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**Cost Benefit Analysis of Performing a Pilot Project for Hydrogen-
Powered Ground Support Equipment at Lemoore Naval Air Station**

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December 2006**

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NAVAL AIR STATION**

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COST BENEFIT ANALYSIS OF PERFORMING A PILOT PROJECT FOR HYDROGEN-POWERED GROUND SUPPORT EQUIPMENT AT LEMOORE NAVAL AIR STATION

ABSTRACT

The primary purpose of this thesis is to provide a cost benefit analysis of a pilot program at NAS Lemoore for the use of hydrogen fuel cell powered aviation ground support equipment (GSE) and provide general background information on hydrogen power. The analysis is conducted to determine expected program costs and to determine what benefits the Navy could achieve by using hydrogen fuel cell powered tow tractors, electric carts and hydraulic carts. Analysis shows benefits in the following areas: reduced green house gas emissions and noise pollution, reduced HAZMAT generation due to reduced oil usage and spills/leaks, reduced maintenance labor costs for fuel cell over diesel engines, and reduced training time required after full fleet fuel cell implementation.

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I. INTRODUCTION

A. PURPOSE

This research will provide a cost benefit analysis and make recommendations for a pilot project for hydrogen-powered aviation ground support equipment (GSE) at Naval Air Station Lemoore, California.

In both his 2003 and 2006 State of the Union Address, President Bush addressed growing concerns about the consumption of fossil fuels and encouraged research in the area of alternative fuels, particularly hydrogen power. He established the Hydrogen Fuel Initiative in 2003 to develop technology for commercially viable hydrogen-powered fuel cells, with a vision of hydrogen-power for use in general transportation at costs that are competitive with gasoline by 2015.¹

1. The Need for Research in Alternative Fuels

Research in alternative fuels is necessary for a multitude of reasons. Federal and local governments in the United States are enacting policies like the Hydrogen Fuel Initiative to encourage the development and use of alternative fuels, and in some cases, establish goals for potentially requiring the use of alternatives. California's Executive Order S704, for example, orders building a network of hydrogen fueling stations sufficient to make hydrogen power accessible to every Californian by 2010.² Concerns motivating this trend include national security, economic, and environmental.

National security and dependence on foreign oil is the primary concern of the Hydrogen Fuel Initiative, as 55 percent of the oil consumed by the U.S. is imported, and

¹ "Background on the Hydrogen Fuel Initiative." White House. <http://www.hydrogen.gov/presidentdetails.html> (accessed November 27, 2006).

² Philip Baxley, Cynthia Verdugo-Peralta, and Wolfgang Weiss. Rollout Strategy Topic Team Report, California 2010 Hydrogen Highway Network. Sacramento, CA: California Environmental Protection Agency, 2005.

this is expected to grow to 68 percent by 2025.³ Many of the major importers to the U.S. are considered unstable areas, and are not friendly to the U.S. See Table 1 for a list of the top 15 oil exporters to the U.S. at the time of writing this report.⁴

Total Imports of Petroleum (Top 15 Countries) (Thousand Barrels per Day)					
Country	Jul-06	Jun-06	YTD 2006	Jul-05	Jan - July 2005
CANADA	2,113	2,258	2,249	2,079	2,121
MEXICO	1,709	1,855	1,784	1,593	1,648
VENEZUELA	1,467	1,306	1,455	1,623	1,590
SAUDI ARABIA	1,313	1,522	1,442	1,689	1,597
NIGERIA	1,073	1,094	1,171	1,156	1,131
ALGERIA	743	740	606	535	467
ANGOLA	695	565	501	219	406
IRAQ	592	617	553	615	558
RUSSIA	425	429	349	587	452
VIRGIN ISLANDS	353	273	305	319	326
UNITED KINGDOM	340	355	294	404	376
BRAZIL	274	151	176	156	127
NORWAY	236	140	199	206	242
NETHERLANDS	196	211	185	197	125
ECUADOR	181	295	271	226	287

Note: The data in the tables above exclude oil imports into the U.S. territories.

Table 1. Top Oil Exporters to the United States

Many economists argue that there are no regional markets for oil, and therefore no country can exclude itself from the price fluctuations of the global market.⁵ Nonetheless, the President's statements and national and state government investment into alternative fuels research indicate that energy security is a matter of significant political concern.

