrogen station is expected to provide services outside the areas with fixed hydrogen stations. It is also expected to cover an area where installation of a fixed hydrogen station is difficult because of restrictions imposed by the Building Standard, High Pressure Gas Safety Law, and other current laws.

A facility for Manufacturing Liquid Hydrogen from Coke Oven Gas is currently operation in Japan. This facility represents the world's first approach to mass-producing liquid hydrogen from large quantities of by-product gas (coke oven gas: COG) generated in the steel making process. The plant can produce 0.2 tons of high-purity liquid hydrogen every day. In addition, they offer reduced cost of deployment by utilizing the existing steel making infrastructure. Advantages of Liquid Hydrogen include its ability to be efficiently transportable and storable. In the current JHFC Demonstration Project, an experiment is being conducted to investigate the full range of system operations, starting with the transportation of manufactured liquid hydrogen and ending with the supply of hydrogen to fuel cell vehicles.

Advancements in hydrogen production may be possible through electrolyzer technology. With this technology, hydrogen is produced through the electrolysis of water. Most of the cost of hydrogen production by electrolysis is from the cost of electricity, and as most of the worlds electricity is produced by the burning of fossil fuels, this entire exercise may seem counterproductive. However, economic ways to produce electricity from environmentally-friendly sources are currently being researched. For example, one transit company in California is using solar power to supplement grid energy as a source of power for its electrolyzer.

Additionally, one effective way to produce hydrogen, investigated by our Power Park team, involves the use of biogas. Biogas can be obtained by anaerobically digesting the sludge created by treating wastewater. Hydrogen obtained from this source is an ideal choice for as a production method because of its environmental friendliness. Since the carbon present in biogas would be vented to atmosphere regardless of whether hydrogen is removed, the production of hydrogen from biogas would effectively be carbon neutral, causing no net increase in the emissions of carbon dioxide or carbon monoxide into the atmosphere. In the design of Gen H Power Park in the previous section, the power park purchases biogas from Blue Plains AWTP to produce hydrogen.

Biogas is 60% methane and 40% carbon dioxide. Hydrogen is produced by stripping the hydrogen from the methane gas. The PSA process is required to harness pure methane, and is based on physical adsorption of gases onto specialized beds of adsorbents. For example, the M-3200 system from QuestAir employs six adsorber beds that are used in parallel to ensure a constant flow of product gas. Then, the methane-rich gas is fed into a reformer at about 150 psig using a compressor.

While there are several different ways to produce hydrogen from methane (or natural gas), the most cost-effective option is to utilize a steam methane reforming (SMR) process with subsequent pressure swing adsorption. For the Gen H Power Park design, a hydrogen generator from Harvest Energy Technology, Inc. (HET) is incorporated to generate hydrogen from a pure stream of methane and input water through the following two chemical reactions.

$$CH_4 + H_2O \longrightarrow 3H_2 + CO$$

$$CO + H_2O \longrightarrow H_2 + CO_2$$

The first reaction takes the methane and combines it with steam to create hydrogen gas and carbon-monoxide. The second reaction combines the carbon monoxide with the water to produce more hydrogen and carbon dioxide.

21.2 Possible NGOs' Involvement in the Transition

The term Nongovernmental Organizations (NGOs) is an umbrella term that covers a range of organizations that work in the public interest without being part of local, state, or federal government. With increased organization and support, NGOs are now a major influence in national and world politics. NGOs have a wide palette, ranging from topics as diverse as international aid to protecting wildlife, and their actions can greatly influence public opinion and public policy[1]. With so much of the hydrogen transition dependent on these two aspects, it would be a mistake to exclude them from consideration.

Three NGOs that have shown particular interest in hydrogen fuel cell vehicles are the Sierra Club, the World Resources Institute, and the National Resources Defense Council. All have environmental issues as part of their core mission, and have specifically addressed hydrogen as a fuel source. In addition, each has a variety of outlets, including newsletters, magazines, press releases, and extensive websites with which to get their message out to the public. Finally, each has a large office in Washington, DC, so a successful demonstration of the benefits of hydrogen there could be very influential.

The Sierra Club is America's oldest and largest grassroots environmental organization[2]. Since their mission is mainly to protect our communities and the planet, they are most concerned with hydrogens ability to reduce emissions and consumption of fossil fuels. As such, they do not approve of great investment in hydrogen infrastructure now unless there are clean sources.

[1] http://www.ngowatch.org/

[2] http://florida.sierraclub.org/central/Issues/iss_0305_hydrogen_society.htm

Similarly, the World Resources Institute cautions against putting too much faith in the hype over hydrogen. In 2004, they cited the growing debate over hydrogen as one of the top stories of the year[3]. They warn that hydrogen is an energy carrier, not an energy source. In order to get pure hydrogen, you need to expend energy, such as electrolysis or extracting it from natural gas and coal. Thus, they urge, it is important to consider what the source of hydrogen will be. They also criticize many auto manufacturers (with the exception of Toyota and Honda) for turning away from hybrid and efficiency research in favor of FCVs.

Finally, the National Resources Defense Council (NRDC), which holds ending dependence on oil as one of its key mission goals, believes that hydrogen technology shows promise, but provides no short-term benefits[4]. They believe that legislative efforts should be focused on forcing car makers to adopt cleaner, more efficient technologies that are available today. That way, the benefits of reduced emissions and reduced consumption of oil could be immediately realized. They argue that, while a complete end to the petroleum-dependent economy would be nice, that does not mean that industry and the government should stand idly by for 20 years waiting for a transition to happen.

Perhaps the most important role that NGOs will play is not a supportive one, but a neutral one. It is hard to imagine organizations like the NRDC putting their collective weight behind hydrogen initiatives unless major hurdles are overcome. However, if NGOs are convinced that sincere efforts are being exerted towards the hybrid and other efficient technologies of today, they might praise those efforts and silently await the long term goals of FCV and hydrogen research.

21.3 Resolving the General Public's Concern about Hydrogen

A high percentage of the population does not possess familiarity with the basic concepts of hydrogen technologies. In order to ease this transition, community programs and education modules could be adopted to instill the correct knowledge of hydrogen to the general public and the future generations.

Community programs such as lectures at public libraries could be used to endorse the hydrogen transition by holding regular meetings and open discussions for communities interested in learning more about hydrogen. Representatives from national agencies, such as the National Hydrogen Association, would visit the local communities to guide their efforts. Additionally, town meetings with local authorities and open forums could be held such that citizens could express their con-

[3]http://pubs.wri.org/pubs_content_text.cfm?ContentID=2416
[4]http://www.nrdc.org/air/transportation/phydrofuel.asp

cerns and voice their questions. Another successful means of overcoming public fear about a new technology is to place the technology where the public may observe it in operation, such as in public transportation. This convinces the public that the technology is safe, and allows them to overcome their innate fear of the unknown and the unproven. Iceland's introduction of hydrogen technology is a perfect example of being confronted by public fear of a technology and using public demonstrations to allay those fears. Iceland's Ecological City Transport System (ECTOS) initiated a pilot program that put hydrogen buses into service in Reykjavik, the capital of Iceland. Since the start of the pilot program approval of hydrogen technology among the population of Iceland has risen to 93% (ECTOS, 2004 [158]).

From an academic standpoint, universities and colleges could help educate students by having seminars and class modules in addition to the opportunity for independent projects and research papers. The existence of student and professional organizations could aid with the implementation of this plan. Engineers for a Sustainable World (ESW)[5] is one of the many non-profit organizations could further transmit the benefits of hydrogen in such a structured manner.

Also, focused career path programs could be created for those interested in hydrogen from a relatively early age, in order to guide their educational efforts. A pro-active setting and educational environment would facilitate this support through hands-on activities, field trips, and semester-long projects. These events would culminate in a yearly science fair, where students could showcase their independent or group projects. Each respective school might apply for funds from sponsoring parties to reward those students who participate. Furthermore, on-site activities and hydrogen production plant tours could also help the students become better acquainted with the hydrogen technology and processes. The teenage years prove critical in developing young people's minds. By conveying a message of safety, reliability, and convenience, the hydrogen industry would benefit greatly on long term basis.

21.4 The Necessity of Government Incentives

After conducting thorough research on the feasibility of a hydrogen transition in the transportation industry, it is our belief that government incentives are absolutely critical in making the hydrogen transition possible. Technical barriers and high business risks have put the current R&D program for the use of hydrogen at a tremendous financial loss. In addition, the creation of infrastructures for the hydrogen distribution network will require the investment of many years and considerable amounts of financial and material resources. Without government incentives, the hydrogen industry

[5] http://www.esustainableworld.org

cannot return a profit quickly enough to be attractive to private enterprises as a purely commercial venture.

The government has certainly recognized the need for its involvement when President Bush pledged a $1.2 billion fuel cell research project at his State of Union address in 2003. The project, however, did not come with higher emission standards or other measures that would force the auto makers to accelerate their research. As a result, the commitment by domestic automakers to the hydrogen transition remains insufficient to carry out a transition to hydrogen in the short to medium term, although it is substantial.

The future of the fuel cell technology is further complicated by the recent success of the hybrid electric vehicles. A successful market penetration of the HEVs could potentially alleviate the pressure to use alternative fuels, since hybrids are significantly cleaner and more efficient. This would delay a transition to hydrogen fuel cell vehicles by as much as 10-20 years, as shown in the HEV section.

The question today is not if government incentives are necessary but how many more of them are needed before the hydrogen transition can become a reality.

Chapter 22

Project Conclusions

22.1 Findings and Results

22.1.1 HEV

We conclude that HEVs will fully penetrate the light vehicle market by 2080 at the latest, and as soon as 2030. This transition will significantly increase average light vehicle efficiency, leading to decreased energy and oil consumption, and reduced carbon dioxide emissions. Successful hybrid penetration will also delay fuel cell vehicle introduction by at least 10 years, since the expected decrease in oil consumption will ease the pressing need to find alternative fuels. Considering all aspects of the two transitions, we find that the hybrid path is more desirable than a direct path to fuel cell vehicles. We say this because the endpoint technology is more efficient, and the cumulative savings in energy and carbon dioxide emissions are greater.

After lengthy investigation, we deem that government involvement is necessary for fuel cell vehicles to successfully enter the market in the next 30 years. We considered the technological and economic difficulties surrounding the transition, and assessed the associated costs. Using the government's current fuel cell roadmap, we determined that business incentives, pilot government fleets, educational programs, and further increased CAFE and emissions standards can help make the hydrogen economy a reality.

22.1.2 HDV

In conclusion to our research and analysis, we believe that transit buses provide an ideal starting point for the hydrogen transition for numerous reasons. The size of transit buses allows them to more easily accommodate the bulky nature of prototype fuel cells and hydrogen storage tanks. Size is less of a limiting factor on larger vehicles, and the removal of size as a constraint on the prototype technology will enable it to develop more quickly. Also, the local, centralized, nature of transit bus fueling and maintenance greatly benefits early hydrogen technology, by reducing the amount of money that must be invested to develop the infrastructure at the beginning of the transition, and making use of shorter-range hydrogen technology as hydrogen storage issues are addressed (Levin et al, 2001 [165]). Furthermore, the high profile nature of transit buses will help maximize the public's exposure to hydrogen technology. Despite the fact that transit buses make up only 1% of the total vehicles on the road, a disproportionately large number of people interact with them each day. This makes transit buses an ideal way to raise awareness of hydrogen technology. In addition, the majority of transit buses operate in high traffic urban areas where pollution is a major issue, exactly the type of area where a zero-emissions technology is the most vital and will be most appreciated (Eudy et al, 2001 [145]). Lastly, transit bus fleets are, in nearly every case, subsidized by the government at the local, state, or federal levels. This counteracts one of the traditional faults of a new technology, its extremely high initial price.

It is important to note that not all heavy duty vehicles are a suitable launch pad for the hydrogen transition. For example, intercity trucking is one of the worst possible areas to begin the hydrogen transition. Intercity trucks cover long distances per trip, and require a correspondingly large fueling and maintenance infrastructure to support their transits. Intercity trucking is also a purely commercial venture, meaning that cost is an overriding concern.

Therefore, we recommend launching the hydrogen transition through the creation of new pilot programs for hydrogen buses and the expansion of programs that are already in operation. Additionally, we recommend the promotion of bridge technologies such as Hythane or hydrogen ICE buses in parallel with these pilot programs. These bridge technologies will help accelerate the growth of the hydrogen infrastructure. The combination of these programs will bring about the hydrogen transition in the quickest, most cost-effective way possible.

22.1.3 Gen H Power Park Design:

With the footprint of 21,000 sq. ft., Gen H Power Park is located at the southernmost tip of Shepherd Parkway, S.W, east of I-295 in Washington D.C.. It is designed to serve Washington D.C., Maryland, Virginia, and West Virginia Primary Metropolitan Area with an average distance of 14 miles from population centers. Based on analysis using LOCATOR software, the location of Gen H Power Park is only 500 ft away from our energy source, Blue Plains Wastewater Treatment Plant.

Blue Plains Wastewater Treatment Plant is the sole provider of biogas, a source of renewable energy. In order to meet the electricity and hydrogen requirements set by the National Hydrogen Association, Gen H acquires 102,900 scf/day of bio gas in 2010 to 178,500 scf/day in 2020. Producing hydrogen, Gen H Power Park utilizes the Steam Methane Reforming process (SMR) with subsequent pressure swing absorption because of its effective cost-saving property. The hydrogen harvested from the process is stored in a cascading storage system for dispensing. The storage system consists of 4 banks in which each bank stores 21kg of hydrogen at 6500 psig. Use of the low-maintenance SMR system from Harvest Energy Technologies, along with other cost-saving systems, enables Gen H to offer hydrogen at \$8.31/kg for vehicle use.

The remaining biogas acquired from Blue Plains Wastewater Treatment Plant is fed into a Proton Exchange Membrane (PEM) fuel cell for electricity generation to provide power for Gen H Power Park, as well as the neighborhood it serves. The commercial viability, low maintenance and operating costs of the PEM fuel cell help make Gen H Power Park economically competitive over other designs. The cost of electricity that Gen H charges the public is \$0.0865/kWh.

Another great advantage of Gen H Power Park is its low probability of accidents, enabling workers to enjoy a relatively accident-free environment. Failure Modes and Effects Analysis (FMEA) and Fault Tree analysis are used to identify 54 different failure modes, and to mitigate the 4 modes most susceptible to accident occurrence. New safety measures and controls, such as spark-free equipment, insulating materials, and a security alarm system directly connected to police department, are in place to effectively prevent Gen H Power Park from catastrophic failures and terrorism attacks.

From the community perspective, Gen H Power Park is designed to be environmentally friendly. Since the energy source is biogas, the only emission is CO_2 from the power swing absorber and the steam reformer. The total emission in 2010 is $1.74 * 10^6$g. However, the process is carbon-neutral due to the fact that the input source is not fossil fuel, but biogas, which is renewable.

In order to promote the hydrogen economy, Gen H Power Park has to have a whole range of marketing and education plan. Academic modules are designed to instill hydrogen economy knowledge to different levels of education. Competitions such as H_2 Challenge, toy lines with Lego Inc., and free fuel coupons, along with other campaigns, will be used to educate the public about hydrogen and increase sales of Gen H, the future of hydrogen economy.

22.1.4 Washington D.C. Rollout

A great deal of information and consideration is needed in order to implement a fully functional and efficient network. Sources like census data and surveys of public opinion will be a necessity to ensure success. Like any complex system, the network will not operate unless the users desires and behavior are taken into account. Accurate demand projections and cooperation with automakers will be a necessity. To maximize acceptance, the interface must be simple and as convenient as possible. A good benchmark will be the most current gasoline technologies. Any sharp increase in the time or complexity of the refueling process will only hinder public acceptance.

Studies suggest that the infancy of the hydrogen transition will take place within the current gasoline infrastructure. Many of the major oil companies have already begun to anticipate this switch, and have conducted extensive research into the process of converting the industry from oil to natural gas and hydrogen. To begin with, a percentage of gasoline stations will have hydrogen pumps added to them. It is believed that this will enable customers to easily see the availability of hydrogen, while reducing the overall construction costs. Research suggests that an appropriate threshold would be 10% of the gasoline stations in service. For the city of Washington, this is about 11 stations.

The cost of this program is widely dependent on the capacity and design of the new stations. Larger capacity and on-site production stations will, in general, cost more than their off-site and smaller companions. Cost will also be dependent on the time when the first stations are constructed, and the development of hydrogen technologies at that time. This study has determined that an off site production station with a capacity of 500 Nm^3/h in the year 2020 will cost between $1.2 million and $1.8 million, depending on the number being constructed and the current level of technology. At this level of investment, a selling price of $3.44/kg of H_2 will result in a successful business model over a 15 year life cycle.

Overall success of the network will be determined by its ability to balance the two objectives of reducing cost and increasing support for hydrogen fuel cell vehicle owners in the beginning. Over time, a successful network will allow users to easily locate stations at which they can quickly refuel. It will also have management of its growth such that expansion with demand will occur in a seamless way.

Without question, management is especially crucial in this phase of the hydrogen transition. Market forces alone can not be expected to facilitate the implementation of an effective network. One company can not be expected to manage the transition alone. The process will require the cooperation of many companies, and most likely, the council of governments for the Washington, DC area as well.

22.2 Recommendations

After completing our research, our group has determined a number of topics related to the hydrogen economy that could be researched further. These topic areas are as follows:

1. Economic and socio-political analysis of potential government incentive plans and their impact on the hydrogen transition.
2. In-depth research to determine U.S. cities that would be viable candidates for hydrogen-powered fleets, based on their proximity to sources of renewable energy and other factors.
3. Quantitative analyses of other fleet-based vehicles to determine if the transition to hydrogen power is feasible.
4. In-depth analysis on the benefits of high-pressure hydrogen storage tanks and metal hydrides.
5. Refine and implement network simulation model to improve performance.
6. Obtain more accurate information pertaining to fuel cell cost, storage system cost, and balance-of-system cost to improve accuracy of cost models.
7. Further exploration into alternative green sources of hydrogen production.
8. Examine requirements for national infrastructure, focusing on possible expansion of pilot programs to satisfy these requirements.
9. Analysis of the American public's perception to hydrogen as well as ways to improve awareness.
10. Detailed risk analysis and risk management plan for hydrogen infrastructure.

Chapter 23

Reflections

23.1 HEV

Nicole Kalb

My role in this project was a researcher on the Hybrid-Electric Vehicles (HEV) team. The HEV team, consisting of Ghan, Peng, and myself, was organized very informally, with the team manager coordinating actions between the other teams. We all contributed equally to both the research and the direction of the project, which helped gain buy-in. Our initial focus on planning and scheduling prevented us from spending too much time to any one topic, yet enabled us to guide the direction of our research as the project progressed. I was also lucky enough to work with two incredible teammates who were both very enthusiastic and dedicated to the project, and the group benefited from their consistent hard work throughout the fall semester and winter session.

Ghan Patel

When I decided to join this research group, I was both excited and curious. I had never been a part of a large scale research team, and had only classroom experience with the research tools we would use: forecasting, modeling, simulation, to name a few. I found that our initial designs and research work were significantly altered by the time we reconvened during the winter. I suppose every important journey involves retracing steps to find the best path to ones destination.

I learned a lot from this experience, and believe I got what I wanted out of it. I wanted to develop my public speaking abilities, apply my classroom knowledge of analysis techniques, and learn more about the world of alternative fuels. Every one of these goals was met and I feel that the time and effort I spent for the group was not unrewarded.

I enjoyed the company, friendship, and teamwork of my fellow group mates. They were all hardworking, intelligent individuals eager to help and learn together. Managing the HEV team was made easy by having such cooperative and knowledgeable members as Peng Wei and Nicole Kalb. Finally, our professor, Francis Vanek, gave us invaluable help and support. Without his leadership and insight, our team would have floundered.

Peng Wei

My role as the project manager for the hydrogen transition team has been the most rewarding part of my research experience. Throughout the project the team faced many hard decisions and difficulties. I was extremely fortunate to be able to work closely with a group of highly intelligent and dedicated members.

Our hydrogen research was conducted through four individual teams. The Hybrid Electric Team investigated the impact of hybrid electric vehicles on the fuel cells. The Heavy Duty Vehicle Team focused on heavy duty vehicles such as fuel cell public transit buses. The Contest Team researched on hydrogen productions, and the Washington D.C. Team looked at the distribution of hydrogen fuel in the D.C. areas. Each team was led by a team manager who oversees the overall progress of the team.

Besides being a project manager, I was also a member of the HEV team. I conducted research on the current battery technology, diesel technology and government policies. The other two members of the team are Ghan and Nicole and we worked very effectively as a team.

The most important lesson I learned from the project was how to build trust. The existence of team trust was absolutely crucial in making a cohesive and productive working unit. The most effective way of building trust, I found, was to allow all team members to voice their visions and concerns, and to give them plenty of autonomy in working as a team.

Everyone has weaknesses, yet with unquestionable trust and unselfish personal sacrifices we were able to build a powerful team out of our finest strength and skills.