³ "Background on the Hydrogen Fuel Initiative." White House. <http://www.hydrogen.gov/presidentdetails.html> (accessed November 27, 2006).

⁴ "Crude Oil and Total Petroleum Imports Top 15 Countries." Energy Information Administration. http://www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/company_level_imports/current/import.html (accessed August 12, 2006).

⁵ Jerry Taylor. "Don't Worry about Energy Security." Cato Institute. <http://www.cato.org/dailys/10-18-01.html> (accessed October 13, 2006).

Furthermore, if political concerns for energy security drive initiatives to cease importing crude oil to the U.S. (as evidenced by increased interest in exploring domestic oil reserves), domestic energy will become significantly more expensive if a mature alternative energy technology has not yet become available. Currently, crude oil imported from the Persian Gulf is significantly less expensive than domestic oil or any available energy alternative.⁶

Other economic concerns include the rising cost and volatility of oil prices. The most common factors driving price volatility include economic or political instability in countries that provide oil, natural disasters, and the accessibility of oil in the ground. Historically, political and natural disasters have caused spikes in prices that eventually subsided. The Iranian revolution in 1979, for example, increased crude oil prices from \$15 per barrel to \$40 per barrel.⁷ Damage to oil infrastructure in the Gulf of Mexico during Hurricane Katrina saw prices exceed \$70 per barrel for the first time in history.⁸ While these factors cause volatility in oil prices, the declining availability of oil reserves will have a more lasting effect. While the world is not running out of oil, it is running out of oil that is economically recoverable.⁹ As oil companies drill into deeper and less-accessible sites for oil, the cost of doing business will gradually increase, as will the price of oil. Increases in fossil fuel efficiency and research into synthetic fossil fuels will not be enough to keep energy affordable in the long term.

Reduction of greenhouse gas emissions is another significant environmental goal motivating alternative fuels research. Carbon dioxide, produced by burning fossil fuels, is the most significant known cause of global warming and is considered to be the most threatening environmental issue. Emissions from automotive vehicles constitute 25% of

⁶ Jerry Taylor. "Don't Worry about Energy Security." Cato Institute. <http://www.cato.org/dailys/10-18-01.html> (accessed October 13, 2006).

⁷ "1979 Energy Crisis." Wikipedia. http://en.wikipedia.org/wiki/1979_energy_crisis (accessed November 27, 2006).

⁸ "No Decision Yet on Oil Reserves: President Bush Weighs Authorizing Tapping into US Petroleum." CBS News, August 29, 2005, <http://www.cbsnews.com/stories/2005/08/29/national/main798952.shtml>.

⁹ "Oil Reserves." Wikipedia. http://en.wikipedia.org/wiki/Oil_reserves (accessed November 27, 2007).

the total greenhouse gas emissions for the U.S. The U.S.' stance on greenhouse gas emissions is that research into increased fuel efficiency and alternative fuels is the answer to improving air quality and reducing environmental risk.¹⁰

2. Advantages of Hydrogen Power

Hydrogen energy shows promise among technologies currently under development. It has the highest energy content per unit of weight of any known fuel source, making it an efficient source. Hydrogen is the most abundant element in the universe, and on Earth, it can be extracted from readily available sources such as water, coal, or waste. When burned in an engine, it produces no emissions but water. Research and development projects underway also show prospects for a zero-emissions extraction process using renewable energy sources or sequestration of carbon dioxide.¹¹ Hydrogen-powered fuel cells also demonstrate some safety and maintenance benefits which will be addressed in this report.

3. Why a Government Sponsored GSE Project is Important

Currently, hydrogen power is not considered a commercially viable energy solution because the technology has not reached maturity, and there is no readily available production, transportation, and delivery infrastructure for hydrogen power in any state. The most commonly available hydrogen extraction processes, such as cryogenic separation and electrolysis, described in Chapter III, require a significant amount of energy, depending on the source of energy used. Therefore, hydrogen power does not yet demonstrate a significant energy savings or show a dramatic reduction in greenhouse gas emissions. Table 2 demonstrates the true carbon dioxide emissions per mile, based on the fuel source and extraction method. Hydrogen derived from gasoline produces nearly as much carbon dioxide as common gasoline combustion. Methods that

¹⁰ Global Climate Change Policy Book. Washington, DC: White House, 2002.