23.2 HDV

Frederic Bruneau

The HDV team consisted of Dan, Jon, and I. Dan was nominated as the team leader making Jon and I group members. I mainly worked on research of the Transition requirements for HDV such as the infrastructure, reconfiguration, and future fuel cell technologies. Our team seemed to get along really well. Dan delegated the work in a responsible matter, making sure me and Jon had enough work but not too much. I felt that our team was well organized and that we scheduled our work in a timely fashion. Due to the loose structure of our team, we were able to get most of our work done ahead of schedule, which also enabled us to use our creativity. I learned that in project management it is important to know when to micro manage and when not to. At the start of the project Dan did not feel necessary to micro manage our group, therefore letting us search for large amounts of material on the internet. Toward the end of the project micro management helped in order to meet the deadlines. I also felt that the communication between the groups was open, in such a way that any member from any group could request information without having to go through the team managers. The Friday evening happy hours also contributed to the cohesiveness of the individual teams as well as the entire project team.

Daniel Chituc

As the HDV team manager I would like to first and foremost thank Jon and Fred for being such phenomenal team members. Our work would not have gone as smoothly, or been of as high quality, without you both. It has been a privilege to be your manager for this project.

With that said, I would like to discuss some of the more important lessons I feel I have learned over the course of our work. The most worthwhile things I feel I have gained are those practical lessons that can only be learned by actually leading. First among these lessons is the need to know the tendencies and personalities of your team members and, as much as possible, match these innate abilities to the tasks that need to be done.

I also cannot emphasis enough the benefits of being more easy going and allowing your team members to guide their own work when possible. This will lead to both your team and yourself being more relaxed and will instill a greater sense of team. Then, when the situation requires a more authoritarian style of management the negative aspects of this style will hopefully be mitigated, as your team will understand it is the situation that requires the changes, and not capricious or poor management. I feel it was this more than anything else that set the entire tone for our teams interactions and made it such an enjoyable work environment.

Jon Leisner

My role in the HDV was that of a team member. In this role, I felt that the group had open and effective lines of communication with the group leader throughout the project. Tasks were assigned fairly democratically, without complaint from any team member. The team was not micro-managed, and I feel that this led to results being ahead of schedule, as members of the team were internally motivated to work, as opposed to being forced to work. I feel that this also led to our groups ability to fully learn about the material we were researching.

I think that the only thing we should have done differently would have been to take notes on the materials that we had researched earlier and at intervals. It was extremely difficult for us to read and take notes on 125 documents in about 5 days to prepare for writing the paper. Perhaps we, as a group, could have managed this better.

I learned that there's not much of a difference between the work ethic of a hard-working sailor and the work ethic of a graduate-level college student. Thus, the leadership skills that enable one to lead sailors effectively, for instance, the ability to have trust in the talents of others, the ability to delegate tasks effectively, and the ability to provide assistance and motivation, when needed, are also applicable in the project setting. I feel that the leaders in this project did a great job of attempting to balance project tasks with the needs of the members of the project.

Lastly, I feel that the happy hours that were organized throughout the project did an excellent job of helping to jell the nucleus of the team, particularly in January, when much of the grunt work had to be accomplished. It was nice to interact with my fellow project members in a social setting, in order to understand the different cultures, backgrounds, and interests that were represented. This helped me gain an understanding of everyone's talents and motivation, and I am certain that others in the group would agree with me.

23.3 Washington D.C. Rollout

Koji Akeno

I really enjoyed working for this project with our group members. We were self-motivated, dedicated and proactive. In collaboration with each other, all members devoted to the success of this project. We were always considerate for each other, leading to derive our excellent abilities from each. That is the most important thing that I have again realized. Another important thing is that I have learned how to cope with unfamiliar matters in the project. I had anxiety to the project at the beginning because I did not have any knowledge about hydrogen fuel. Through the project, I have developed skills for gathering and analyzing information. This project was a really good opportunity to use our knowledge that I had acquired.

I was glad to introduce Japans hydrogen project to our project. I did not know Japan has already developed 9 hydrogen stations before I joined this project. Now that I noticed Japanese auto manufacturers are eager to develop HFCVs as well. So, I hope that I will be the first to own a HFCV among our project members.

Dan Herstine

Kang, Koji and I worked together on the DC team. Though I didnt have any aspirations of being a team leader, I was elected because I think Kang and Koji were unsure about their communication skills and felt I could interact better with the other team managers and our advisor. Perhaps because of this, I made communication a top priority in my managerial duties. I quickly learned the value of understanding, and the consequences when it was absent. I tried to always be absolutely clear in what I said and my team and I often engaged in open discussion to make sure that everyone was on the same page. It was very important to me that I allow information to flow easily from my team members to my fellow team leaders and the advisor. I hope very much that I succeeded in at least this aspect of my management.

In the larger scheme, I felt that the group as a whole worked very well together. The atmosphere on the project as well as in the classes we shared was always one of openness and helpfulness. It pains me to think that I might not see some of these people nearly as often in the office, as I enjoyed the camaraderie as well as the extra support system. I think our advisor Francis can take some credit for this, as he always stressed the importance of cooperativeness over competitiveness and friendliness over formality.

If I had the chance to redo the project, I would have done more detailed planning at the beginning. While its hard to know what the final scope is going to be on such a dynamic project, I feel like we could have done a better job of anticipating some of the delays and getting some of the more tedious tasks out of the way before the winter session began. However, I am not disappointed at all in the final project that we presented. There were times when I was simply amazed at how dedicated and efficient my team could be. I feel like we did a fantastic job throughout, and I would welcome the chance to work with Kang and Koji again.

Kang-Wei Hsiao

Our team is an international team; members come from different countries with the same passion for our project. We worked together for moths and demonstrated the unrivaled esprit de corps from stem to stern. As a staff in DC team, the best thing that worked well for me was communication mechanism. Because of well communication, diversity in opinion became not an obstacle in the way but an opportunity to the prime. Everyones ideas would be respected and discussed conscientiously;

the sparkle of our team then kept flaming. Our team is really the one with self-motivation, efficiency and competitiveness in a harmony atmosphere. I learned much not only from this project but also from my teammates. Every time when we were together and discussing, I was so confident that any problem would be gone and then new ideas popped up. This is a good example of how a global team in a project should work to success and I am glad to be part of it.

23.4 Gen H Power Park

Walter Chen

The Contest Team organized itself around the contest. Jason was named the team leader in charge of communicating with the other groups. JJ handled most of the internal group management, doing a lot of work delegation and scheduling and the sort. Each team member was put in charge of a particular subject area within the project. For instance, I was named Lead Environmental Analyst. Accordingly, a large part of my role was making sure that the environmental analysis was completed properly. However, I, like the other team members, also supported the leaders of other sections. I did some safety analysis research as well as contributing to the discussions surrounding the technical design. Because of my proficiency with LaTeX, I took charge of assembling the final document, editing it for composition, and typesetting it according to the contest specifications. Generally, this worked out well for our team, as things proceeded smoothly.

However, some problems did present themselves. For example, while we each took charge of separate parts of the project, we oftentimes did not check over each others' work. By the time we checked things over, the project was nearing its deadline. In effect, this compounded the amount of work necessary to complete the project prior to the deadline. In terms of what I would have done differently for next time – I would have more vigorously tried to meet our schedule which indicated that we were to be completely done with research prior to Christmas break. Then, we would have had all of the winter session to polish up our final product.

Learning from one's mistakes is an important part of management. Per the statements above, I have indicated a few mistakes, which I should not like to repeat. As far as people are concerned – it is easy to work with people who are as highly self-motivated and intelligent as my power park colleagues. However, even then, such people (including myself) need a kick in the pants.

Perla Lastra

The team was sub-divided into 5 focus areas: Technical Design, Environmental Analysis, Economic Analysis, Marketing & Education, and Safety Analysis. Though we all collaborated with ideas and research in these areas, I was in charge of the Marketing & Education Plan as well as a section in the Technical Design regarding the power parks location.

All team members were dedicated and open to suggestions, willing to be flexible and adapt to situations as needed. We worked effectively together.

Planning out the necessary project tasks more thoroughly would have saved some time as well as provided more direction in critical moments. Time is of the essence in this particular project, since the National Hydrogen Association contest deadline is a crucial two weeks before the final M Eng. group deadline. Never underestimate the time it takes to compile a final version of the report.

It is always challenging to juggle the many classes and commitments of a group's members in order to find appropriate meeting times, work methods, and measures of performance. Nevertheless, the effort can be very rewarding if done so properly.

This project is highly inter-disciplinary. It offers great opportunities in systems engineering, project management, business administration, and performance analysis.

Jason Leung

Being a team leader for the contest team, my role had several functions. In terms of the Gen H Power Park design, I was in charge of the safety analysis and assisted in technical design and economic analysis. From a project management perspective, I had to ensure all the design requirements were met, designated roles to members according to interests and strengths and made sure the team was on track. Managing the team gave me a good experience of how the team dynamics works and how to influence people without using authority.

As a team, we had a very diverse group of members in terms of interests and majors. The diversity helped us accomplish all parts of the design. Although there were conflicts in dealing with technical designs and formatting, all obstacles were overcome peacefully and objectively. If we were given another chance, we should finish all the research and to start the write-up earlier such that we would not have to stress at the late stage of the project. The most important thing that I learned was listen to all opinions from all members and pick the best option for the team. When a member had a concern, he or she should let the whole group know such that the group could acknowledge it and make corresponding accommodation.

After all, I would like to thank my team for being such a good team striving for the same goal.

Joseph W. Schwarz IV

The Gen H Power Park design team was organized into the five different areas. I was in charge of the Technical Design portion of the power park design. While, each of us was put in charge of a certain section, everyone participated in all aspects of the report.

We worked well with each other and seemed to really share ideas and research amongst the group well.

I think we should have worked a little earlier in the process. We should have afforded more time and effort in contacting manufacturers as well as looking at the different parts of the report (economic, safety, and environmental) earlier in the process.

The most important thing about a project like this is getting a good schedule and plan together and then work the plan. We could have done a better job at this, saving us a lot of headache later in the project.

Everyone has a their own ideas about how certain things should be done, and as a group you have to get the ideas out on the table so the group can acknowledge them.

Overall, I thought this was a really good project. The team interactions and transitions could have been smoother. I would recommend this project to anyone who is interested in applying a multitude of systems engineering skills to a project.

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Appendix A

Hybrid vs Direct Path Comparison Parameters

Direct Path Parameters/Constants			
	FC Penetration Parameters		
	Penetration Start	**2020**	
	Penetration Cross	**2040**	
	Penetration End	**2060**	
Constants:			
FC MPG equivalent =		**29.5**	
energy/mi for FCV =		**4063728.8**	J/mi
1 gallon of gas = 1 gge =		**120287300**	J
CO2 in 1 Joule from H2		**10.8**	kg
CO2 in 1 gallon gasoline		**9.46**	kg
Hybrid Path Parameters/Constants			
	FC Penetration Parameters		
	Penetration Start	**2030**	
	Penetration Cross	**2055**	
	Penetration End	**2070**	
Constants:			
FC MPG equivalent =		**38.8**	
energy/mi for FCV =		**3089690.7**	J/mi
1 gallon of gas = 1 gge =		**120287300**	J
CO2 in 1 Joule from H2		**10.8**	kg
CO2 in 1 Joule from gasoline		**9.46**	kg

Appendix B

HDV Appendix

B.1 Historical Bus Data

Year	Number of Buses
1960	49600
1970	49700
1980	59411
1990	58714
1994	68123
1995	67107
1996	71678
1997	72770
1998	72142
1999	74228
2000	75013
2001	76075

B.2 Bus Forecast By Year

Year	Forecast
1960	49600
1970	49700
1980	59411
1990	58714
1994	68123
1995	67107
1996	71678
1997	72770
1998	72142
1999	74228
2000	75013
2001	76075
2002	77618
2003	78835
2004	80052
2005	81268
2006	82485
2007	83702
2008	84919
2009	86136
2010	87353
2011	88570
2012	89786
2013	91003
2014	92220
2015	93437
2016	94654
2017	95871
2018	97088
2019	98304
2020	99521
2021	100738
2022	101955
2023	103172
2024	104389
2025	105606

Year	Forecast
2026	106822
2027	108039
2028	109256
2029	110473
2030	111690
2031	112907
2032	114124
2033	115340
2034	116557
2035	117774
2036	118991
2037	120208
2038	121425
2039	122642
2040	123858
2041	125075
2042	126292
2043	127509
2044	128726
2045	129943
2046	131160
2047	132376
2048	133593
2049	134810
2050	136027
2051	137244
2052	138461
2053	139678
2054	140894
2055	142111
2056	143328
2057	144545
2058	145762
2059	146979
2060	148196

B.3 30% Growth Rate Scenario

Year	Hydrogen
1960	0
1970	0
1980	0
1990	0
1994	0
1995	0
1996	0
1997	0
1998	0
1999	0
2000	0
2001	0
2002	0
2003	0
2004	0
2005	10
2006	11
2007	14
2008	18
2009	23
2010	30
2011	40
2012	52
2013	67
2014	87
2015	114
2016	148
2017	192
2018	250
2019	324
2020	421
2021	547
2022	710
2023	920
2024	1193
2025	1544

Year	Hydrogen
2026	1998
2027	2580
2028	3328
2029	4284
2030	5501
2031	7042
2032	8980
2033	11399
2034	14387
2035	18034
2036	22420
2037	27605
2038	33612
2039	40413
2040	47921
2041	55985
2042	64398
2043	72924
2044	81320
2045	89369
2046	96899
2047	103795
2048	110003
2049	115517
2050	120370
2051	124620
2052	128336
2053	131592
2054	134460
2055	137006
2056	139286
2057	141350
2058	143240
2059	144991
2060	146630

B.4 40% Growth Rate Scenario

Year	Hydrogen
1960	0
1970	0
1980	0
1990	0
1994	0
1995	0
1996	0
1997	0
1998	0
1999	0
2000	0
2001	0
2002	0
2003	0
2004	0
2005	10
2006	11
2007	16
2008	23
2009	32
2010	44
2011	62
2012	87
2013	122
2014	172
2015	240
2016	337
2017	471
2018	659
2019	922
2020	1287
2021	1794
2022	2495
2023	3462
2024	4787
2025	6586

Year	Hydrogen
2026	9005
2027	12210
2028	16378
2029	21673
2030	28201
2031	35969
2032	44834
2033	54492
2034	64510
2035	74402
2036	83726
2037	92161
2038	99538
2039	105828
2040	111105
2041	115496
2042	119152
2043	122217
2044	124821
2045	127071
2046	129052
2047	130833
2048	132464
2049	133985
2050	135424
2051	136804
2052	138140
2053	139443
2054	140724
2055	141987
2056	143237
2057	144479
2058	145714
2059	146944
2060	148170

B.5 Pessimistic Scenario (20% Growth Rate)

Year	Hydrogen
1960	0
1970	0
1980	0
1990	0
1994	0
1995	0
1996	0
1997	0
1998	0
1999	0
2000	0
2001	0
2002	0
2003	0
2004	0
2005	10
2006	489
2007	685
2008	959
2009	1341
2010	1871
2011	2604
2012	3613
2013	4992
2014	6856
2015	9348
2016	12621
2017	16831
2018	22100
2019	28481
2020	35911
2021	44186
2022	52971
2023	61849
2024	70402
2025	78296

Year	Hydrogen
2026	85320
2027	91397
2028	96553
2029	100883
2030	104512
2031	107569
2032	110173
2033	112428
2034	114416
2035	116203
2036	117840
2037	119365
2038	120808
2039	122191
2040	123529
2041	124835
2042	126117
2043	127381
2044	128632
2045	129875
2046	131110
2047	132340
2048	133567
2049	134791
2050	136013
2051	137234
2052	138453
2053	139672
2054	140890
2055	142108
2056	143326
2057	144543
2058	145761
2059	146978
2060	148195

B.6 DOT Front Loaded Scenario

Year	Number of Buses
1960	49600
1970	49700
1980	59411
1990	58714
1994	68123
1995	67107
1996	71678
1997	72770
1998	72142
1999	74228
2000	75013
2001	76075

B.7 DOT Rapid Growth Scenario

Year	Hydrogen
1960	0
1970	0
1980	0
1990	0
1994	0
1995	0
1996	0
1997	0
1998	0
1999	0
2000	0
2001	0
2002	0
2003	0
2004	0
2005	10
2006	22
2007	47
2008	101
2009	218
2010	470
2011	1008
2012	2147
2013	4512
2014	9220
2015	17874
2016	31706
2017	49612
2018	67521
2019	81536
2020	90756
2021	96367
2022	99829
2023	102150
2024	103901
2025	105373

Year	Hydrogen
2026	106712
2027	107987
2028	109231
2029	110461
2030	111684
2031	112904
2032	114122
2033	115340
2034	116557
2035	117774
2036	118991
2037	120208
2038	121425
2039	122642
2040	123858
2041	125075
2042	126292
2043	127509
2044	128726
2045	129943
2046	131160
2047	132376
2048	133593
2049	134810
2050	136027
2051	137244
2052	138461
2053	139678
2054	140894
2055	142111
2056	143328
2057	144545
2058	145762
2059	146979
2060	148196

B.8 Historical Vehicle Miles Traveled for Transit Buses

Year	Bus VMT (million)
1960	1576
1970	1409
1980	1677
1990	2130
1994	2162
1995	2184
1996	2221
1997	2245
1998	2175
1999	2276
2000	2315
2001	2377

B.9 Historical Energy Consumption for Transit Buses

Year	Bus Energy (Trillion BTU)
1985	116
1990	124
1991	120
1992	122
1993	129
1994	134
1995	134
1996	137
1997	142
1998	144
2000	154

B.10 Major Bus and Trolleybus Agency Vehicle Data, Fiscal Year 2002

Atlanta, GA	Metropolitan Atlanta Rapid Transit Authority	712
Austin, TX	Capital Metropolitan Transportation Authority	497
Baltimore, MD	Maryland Transit Administration	1,010
Boston, MA	Massachusetts Bay Transportation Authority	1,067
	Bus	1,043
	Trolleybus	24
Buffalo, NY	Niagara Frontier Transit Metro System	317
Charlotte, NC	Charlotte Area Transit System	271
Chicago, IL	Regional Transportation Authority	2,750
	Chicago Transit Authority	2,013
	PACE Suburban Bus	737
Cincinnati, OH	Southwest Ohio Regional Transit Authority	432
Cleveland, OH	Greater Cleveland Regional Transit Authority	748
Columbus, OH	Central Ohio Transit Authority	298
Dallas, TX	Dallas Area Rapid Transit Authority	980
Dayton, OH	Greater Dayton Regional Transit Authority	243
	Bus	186
	Trolleybus	57
Denver, CO	Regional Transportation District	1,134
Detroit, MI	City of Detroit Department of Transportation	548
Detroit, MI	Suburban Mobility Authority for Regional Transportation	283
El Paso, TX	El Paso Mass Transit Department	159
Ft. Lauderdale, FL	Broward County Division of Mass Transit	324
Ft. Worth, TX	Fort Worth Transportation Authority	141

Hartford, CT	Connecticut Transit	392
Honolulu, HI	City and County of Honolulu Department of Transportation Services	525
Houston, TX	Metropolitan Transit Authority of Harris County	1,408
Indianapolis, IN	Indianapolis Public Transportation Corporation	151
Jacksonville, FL	Jacksonville Transportation Authority	168
Kansas City, MO	Kansas City Area Transportation Authority	282
Las Vegas, NV	Regional Transportation Commission of Southern Nevada	304
Long Beach, CA	Long Beach Transit	224
Los Angeles, CA	City of Los Angeles Department of Transportation	256
Los Angeles, CA	Foothill Transit	299
Los Angeles, CA	Los Angeles County Metropolitan Transportation Authority	2,643
Louisville, KY	Transit Authority of River City	276
Memphis, TN	Memphis Area Transit Authority	221
Miami, FL	Miami-Dade Transit Agency	969
Milwaukee, WI	Milwaukee County Transit System	501
Minneapolis, MN	Metropolitan Council	1,255

	Metro Transit	980
	Metropolitan Council	275
New Orleans, LA	Regional Transit Authority	364
New York, NY	Metropolitan Transportation Authority	4,832
	MTA Long Island Bus	336
	MTA Metro-North Railroad	10
	MTA New York City Transit	4,486
New York, NY	New York City Department of Transportation	1,296
Newark, NJ	New Jersey Transit Corporation	2,186
Norfolk, VA	Transportation District Commission of Hampton Roads	322
Oakland, CA	Alameda-Contra Costa Transit District	779
Oceanside, CA	North San Diego County Transit Development Board	154
Orlando, FL	Central Florida Regional Transportation Authority	244
Philadelphia, PA	Southeastern Pennsylvania Transportation Authority	1,425
	Bus	1,359
	Trolleybus	66
Phoenix, AZ	City of Phoenix Public Transit Department	462
Pittsburgh, PA	Port Authority of Allegheny County	1,055
Portland, OR	Tri-County Metropolitan Transportation District of Oregon	695