¹¹ "Fact Sheet: Hydrogen Fuel: A Clean and Secure Energy Future." White House. <http://www.whitehouse.gov/news/releases/2003/02/20030206-2.html> (accessed November 27, 2006).

are still under development, such as hydrogen extraction from methane or hydrogen extracted using renewable energy sources, show the real future promise of hydrogen power.¹²

Engine Type	Water Vapor/Mile	Carbon Dioxide/Mile
Gasoline Combustion	0.39 lb.	0.85 lb.
Fuel Cell Running on Hydrogen from Gasoline	0.32 lb.	0.70 lb.
Fuel Cell Running on Hydrogen from Methane	0.25 lb.	0.15 lb.
Fuel Cell Running on Renewable Hydrogen	0.25 lb.	0.00 lb.

Table 2. Emissions by Fuel Type

Technical and economic barriers to commercializing hydrogen power include lack of transportation and delivery infrastructures, high costs of capital, and significantly low economies of scale.¹³ Expanding the customer base through research projects not only increases public awareness and demonstrates the feasibility of hydrogen power, it helps to develop the commercial infrastructure, amortize capital investment, and improve economies of scale. The DoD, as the largest consumer of fossil fuels in the United States, is in a unique position to provide a significant contribution to developing and expanding hydrogen technology.

Aircraft ground support equipment (GSE) is a good candidate for a hydrogen-powered pilot project for two reasons. First, GSE is a major contributor to the carbon dioxide emissions problem. Airport traffic is responsible for 2-3% of carbon dioxide emissions from U.S. metropolitan areas, and this number is expected to increase as the air

¹² "Hydrogen Fuel Cells: Benefits of Fuel Cells." Bullnet eCommerce Solutions, Bull Group. <http://www.bullnet.co.uk/> (accessed November 25, 2006).

¹³ Philip Baxley, Cynthia Verdugo-Peralta, and Wolfgang Weiss. Rollout Strategy Topic Team Report, California 2010 Hydrogen Highway Network. Sacramento, CA: California Environmental Protection Agency, 2005.

transportation industry grows.¹⁴ Of the three categories of airport traffic, including aircraft, GSE, and commuter traffic into and out of airports, GSE and commuter automotive vehicles are the most feasible candidates for conversion. DoD has more control over GSE than commuter traffic. If a DoD facility or program office chooses to run a pilot project for hydrogen-powered support equipment, despite emissions generated by hydrogen extraction, the DoD stands to benefit from environmental, safety, and maintenance advantages. By carefully selecting a hydrogen refueling source, problems from emissions from extraction can be reduced or eliminated.

B. RESEARCH GOALS

The primary goal of this research is:

- To perform a cost-benefit analysis of a pilot program for hydrogen-powered GSE.

Secondary goals are:

- To review past and present hydrogen-powered and hybrid-electric GSE and lessons learned from those programs.
- To provide background on technical hydrogen-power options for GSE in general: hydrogen feed stocks, power cells, and hydrogen storage and extraction.
- To generate a spreadsheet model that can be used to analyze the cost of a program using any type of equipment, power cells, or recharging station. Naval Air Station Lemoore, California will be used as a notional location to demonstrate the model.

C. SCOPE

This project will review past and present programs using hydrogen-powered and hybrid-electric GSE with attention to cost and management of the program, and make recommendations based on the results of this research to implement a program successfully. Finally, after reviewing available options for recharging stations, power

¹⁴ Technical Support for Development of Airport Ground Support Equipment Emission Reductions. Sacramento, CA: Sierra Research, Inc for the Office of Mobile Sources, US Environmental Protection Agency, 1999.

cells, and converting existing or designing new GSE to accept those power cells, this project will conclude with a cost-benefit analysis for specific equipment to be used in a pilot project at NAS Lemoore.

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II. BACKGROUND

Background information is provided here on various technical options available and environmental and logistics concerns associated with them, and on two military hydrogen power programs that have already been implemented.