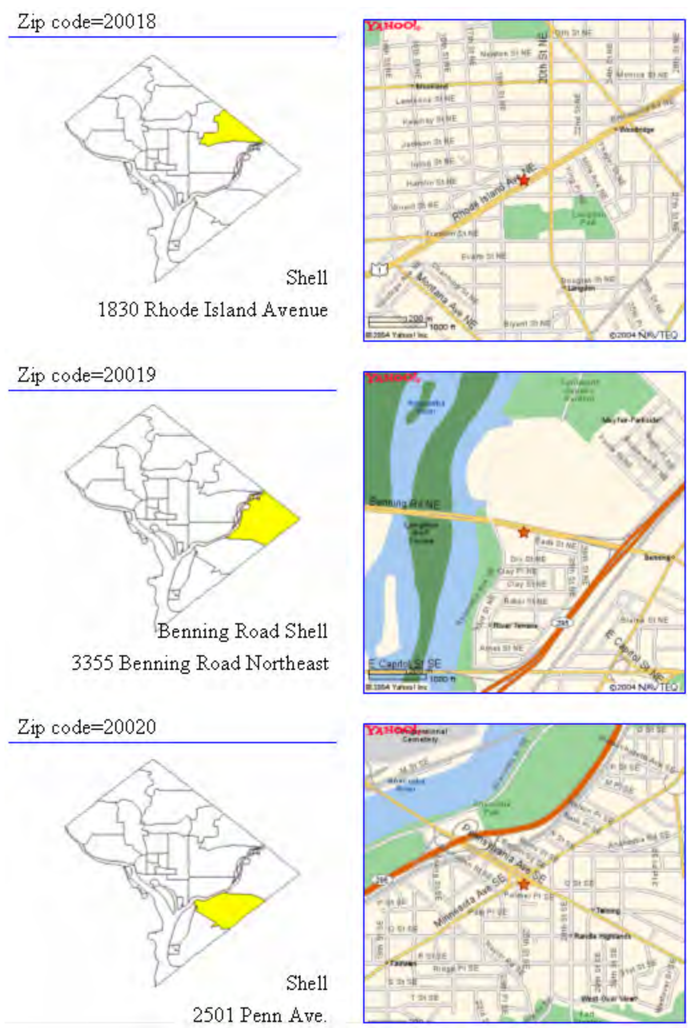
Providence, RI	Rhode Island Public Transit Authority	190
Riverside, CA	Riverside Transit Agency	132
Rockville, MD	Montgomery County Ride-On	317
Sacramento, CA	Sacramento Regional Transit District	214
St. Louis, MO	Bi-State Development Agency	473
St. Petersburg, FL	Pinellas Suncoast Transit Authority	172
Salt Lake City, UT	Utah Transit Authority (b)	442
San Antonio, TX	VIA Metropolitan Transit	499
San Bernardino, CA	Omnitrans	179
San Diego, CA	San Diego Metropolitan Transit System	557
	County of San Diego Transit System	102
	Metropolitan Transit Development Board	121
	San Diego Metropolitan Transit System	334
San Francisco, CA	Golden Gate Bridge, Highway and Transportation District	278
San Francisco, CA	San Francisco Municipal Railway	927
	Bus	577
	Trolleybus	350
San Francisco, CA	San Mateo County Transit District	332
San Jose, CA	Santa Clara Valley Transportation Authority	524
San Juan, PR	Metropolitan Bus Authority	313
Santa Ana, CA	Orange County Transportation Authority	592

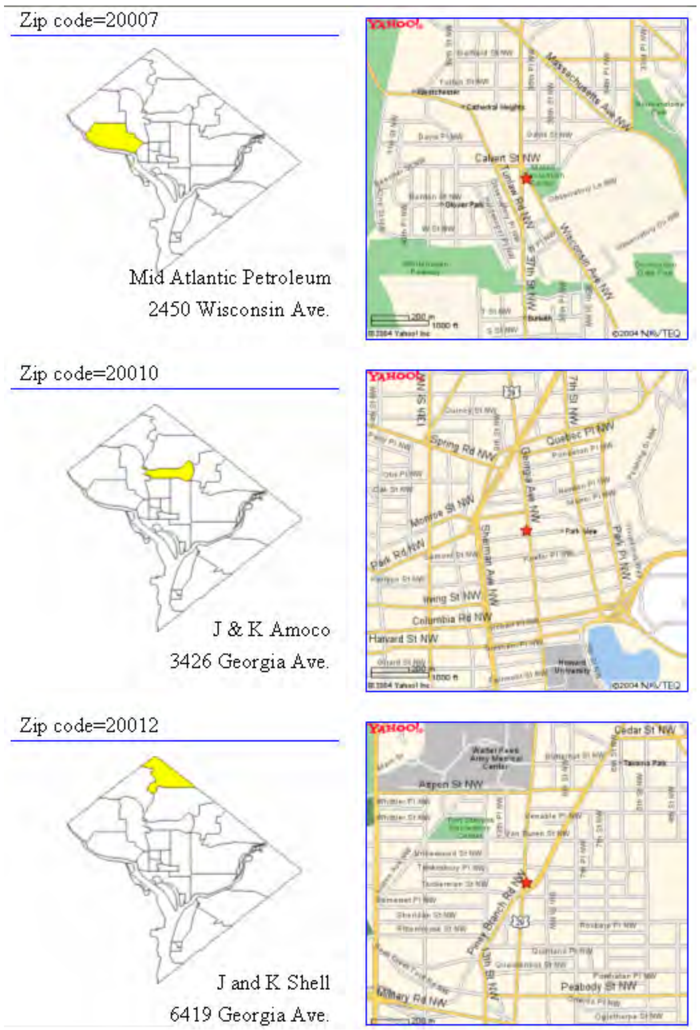
Santa Monica, CA	Santa Monica's Big Blue Bus	216
Seattle, WA	King County Department of Transportation	1,110
	Bus	991
	Trolleybus	119
Seattle, WA	Snohomish County Public Transportation Benefit Area Corporation	308
Springfield, MA	Pioneer Valley Transit Authority	190
Tacoma, WA	Pierce Transit	249
Tampa, FL	Hillsborough Area Regional Transit Authority	NA
Tucson, AZ	City of Tucson Transit System	199
Washington, DC	Washington Metropolitan Area Transit Authority	1,442
White Plains, NY	Westchester County Department of Transportation	357
Wilmington, DE	Delaware Transit Corporation	202

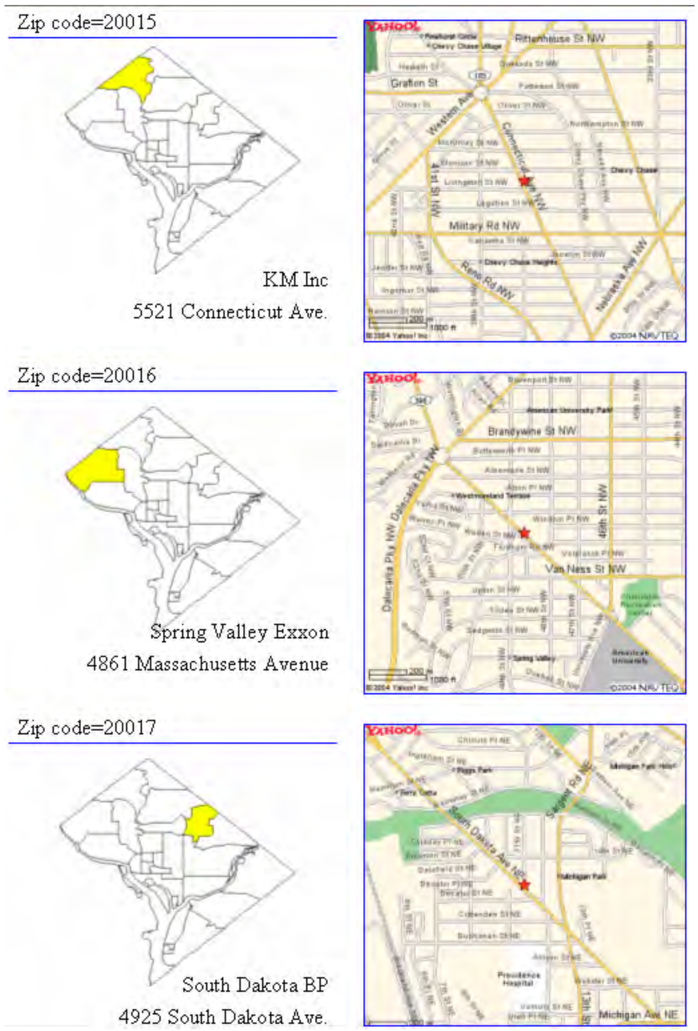
Appendix C

Station Placement in Phases

C.1 Station for Phase I




Zip code=20007
Mid Atlantic Petroleum
2450 Wisconsin Ave.
Zip code=20010
J & K Amoco
3426 Georgia Ave.
Zip code=20012
J and K Shell
6419 Georgia Ave.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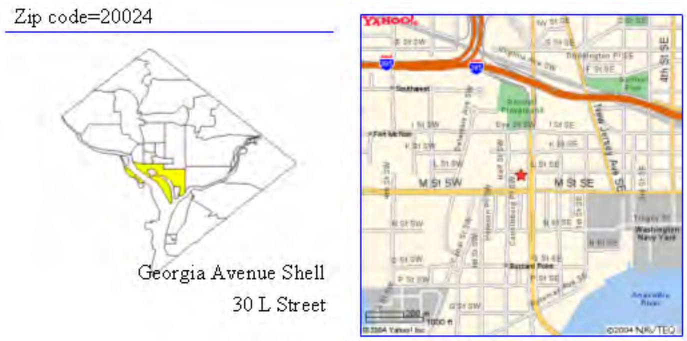
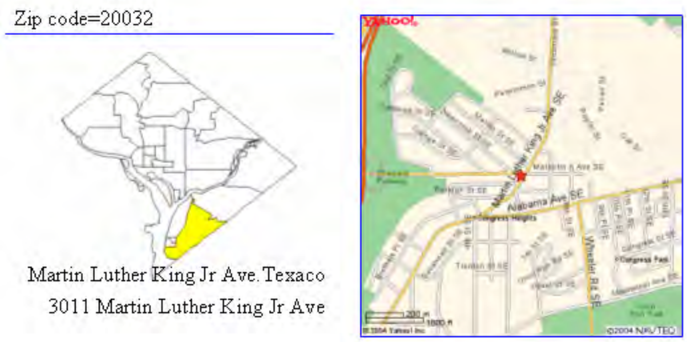
KM Inc
5521 Connecticut Ave.
Zip code=20016
Spring Valley Exxon
4861 Massachusetts Avenue
Zip code=20017
South Dakota BP
4925 South Dakota Ave.

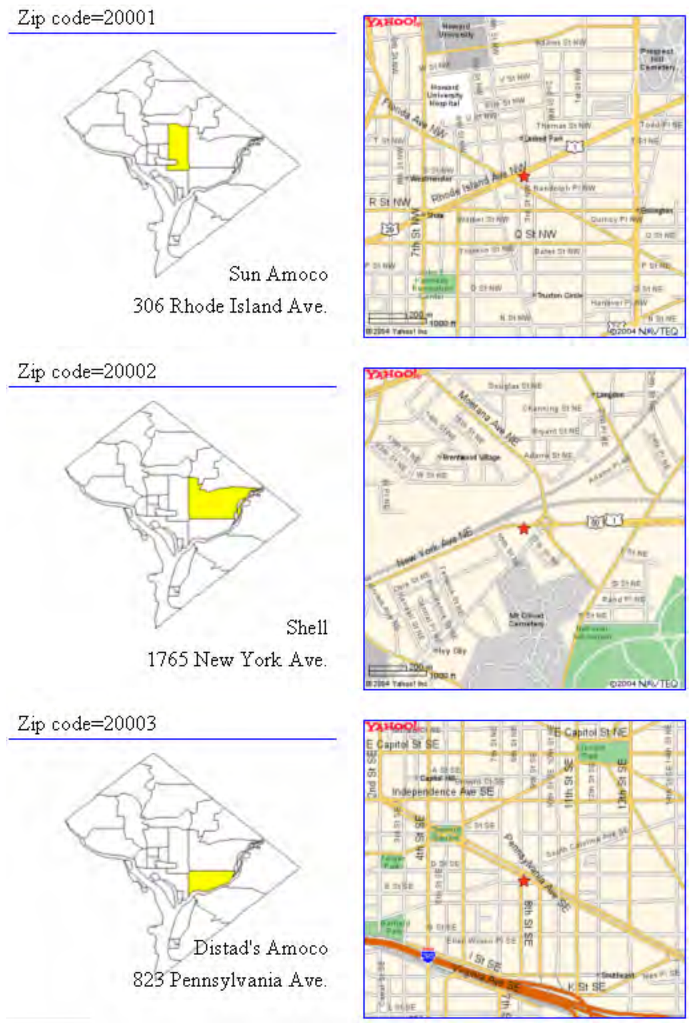


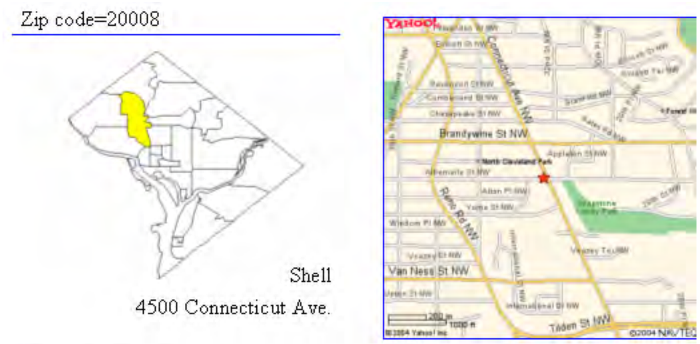


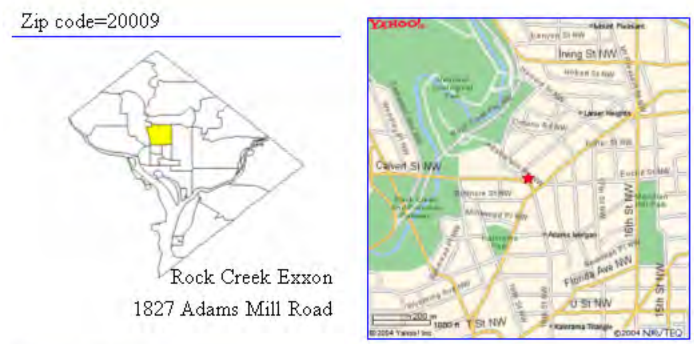
The stations above are suggested for hydrogen transition in phase I.

The brand names address may change due to the companies' decision in reality.

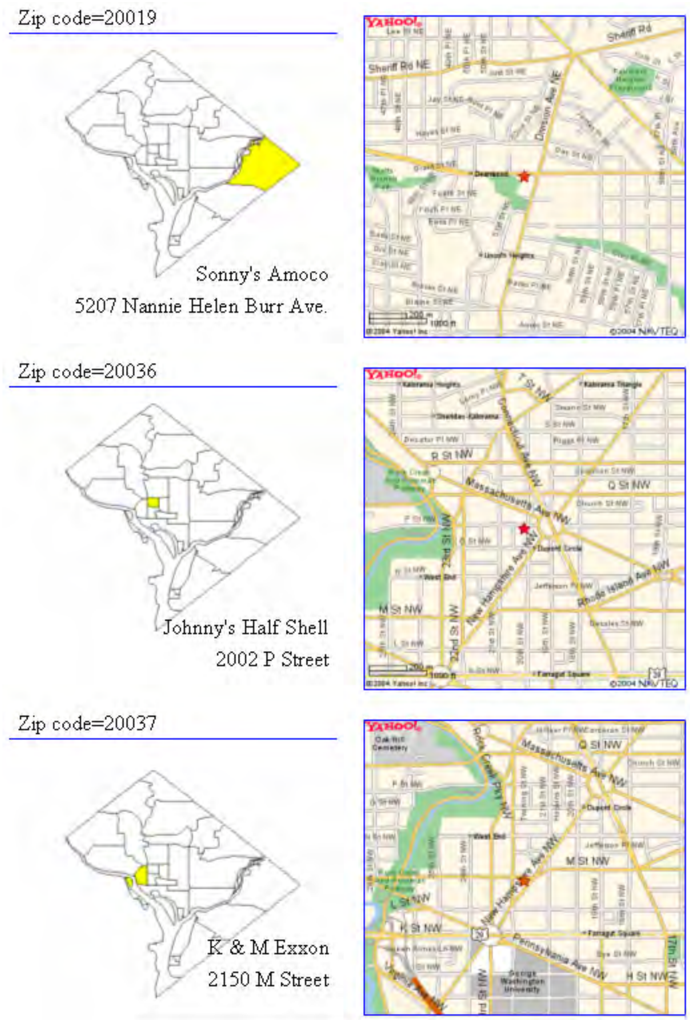
C.2 Station for Phase II




Zip code=20008
Shell
4500 Connecticut Ave.
Brandywine St NW
Van Ness St NW
Tilden St NW

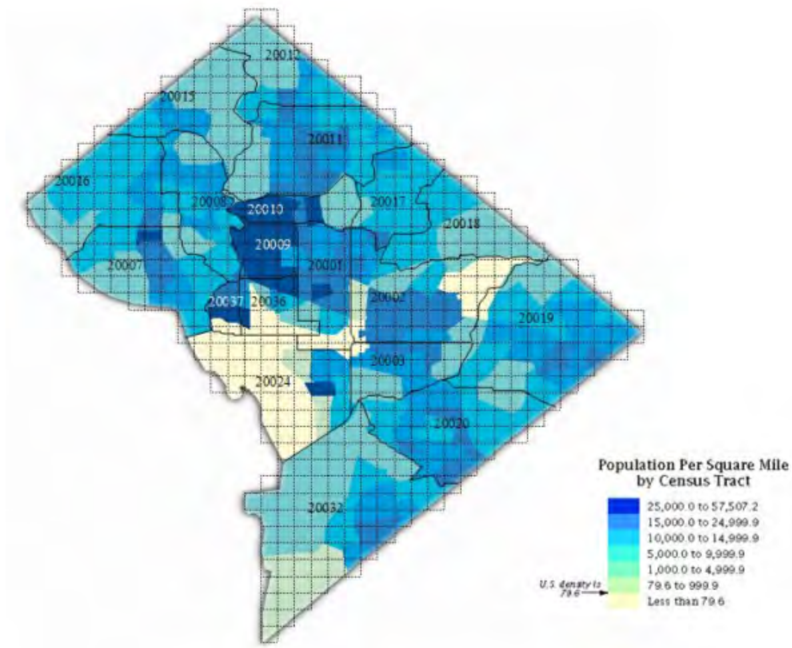

Zip code=20009
Rock Creek Exxon
1827 Adams Mill Road
Calvert St NW
Irving St NW
U St NW
T St NW


Zip code=20011
Miller Brothers Exxon
264 Missouri Ave.
Peabody St NW
Missouri Ave NW
Gallatin St NW



The stations above are suggested for hydrogen transition in phase II.

The brand names address may change due to the companies' decision in reality.


20012
20015
20011
20016
20008
20010
20017
20018
20009
20007
20001
20037
20036
20002
20019
20003
20024
20020
20032
Population Per Square Mile
by Census Tract
25,000.0 to 57,507.2
15,000.0 to 24,999.9
10,000.0 to 14,999.9
5,000.0 to 9,999.9
1,000.0 to 4,999.9
79.6 to 999.9
Less than 79.6
U.S. density is 79.6

Appendix D

Contest Appendix

D.1 CASCADE v3.0 Software

The CASCADE software helps in assessing the performance of a cascade-type ground storage system. It effectively determines the ability of the power park to meet the daily required amount of hydrogen needed for dispensing. By setting the fleet size parameters at a constant value, the compressor and storage vessels can be sized to meet the required performance by running a CASCADE simulation against a daily demand profile.

There are five required inputs: fleet/vehicle, vehicle storage/refueling, ground storage, and fleet refueling characteristics. These four characteristics can be seen in figure D.1. The fifth input is the compressor characteristics and can be seen in figure D.4.

The fleet characteristics inputs require the user to input the fleet size, the vehicle fuel efficiency, and the daily vehicle route. Each refuel is to be considered a complete fill, so the fuel efficiency and vehicle route are set so that each vehicle is essentially empty at the start of the refueling process. The fleet characteristics used in the analysis are a vehicle fuel efficiency of 50 mpg and a daily vehicle route of 182 miles[1]. These input values yield an end of day vehicle with 600 scf of hydrogen, or 1.42 kg, at 1194 psig. These values can be seen in figure D.4.

The cascading refueling system refuels the cars to 5 kg, so each fill is 3.58 kg. The hydrogen temperature rises in the vehicle storage vessel to a temperature of 151°F, so each vehicle must be filled to an overpressure of 5805 psig. These calculations can also be seen in figure D.4.

The fleet size, along with the fleet refueling characteristics, was modified on an hourly basis to reflect the number of refuels per hour according to the daily load profile. The output of one hour serves as the input to the next hour. Therefore, the only ground storage characteristic that was changed from period to period was the ground storage pressure. However, the input value is the maximum storage pressure, not starting storage pressure. The software does not allow the user to input a starting bank storage pressure and a maximum storage pressure. This yields a conservative approach when analyzing the cascading storage system because it limits each bank's maximum pressure. The total mass entering the storage remains the same, but the amount available is actually higher than what the software calculates.

The vehicle storage/refueling characteristics are set so a complete fill equals 5 kg at 5000 psig. The value needed is a vehicle tank volume of 7.72 ft^3, with the tank rated pressure of 5000 psig

[1] These numbers were based on Toyotas FCHV, taken from their website.