A. HETT PROJECT AT NAS NORTH ISLAND AND MCAS MIRAMAR

Review of the U.S. Navy's hybrid electric tow tractor (HETT) test project between 1999 and 2002 reveals a number of useful and important lessons that can be applied to future pilot projects and equipment purchases. The following summarizes the project's background, equipment used, and methodology, followed by the resultant lessons learned from the project, which can be applied to future projects.

1. Project Review

The HETT project evolved from the Navy's pollution prevention (P2) initiative, which allowed for procuring pollution prevention equipment under the Preproduction Initiative or the Competitive Procurement Initiative. These programs were administered by Naval Air Systems Command Lakehurst and Naval Facilities Engineering Services Center, who were authorized by the Chief of Naval Operations (CNO), Environmental Protection, Safety, and Occupational Health Division (N45) through the establishment of the P2 Equipment Program (PPEP). The HETT equipment selection derived from a bi-service Navy/Air Force program to purchase several light duty electric and hybrid vehicles. This program's funding allowed the Navy to receive one hybrid tow tractor.¹⁵

The HETT was based on a standard MB-4 tow tractor from the Air Force which is equivalent to the Navy's A/S32A-37, after adding 4 battery packs, ISE Research ThunderVolt drive system, speed increaser, AC generator, controller, electric motor, and battery management and recharging system. This equipment allowed the HETT to operate electrically and to recharge during the day if necessary. It was a recommended

¹⁵ Hybrid Electric Tow Tractor Preproduction Initiative Final Report. Lakehurst, NJ: Pollution Prevention Equipment Program, US Navy, 2006.

requirement that the tow tractor be plugged into the electrical grid during the night to balance the battery charge. The June 2000 cost for the HETT was \$297,000, compared to the replacement cost of \$60,500 for an A/S32A-37 tow tractor.¹⁶

End users employed two different manual methods of data collection for this program, in addition to automatic data logging with a data logger wired into the HETT. No useful data was collected by the system due to failure of the data logger equipment; however, the data provided manually by the users lead to the following conclusion:

Due to maintainability issues, the performance of the hybrid electric drive system in the HETT could not be adequately evaluated under typical operating conditions. The manufacturer recommended that the HETT be charged every night, but also indicated that connecting HETT to grid power once per week should be sufficient... the HETT performance deteriorated after approximately two days without connection to the grid power. For these reasons, the performance of the HETT was unacceptable for implementation on a Navy-wide basis.¹⁷

2. Lessons Learned

Initial training on the daily and weekly inspections/maintenance procedures of the equipment should be provided to personnel responsible for training others in operator licensing courses.

Ensure that the facility designated for use of the equipment can handle all the required maintenance; i.e. a proper electrical plug at the end users location, which was not the case for this HETT project.

Ensure equipment operation counters are functional.

Ensure the end users are properly trained and monitored periodically until the equipment becomes standard.

Ensure there is enough equipment on hand to collect proper usage data.

¹⁶ Hybrid Electric Tow Tractor Preproduction Initiative Final Report. Lakehurst, NJ: Pollution Prevention Equipment Program, US Navy, 2006.

¹⁷ Ibid.

Create a user-friendly data collection system (installed on the machine or separate) for users and maintainers to enter usage and maintenance data.

Choose an electric drive system that has been tested commercially in a like item to prove the maintainability of the system.

End users really do want an electric drive tow tractor to reduce the noise levels they are exposed to daily.¹⁸

B. CAMP PENDLETON TRANSPORTATION DEPARTMENT

1. Program Review

The Camp Pendleton program is limited with regards to lessons learned in implementing a hydrogen-based fueling process; but it is primed for opportunity to implement and leverage benefits identified and employed from other DoD locations where alternate fueling programs are more mature. While other programs previously discussed speak to fuel cell systems, Camp Pendleton is primarily an on-site hydrogen generation station. Although the base has vast experience with alternative fueling options, its primary focus is on generating hydrogen power.

How did Camp Pendleton arrive at hydrogen power as a dominant solution? The base has a history of proactively implementing alternate fuel sources to reduce oil based energy dependency. The Regional Fleet manager of transportation at Camp Pendleton is Mr. Gary Funk, who drives transportation procurements to ensure 75% of equipment is powered by alternate energy options. The most challenging part of meeting that goal is the acquisition process. Existing Blanket Purchase Agreements, lengthy budgeting and planning cycles and execution of contract options covering an increased period often slows migration to new technological opportunities. However, with increased investment in emerging technologies and the realization of a rapidly changing energy environment, Mr. Funk has the ability to interject more flexibility into the acquisition process, which will ultimately enable an expeditious shift as technologies become available or are required.