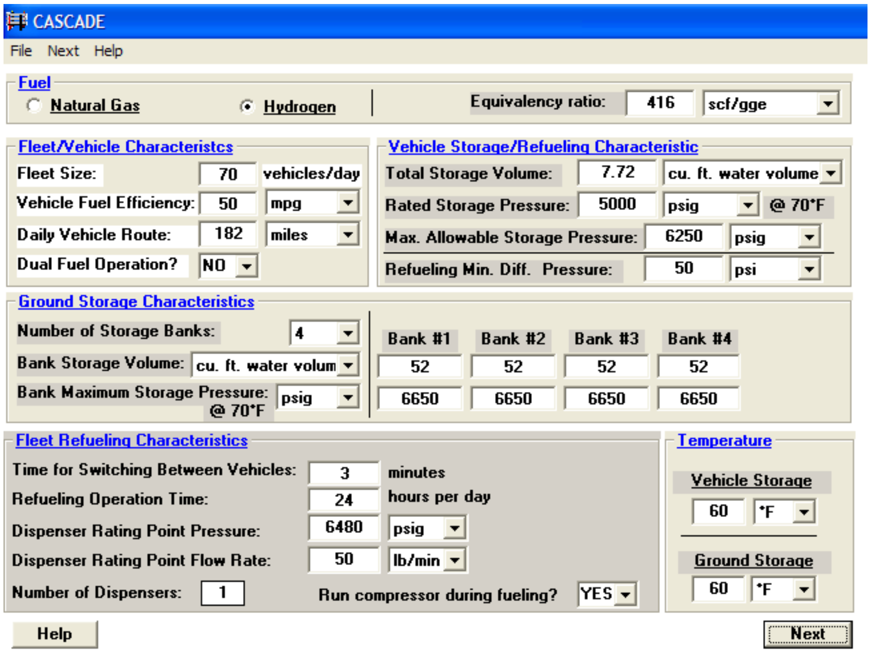


Figure D.1: CASCADE Main Screen

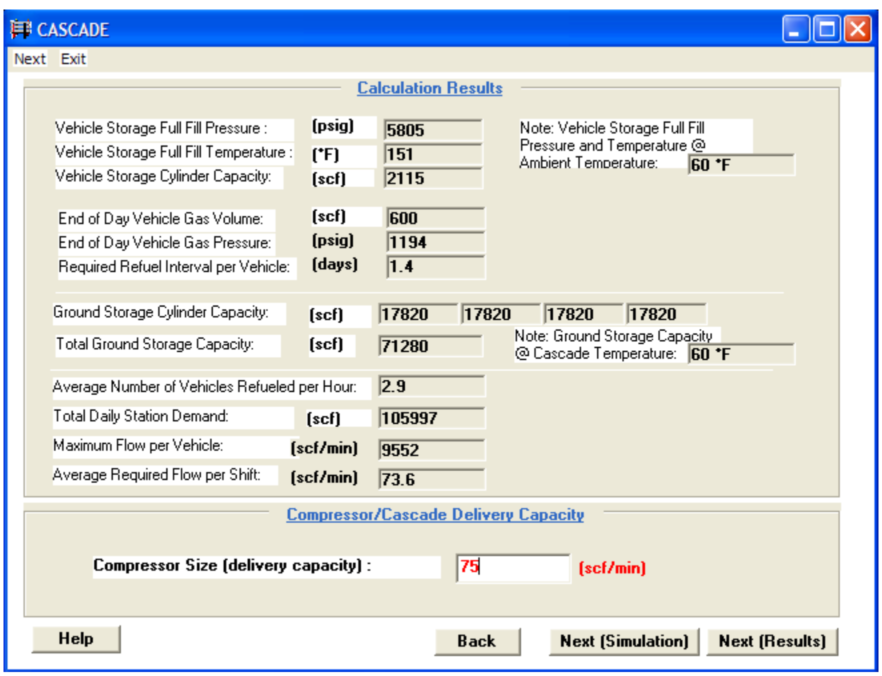


Figure D.2: CASCADE Calculation Results

Detailed Report

File Location:

Fuel Type: Hydrogen		Vehicle	Bank 1	Bank 2	Bank 3	Bank 4
00:46:37	Start filling Vehicle 4 / Compressor->Bank 1 / Bank 1->Vehicle					
	Pressure (psig)	491	5,984	6,616	6,616	6,616
	Capacity (SCF)	211	16,898	17,820	17,820	17,820
00:46:49	Vehicle switched to Bank 2 / Compressor->Bank 1 / Bank 2->Vehicle					
	Pressure (psig)	6,263	5,384	6,616	6,616	6,616
	Capacity (SCF)	1,605	16,320	17,820	17,820	17,820
00:46:50	Compressor switched to Bank 2 / Compressor->Bank 2 / Bank 2->Vehicle					
	Pressure (psig)	6,470	5,384	6,602	6,616	6,616
	Capacity (SCF)	1,638	16,320	17,750	17,820	17,820
00:46:51	End filling Vehicle 4					
	Pressure (psig)	6,791	5,384	6,458	6,616	6,616
	Capacity (SCF)	1,726	16,320	17,700	17,820	17,820

Figure D.3: Detailed Simulation Output Report

at 70 °F. Each ground storage input was calculated according to the 17 hour daily load profile, discussed in the Hydrogen Storage section on page 215. A ground storage pressure of 6650 psig was inputted to yield an effective storage pressure of 6500 psig. The fleet refueling characteristics were taken from the dispenser specifications. The time interval for switching between vehicles along with the fleet size and the refueling operation time allows the user to set the number of refuels per hour. For example, a fleet size of 6 cars, a time between switching of 10 minutes, and a refueling operation time of 1 hour, allows the user to set the hourly demand at six refuels. The output of these inputs can be seen in figure D.4.

The software allows the user to input the compressor size to meet the daily production demand. The analysis was completed for the year 2020, so the compressor was sized to handle a flow of 75 scf/m. Figure D.3 shows the output of the 7am hour, during which 4 cars are refueled. This output becomes the input to the 8am hour. This process was iterated for the complete 24 hour period and the software ensured that enough hydrogen remained at high enough pressure to meet the hourly demand.

D.2 Safety

D.2.1 Safety Codes

Due to budget constraints, the details of standards and codes of ISO, ASME and other organizations could not be accessed. However, the followings are the codes that are related to Gen H Power Park design, HMax and eMax productions.

Organization	Code	Application
NFPA	50A, 50B	Gaseous and liquefied hydrogen system at consumer site
	55	Standard for storage, use, handling of compressed gases in stationary tanks
SAE	J2600	Compressed hydrogen surface vehicle refueling connections
	J2601	Compressed hydrogen vehicle fueling communication device
CGA	G-5	Hydrogen
	G-5.3-5.5	Hydrogen systems for piping, commodity and ventilation
ISO	13984	Liquid hydrogen -- Land vehicle fuelling system interface
	15916	Basic considerations for the safety of hydrogen systems
BSR	HV4.1 – 4.8	Hydrogen application and systems for dispensing

Table D.1: Safety Codes

D.2.2 Failure Modes and Effects Analysis

The following severity rating table is in the range of 1 to 5 with 5 being the most severe:

Severity Rating	Consequence
1	Machine breakdown or degraded performance
2	Extreme noise or any form of annoyance caused by component failures or alike
3	Mild injuries, small fire, hydrogen leakage or alike
4	Severe injuries or massive component damages, huge fire or alike
5	Deaths or explosions

Table D.2: Severity Rating and Consequences

The following occurrence rating table is in the range of 1 to 5 with 5 being the most frequent or highly probable:

Occurrence Rating	Frequency
1	1 in 50 years
2	1 in 10 years
3	1 in 5 years
4	1 in 1 year
5	1 in 1 month

Table D.3: Probability and Occurence Rating

The following detection rating is based on the ease of detection or prevention with 1 being easily detected or stopped and 5 being an emergency.

Detection Rating	Ease of Detection
1	Easily detected
2	Inspected regularly or immediate actions
3	Visit by manufacturer
4	Shut down of component
5	Emergency Force Deployed

Table D.4: Detection Rating and Ease of Detection

The following table is the full version of the FMEA for all components in Gen H Power Park.

Item No.	Component	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Process Controls	DET	RPN
1	**Bio Gas Flow Meter**	Possible pressure build-up and component breakage	Spillage of bio gas or injuries due to high pressure	2	Meter broken due to electronic or mechanical failure	3	Regular Inspection / Replacement	2	12
2	**Bio Gas Compressor**	Extreme heat, noise	Causing Annoyance and burnt injuries due to excessive heat	2	Bearing failures	4	Manufacturer specification	3	24
3			Causing Annoyance	2	Insufficient lubricant or leakage	4	Manufacturer specification	3	24
4		Leakeage of compressed bio gas	Mild injuries due to compressed gas	3	Seals leakage	4	Regular Inspection / Replacement	2	24
5	**Pressure Gage**	Possible pressure build-up and component breakage	Mild injuries due to compressed gas	3	Gage broken due to electronic and mechanical failure	3	Manufacturer specification	3	27
6	**Bio Gas Pipes & Valves**	Pipe Rupture	Mild injuries due to compressed gas	3	Collision by hard objects or corrosion	3	Component shutdown	4	36
7		Valve breakage	Mild injuries due to compressed gas	3	Valves broken due to electronic and mechanical failure	3	Regular Inspection / Replacement	2	18
8	**Carbon Dioxide Pipe & Valves**	Valve breakage	Mild injuries due to compressed gas	3	Valves broken due to electronic and mechanical failure	3	Regular Inspection / Replacement	2	18
9		Pipe Rupture	Poisoning of Carbon Dioxide	4	Collision by hard objects or corrosion	3	Component shutdown	4	48
10	**Power Swing Absorber**	Component breakage	Poisoning of Carbon Dioxide	4	Collision by hard objects or corrosion	3	Component shutdown	4	48

11			Poisoning of Methane	4	Collision by hard objects or corrosion	3	Component shutdown	4	48
12			Mild to Severe burnt injuries	4	Ignition at opening	2		5	40
13	**Methane Pipes & Valves**	Valve breakage	Mild injuries due to compressed gas	3	Valves broken due to electronic and mechanical failure	3	Regular Inspection / Replacement	2	18
14		Pipe Rupture	Poisoning of Methane	4	Collision by hard objects or corrosion	3	Component shutdown	4	48
15			Mild to Severe burnt injuries	4	Ignition at opening	2		5	40
16	**Steam Reformer**	Component breakage	Poisoning of Carbon Dioxide	4	Collision by hard objects or corrosion	3	Component shutdown	4	48
17			Poisoning of Methane	4	Collision by hard objects or corrosion	3	Component shutdown	4	48
18			Mild to Severe burnt injuries	4	Ignition at opening	2	Automatic shutdown	5	40
19	**Water Purifier**	Leakage	Spillage of water / Slippery Floor	1	Collision by hard objects or corrosion	3	Component shutdown	4	12
20			Spillage of water / Slippery Floor	1	Seal leakage	4	Regular Inspection / Replacement	2	8
21	**Water Tank**	Leakage	Spillage of water / Slippery Floor	1	Collision by hard objects or corrosion	3	Component shutdown	4	12
22			Spillage of water / Slippery Floor	1	Seal leakage	4	Regular Inspection / Replacement	2	8
23	**Water Pump**	Leakage	Spillage of water / Slippery Floor	1	Collision by hard objects or corrosion	3	Component shutdown	4	12
24			Spillage of water / Slippery Floor	1	Seal leakage	4	Regular Inspection / Replacement	2	8
25	**Purified Water Pipes**	Leakage	Spillage of water / Slippery Floor	1	Collision by hard objects or corrosion	3	Component shutdown	4	12
26	**H2 Compressor**	Component breakage	Leakage of hydrogen	3	Collision by hard objects or corrosion	3	Component shutdown	4	36