¹⁸ Hybrid Electric Tow Tractor Preproduction Initiative Final Report. Lakehurst, NJ: Pollution Prevention Equipment Program, US Navy, 2006.

Currently, Camp Pendleton's alternate fuel equipment inventory consists of more than 300 electric vehicles, which are recharged via solar power at a single station capable of charging 8 vehicles simultaneously. "Camp Pendleton also uses hundreds of CNG vehicles. Camp Pendleton is the nation's largest buyer of bio-diesel with annual purchasing of over one million gallons of B20. These one million gallons from virgin soy is a million less gallons of diesel from oil. The use of B20 has been relatively problem free. Some commercial vehicles, such as buses, have fewer problems with B20 than JP-8."¹⁹

On the forefront of employed hydrogen technologies, Camp Pendleton began operating a single hydrogen station in the first quarter of fiscal year 2007. Hydrogen is produced from natural gas using a commercial reformer. Production levels are approximately 30 kilograms per day. With plans to expand, 60 kilograms of hydrogen storage is currently possible and the fueling station operates at 5,000 pounds pressure per square inch. Placing the hydrogen station near the main interstate provides convenient access to the refilling station. When introducing new technologies, it is important to make their benefit convenient and easy to exercise, as reluctance to participate alone presents a challenge.

The location of the hydrogen plant proved to be a challenge, as site location required a significant environmental study.²⁰ Both site location and construction required a thorough environmental assessment (EA) covering the construction and operation of a compressed hydrogen fueling station to evaluate the following areas: topography, geology, and soils; hydrology; biological resources; cultural resources; air quality; noise; land use; safety and environmental health (including hazardous materials and wastes); utilities; and traffic and transportation.²¹ Specific considerations regarding EA concerns are covered more thoroughly in the environmental section. However, the

¹⁹ John Addison. "United States Marine Corps Uses Hydrogen." California Hydrogen Fleets and Fueling. http://www.cah2report.com/vault/camp_pendleton.htm (accessed October 30, 2006).

²⁰ Ibid.

²¹ Environmental Assessment, Hydrogen Fueling Station Marine Corps Base Camp Pendleton. San Diego, CA: Naval Facilities Engineering Service Center, 2005.

in-depth EA conducted by Marine Corps Base Camp Pendleton would serve other DoD and Governmental organizations well in conducting similar analyses on establishing a hydrogen plant.

2. Current Project Highlights

With regard to hydrogen compressors, cost varies widely depending on size and type. Much of the industry is using diaphragm compressors. These are not low in cost but have inherent advantages in maintaining safety and hydrogen purity. Approximate cost for a system that compresses 700 standard cubic feet per hour (scfh), or approximately 40 kilograms per day, is \$140,000, assuming a 6,500 psig discharge pressure. A piston type compressor may be procured at a reduced cost, which reduces maintenance requirements and complexity but compromises safety and purity.

The hydrogen plant requires on-site utility capabilities of 208/110 Volts Alternating Current (VAC), three phase, or power at 480 VAC. Most larger compressors are designed to operate at 480 VAC. The station's reformer requires two gallons of water per hour and 200 scfh of natural gas to operate. Target efficiency of the natural gas reformer system is 65%, though power for the compressor will draw another 5% of reduced efficiency from the reformer. The system does not generate power, though the reformer could be supplemented with a 10kw fuel cell to provide a continuous load, minimizing the idle time overnight and during weekends. The station will store 30 kilograms of useable stored hydrogen, with approximately 40% useable assuming 5000 psig fill conditions, which are standard for most vehicles. While the hydrogen plant offers promise, there are 1,180 light duty vehicles on base; assuming each vehicle is driven 10,000 miles per year and all vehicles are fuel cell vehicles, the base would need to produce approximately 260,000 kilograms of hydrogen power annually.

As the project continues to develop, forecasted annual preventative maintenance costs per hydrogen plant are expected to be \$30,000 for the fuel processor and hydrogen compressor combined.

Annual operating expenses for indirect costs, including utilities, consumables, and fire and security services, are estimated at \$15,000.

Training for the station equipment will cost approximately \$10,000. Safety, emergency response, and fire department service must also be included. California Fuel Cell Partnership provides some of the training for emergency responders at no cost; however, it is estimated that one plant will require one week of training per year for 10 persons.

Infrastructure to support the vehicles will require a hydrogen compatible intrinsically safe garage space, at an expected cost of \$175,000 for a single bay, which would include a vehicle lift to repair fuel cell vehicles.

Risks and benefits involved with implementing the new equipment center around sabotage and potential storage tank failure, or leaking and subsequent hydrogen ignition. Although the ultimate location was determined to be safe, initially there were concerns that terrorism or tank sabotage could have catastrophic effects. The EA determined an explosion was not likely. Hydrogen is eight times lighter than air, coupled with the fact that the hydrogen station is located outside, a tank puncture would vent hydrogen directly into the open air. The base was required to assume worse case tank failure and provide a conservative setback from nearby activities. Many of these leak related concerns are alleviated by hydrogen's lighter than air properties, which reduce the chance of forming a combustible mixture for any length of time. Due to its low energy density, hydrogen must be stored at high pressures, which has driven further research into low pressure storage systems.²²

The Camp Pendleton base includes over 125,000 acres in Southern California. Providing a year round training environment for Marine Corps personnel, housing more than 38,000 military families and with a population during normal working hours exceeding 60,000 military and civilian personnel, it is a prime location to introduce alternate sources of energy for testing and development.²³

²² Environmental Assessment, Hydrogen Fueling Station Marine Corps Base Camp Pendleton. San Diego, CA: Naval Facilities Engineering Service Center, 2005.

²³ Environmental Assessment, Hydrogen Fueling Station Marine Corps Base Camp Pendleton. San Diego, CA: Naval Facilities Engineering Service Center, 2005.

C. TECHNICAL OPTIONS FOR HYDROGEN-POWERED GSE

1. Overview

GSE vehicles are either self propelled, such as tow tractors, or towed, such as electric carts and hydraulic power carts. Self-propelled equipment is propelled by an internal combustion engine (ICE) or an electric drive motor. The ICE commonly burn fossil fuels (gasoline, natural gas, propane, diesel, and other petroleum formulate), but can also burn gaseous hydrogen in a diesel cycle engine.²⁴ The electric drive motor requires a source of electricity. The common form of electric storage is a battery and the common form of an electric producer is a generator powered by an engine, steam turbine or ICE. Another source of electricity is a fuel cell.

Batteries and fuel cells are similar in that electricity is produced by electrochemical reaction. However, batteries store a finite amount of energy within the materials constructing the battery. In a fuel cell, energy is stored in hydrogen gas and released through a catalytic process and chemical reaction with oxygen in the air to form water. Common materials for batteries are: lead acid solution, nickel metal hydride (NiMH), nickel cadmium (NiCd), and lithium-ion polymer.²⁵

Fuel Cells can be produced in seven different varieties: alkaline (AFC), direct methanol (DMFC), molten carbonate (MCFC), phosphoric acid (PAFC), proton exchange membrane (PEM), solid oxide (SOFC), and regenerative (RFC). Each of these types perform best for different types of applications, from stationary power generation, to space based usage, to usage in mobile application, i.e. cell phones and laptop backup power supplies, or as a battery replacement power source for vehicles.²⁶

All fuel cells require a source of hydrogen and oxygen to produce electricity. Oxygen for the most part comes freely from the air for most fuel cell applications. The

²⁴ Joerg Dittmer. "A Closer Look at Hydrogen." Machine Design (February 2006): November 20, 2006, <http://www.machinedesign.com/ASP/viewSelectedArticle.asp?strArticleId=55381>.

²⁵ "Battery Electric Vehicle." Wikimedia. http://en.wikipedia.org/wiki/battery_electric_vehicle#cost (accessed November 27, 2006).