26	**H2 Compressor**	Component breakage	Leakage of hydrogen	3	Collision by hard objects or corrosion	3	Component shutdown	4	36
27			Mild to Severe burnt injuries	4	Ignition	2	Automatic shutdown	4	32
28	**Fuel Cell**								
29	**Fuel Processor**	Component breakage	Leakage of hydrogen	3	Collision by hard objects or corrosion	3	Component shutdown	4	36
30			Mild to Severe burnt injuries	4	Ignition	2	Automatic shutdown	4	32
31	**Power Conditioner**	Power leakage	Electric shock	4	Humid atmosphere / mishandling	4	Component shutdown	4	64
32	**Heat Exchanger**	Rupture	Severe injuries due to hot water	4	Collision by hard objects or corrosion	3	Component shutdown	4	48
33	**Hot Water Pipes & Valves**	Pipe Rupture	Severe injuries due to hot water	4	Collision by hard objects or corrosion	3	Component shutdown	4	48
34		Valve breakage	Severe injuries due to hot water	4	Collision by hard objects or corrosion	3	Component shutdown	4	48
35	**Electricity Cables**	Power leakage	Electric shock	4	Humid atmosphere / mishandling	4	Regular Inspection / Replacement	2	32
36	**Storage System**	Component breakage	Leakage of hydrogen	3	Collision by hard objects	3	Component shutdown	4	36
37			Mild to Severe burnt injuries	4	Ignition	2		5	40
38			Catastrophic consequences due to explosion	5	Ignition	2		5	50
39		Rupture in tank	Leakage of hydrogen	3	H2 embrittlement	3	Tank Emptying	4	36
40	**Sequencing Panel**	Component breakage	Leakage of hydrogen	3	Collision by hard objects	3	Component shutdown	4	36
41			Mild to Severe burnt injuries	4	Ignition	2	Automatic shutdown	4	32
42		Rupture	Leakage of hydrogen	3	H2 embrittlement	3	Tank Emptying	4	36
43	**Hydrogen Pipes & Valves**	Component breakage	Leakage of hydrogen	3	Collision by hard objects	3	Component shutdown	4	36
44			Mild to Severe burnt injuries	4	Ignition	2		5	40
45			Catastrophic consequences due to explosion	5	Ignition	2		5	50

47	**Dispensing System**	Component breakage	Leakage of hydrogen	3	Collision by hard objects	3	Component shutdown	4	36
48			Mild to Severe burnt injuries	4	Ignition	2	Automatic shutdown	4	32
49		Rupture	Leakage of hydrogen	3	H2 embrittlement	3	Tank Emptying	4	36
50	**DispensingHose & Valves**	Hose Rupture	Leakage of hydrogen	3	Wear	4	Regular Inspection / Replacement	2	24
51			Mild to Severe burnt injuries	4	Ignition	2		5	40
52			Catastrophic consequences due to explosion	5	Ignition	2		5	50
53		Valve breakage	Leakage of hydrogen	3	Valve broken due to electronic and mechanical failure	3	Regular Inspection / Replacement	2	18
54			Mild to Severe burnt injuries	4	Ignition	2	Automatic shutdown	4	32

Table D.5: Severity Rating and Consequences

D.2.3 Fault Tree

OCC and Probability in Fault Tree Conversion:

Conversion Scale	
OCC	**Prob**
1	1/18250
2	1/3650
3	1/1825
4	1/365
5	1/30

Table D.6: Conversion Scale between Fault Tree and FMEA OCC

D.3 Carbon Dioxide Emission Calculations

D.3.1 Carbon Dioxide Resulting from Swing Adsorption

The conversion of biowaste to biogas yields 18,900 scf of biogas per day during 2010 when producing 50 kg of hydrogen per day. This is used to calculate the grams of carbon dioxide resulting from Swing Adsorption per kilogram of hydrogen ultimately produced.

$$\frac{18,900 \text{ scf biogas}}{\text{day}} * \frac{1 \text{ day}}{50 \text{ kg } H_2} * \frac{.4 \text{ scf } CO_2}{\text{scf biogas}} * \frac{52.66\text{g}CO_2}{\text{scf } CO_2} = 7,962\frac{\text{g } CO_2}{\text{kg } H_2}$$

D.3.2 Carbon Dioxide Resulting from Steam Reformation

$$\frac{9,072 \text{ scf of } CH_4}{\text{day}} * \frac{1 \text{ day}}{50 \text{ kg of } H_2} * \frac{0.0192 \text{ kg } CH_4}{\text{scf of } CH_4} * \frac{44.01\text{kg } CO_2}{16.043 \text{ kg } CH_4} = 9,557\frac{\text{g of } CO_2}{\text{kg of } H_2}$$

D.4 Cash Flow Analysis Spreadsheet

DISCOUNTED CASH FLOW ANALYSIS *using CAPM model*											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Revenue	257,473	302,983	348,493	394,003	439,512	485,022	579,834	674,646	769,458	864,270	
Variable Cost	183,577	179,220	174,587	177,754	179,920	193,087	195,985	204,882	211,779	225,677	
Operating Cash Flow (CF)	73,896	123,763	173,906	216,249	259,592	291,935	383,850	469,764	557,679	638,594	
Depreciation[1]	250,625	250,625	250,625	250,625	250,625	250,625	250,625	250,625	250,625	250,625	
Taxable Income	-176,729	-126,862	-76,719	-34,376	8,967	41,310	133,225	219,139	307,054	387,969	
Tax @ 15% upto $ 50k	-7,500	-7,500	-7,500	-5,156	1,345	6,197	7,500	7,500	7,500	7,500	
Tax @ 25% $ 50 - 75k	-6,250	-6,250	-6,680	0	0	0	6,250	6,250	6,250	6,250	
Tax @ 34% $ 75 - 100k	-8,500	-17,633	0	0	0	0	8,500	8,500	8,500	8,500	
Tax @ 39% $100 - 335k	-29,924	0	0	0	0	0	12,958	46,464	80,751	112,308	
Tax @ 34% $ 335 - 1,000k	0	0	0	0	0	0	0	0	0	0	
Corporate Tax	-52,174	-31,383	-14,180	-5,156	1,345	6,197	35,208	68,714	103,001	134,558	
After Tax CF	126,070	155,146	188,086	221,405	258,247	285,739	348,642	401,050	454,678	504,036	
Free CF	376,695	405,771	438,711	472,030	508,872	536,364	599,267	651,675	705,303	754,661	
Terminal Value[2]											259,374
Total CF	376,695	405,771	438,711	472,030	508,872	536,364	599,267	651,675	705,303	754,661	259,374
Present Value of CF@10% (IRR of 10%)	$342,450	$335,348	$329,610	$322,403	$315,969	$302,763	$307,519	$304,011	$299,117	$290,954	$100,000
Enterprise Value	$3,250,145										
Current Outstanding Debt (fixed cost is met by debt)	$3,250,145										
NPV	0										
Price of *H*max per kg	8.31229	found Hmax price by setting NPV = 0 with IRR@10%									
Price of *e*Max per kWh	0.0865										

[1] assuming construction does not carry any value by 2010

[2] assuming land appreciates at 10%

Figure D.4: Cash Flow Analysis Spreadsheet

D.5 Marketing Budget

End of Year	General	Education				Marketing & Advertising				PLAN
	Public Awareness	University	High School	Jr. High School	Elementary School	Materials	Toy Lines	Proposals	H2 Challenge	TOTAL
1	$12,000	$5,000	$5,000	$5,000	$5,000	$10,000	$5,000	$10,000	$6,000	$63,000
2	$12,000	$5,000	$5,000	$5,000	$5,000	$10,000	$5,000	$5,000	$7,000	$59,000
3	$12,000	$5,000	$5,000	$5,000	$5,000	$10,000	$0	$0	$8,000	$50,000
4	$10,800	$5,000	$5,000	$4,000	$5,000	$10,000	$0	$0	$9,000	$48,800
5	$9,600	$4,000	$4,000	$4,000	$5,000	$10,000	$0	$0	$10,000	$46,600
6	$8,400	$4,000	$4,000	$4,000	$5,000	$10,000	$5,000	$0	$11,000	$51,400
7	$7,200	$4,000	$4,000	$3,000	$5,000	$10,000	$0	$0	$12,000	$45,200
8	$6,000	$4,000	$4,000	$3,000	$5,000	$10,000	$0	$0	$13,000	$45,000
9	$4,800	$3,000	$3,000	$3,000	$5,000	$10,000	$0	$0	$14,000	$42,800
10	$3,600	$3,000	$3,000	$3,000	$5,000	$10,000	$5,000	$0	$15,000	$47,600
Individual Totals:	$86,400	$42,000	$42,000	$39,000	$50,000	$100,000	$20,000	$15,000	$105,000	

Total 10 Year Budget: $499,400

NOTES:

- The budget for "General Public Awareness" will remain constant the first 3 years. Gen H will make a strong start, but will eventually decrease its spending by $1,200 a year, since public awareness should increase slightly with time as educational efforts continue.
- The "Education at University Level" budget will decrease every four years, since that is the normal duration in this range of the target subjects (students in college). At the end of the fourth year, new students will generally come in from high school, and they will already have exposure to Gen H's marketing and educational efforts.
- The budget for "Education at High School and Junior High School Levels" will be reduced due to the same reasons, at the end of the year when incoming students from the lower level arrive. Notice that due to the variability of school systems, Junior High Schools can host 2 - 3 different grade levels. Taking a conservative approach, Gen H chose 3 years as the budget change period.
- The "Education at Elementary School Level" budget will remain constant throughout the 10 year period. This is justified by the fact that there are always new students coming in who have not had any strong exposure besides perhaps, the Toy Lines, to Gen H's marketing and educational efforts.
- The budget for "Marketing Materials" will also remain constant. This will ensure uniformity of product distribution throughout the 10 year period.
- The "Toy Lines" budget will be the same during the first and second years. There will be no other expenses until the sixth and tenth years, where revalidation and restructuring of products occurs.
- The budget for "Proposals" will only have funds allocated during the first and second years. These amounts account for the costs of creating the proposals themselves, as well as any fees that corporations might charge Gen H. These expenditures are not continuous.
- The "H2 Challenge" budget will increase as time passes. This is due to the popularity Hydrogen will gain among the population, driving Gen H to spend more money promoting its products with this method.

Figure D.5: Marketing Budget