²⁶ "Types of Fuel Cells." SAE International. <http://www.sae.org/fuelcells/fuelcells-types.htm> (accessed November 20, 2006).

hydrogen must be produced and stored to be used in the fuel cell. There are numerous methods of producing and extracting hydrogen. However, not all methods are energy efficient when considering the life cycle costs and emissions produced.²⁷

The equipment reviewed for use in this pilot program fit into three main categories: hydrogen fuel cell technology, hydrogen storage, and hydrogen production. Within each of these areas there are a few manufactures that produce the required equipment to produce and support hydrogen fuel cells.²⁸

2. Fuel Cells

Reviewing fuel cell technology with electric drive systems found two viable options for fuel cells, PEM and DMFC, because they operate in the temperature range appropriate for automobiles and ground support equipment. The PEM fuel cell is the most widely used in research today. PEM fuel cells have a theoretical upper efficiency of 60%. The DMFC is a newer technology with a fuel cell construction similar to PEM fuel cells, but which extracts hydrogen directly from methanol fuel in the engine. DMFC has a theoretical upper efficiency of 40%. Although methanol is considered to be environmentally beneficial, there are some downsides to its use in DMFC technology. Methanol is a known toxic material when sufficient quantities are present, and the “low-temperature oxidation of methanol to hydrogen ions and carbon dioxide in DMFC requires a more active catalyst so a larger quantity of expensive platinum catalyst is typically required than in conventional PEM” fuel cells.²⁹ Additionally, DMFC technology is limited to licensing agreements from one company that does not manufacture the cells, and the technology is three to five years behind PEM technology in development.

²⁷ Albert Germain et al. *Hydrogen as an Energy Carrier*. Brussels, Belgium: Royal Belgian Academy Council of Applied Science, 2006.

²⁸ "Fuel Cells Technology Showcase." SAE International. <http://www.sae.org/fuelcells/fuelcells.htm> (accessed November 20, 2006).

²⁹ "Types of Fuel Cells." Rocky Mountain Institute. <http://www.rmi.org/sitepages/pid556.php> (accessed November 20, 2006).

PEM fuel cells are manufactured by Ballard Power, General Hydrogen, and Hydrogenics. All three companies manufacture PEM fuel cell stacks or provide them in self contained units similar to battery packs. According to Ballard and Hydrogenics their fuel cells can obtain an average efficiency of approximately 50%.

3. Storage

Hydrogen storage includes two options. One is the vehicle storage tank and the other is bulk hydrogen storage for a refueling station. Vehicle storage tanks have vastly improved and are commercially available through a number of vendors. Bulk storage uses similar tanks but group the tanks in a variety of configurations. Another source of storage tanks is from gas producing companies who lease/rent gas storage trailers.

4. Hydrogen Refueling Equipment

There are two types: pressurized and free flow. A pressurized delivery system ensures complete refill of the onboard storage tank by using a compressor. A free flow delivery system is simpler, but will fail to ensure a complete refill of the onboard storage tank, decreasing the useful hours of fuel cell operation. The pressure of the stations refill tank is the pressure that is attained by the onboard storage tank (i.e. if the pressure in the stations tank is at 5000 psig then the onboard storage tank will be at 5000 psig).

Typical fuel cell power systems require an external source of electrical power to start the power fuel cell power process. This external power source is a battery or a capacitor. Recent developments in ultra high capacitor designs have made this source of power storage the preferred method of providing starting power for the fuel cell. According to Frank Trotter, General Hydrogen president and CEO, "ultracapacitors help triple forklift runtime, eliminating the average three lead-acid battery sets per vehicle and extensive related infrastructure; Ultracapacitors' burst power capabilities, energy recapture efficiency, and long operating life make them an ideal complement to hydrogen fuel cells." The batteries are being replaced with 30-120 ultracapacitor cells.³⁰

³⁰"Ultracapacitors Help Fuel Cells Replace Lead-Acid Batteries." Control Engineering (March 2006): November 26, 2006, <http://www.manufacturing.net/ctl/article/CA6311938.html>.

5. Hydrogen Production

Reviewing hydrogen production revealed several options: “thermal (natural gas reforming, renewable liquid and bio-oil processing, and biomass and coal gasification), electrolytic (water splitting using a variety of energy resources), and photolytic (splitting water using sunlight via biological and electrochemical materials).”³¹ Some of these technologies are barely out of the experimental testing phase, such as using photosynthesis to create hydrogen. The production options which currently produce commercially viable quantities of hydrogen are natural gas reforming, cryogenic gas separation, and electrolysis. The following is a brief description of each process.

Natural gas reforming is a process where thermal energy in the form of high temperature steam is mixed with natural gas which causes chemical reactions to break down natural gas and steam to form carbon monoxide, hydrogen, carbon dioxide, and a little natural gas. The carbon monoxide and water vapor react in the presence of a catalyst to form more carbon dioxide and hydrogen, in a process known as water-gas shift reaction. The gases are then filtered through other scrubber equipment to purify the hydrogen and to capture the carbon dioxide and other impurities. Currently 95% of hydrogen produced in the United States is made using this process.³²

Coal gasification is another thermal process that mixes high temperature steam with coal and air to form synthesis gas, a mixture of hydrogen gas, carbon monoxide and dioxide gases. The synthesis gas is processed using water-gas shift reaction to convert more carbon monoxide and water vapor to hydrogen and carbon dioxide. The gas is then passed through absorbers and membranes to purify the hydrogen. Coal gasification technology is most appropriate for large-scale, centralized hydrogen production, because of the challenge of handling large amounts of coal and the carbon capture and sequestration technologies that must accompany the process. Additionally this sequestration technology needs time to mature.

³¹ "Hydrogen Production Basics." US Department of Energy, Energy Efficiency and Renewable Energy. <http://www.eere.energy.gov/hydrogenandfuelcells/production/basics.html> (accessed November 26, 2006).

³² Ibid.

The other three types of thermal hydrogen production sources rely on pyrolysis or gasification of bio streams to produce a liquid that can then be steam reformed into hydrogen, as described above.

The electrolytic means of producing hydrogen is the process by which electricity is passed through water to split the water into hydrogen and oxygen. The typical system setup is a source of pure water, electric current applied to positive and negative electrodes in a tank of water conditioned with an electrolyte chemical, such as potassium hydroxide, and a separation grid to separate hydrogen and oxygen into their proper storage tanks. These units can be of any size due to the modularity of the design.

Photolytic hydrogen production methods rely on the sun as the energy source to split water or methane into hydrogen.

The process of solar thermal water splitting uses solar collector concentrators to generate the high temperatures needed to directly cause methane to breakdown chemically and react via water-gas shift reaction to form hydrogen and carbon dioxide. This process requires large areas of land and weather conditions that permit abundant sunlight. Due to high efficiency and rates of production, bad weather days can be compensated for by this process on an average production rate basis.³³

Solar energy can be converted by plants, algae, and microbes into hydrogen or oxygen. Current research is trying to find a means of developing a chemical switch by which microbes and algae cells can be harnessed to be self-growing and hydrogen producers in a cyclic pattern.³⁴ This method of production will require sulfur and proper sunlight conditions in addition to large areas to hold the growth vats for the biological water mix that is used for production.

Lastly, hydrogen can be produced via photochemical water splitting by passing water through a multijunction photovoltaic cell, which produces the necessary voltage to split water. This option has a low hydrogen production efficiency, which requires a large

³³ "Hydrogen Production and Delivery." National Renewable Energy Laboratory, Department of Energy. http://www.nrel.gov/hydrogen/proj_production_delivery.html (accessed November 26, 2006).

³⁴ "Hydrogen Production and Delivery." National Renewable Energy Laboratory, Department of Energy. http://www.nrel.gov/hydrogen/proj_production_delivery.html (accessed November 26, 2006).

amount of photovoltaic cells to produce clean hydrogen. Currently, research is underway to identify more efficient, lower cost materials and systems that are durable and stable against corrosion in an aqueous environment.³⁵

D. ENVIRONMENTAL CONSIDERATIONS

Use of hydrogen power yields both risks and benefits. The obvious benefit is derived from end use applications; hydrogen-powered fuel cells generate zero emissions. Generating hydrogen for fueling those cells, however, has unique risks depending on the method used.

There are multiple possible methods for hydrogen generation. Descriptions of these methods can be found in Chapter Three of this report. All methods require some source of energy, some more than others. Options range from powering the process using the common electrical grid to using purely renewable energy sources. Some methods use fossil fuel feedstocks, such as coal, while others use renewable feedstocks, such as water. Environmental risks vary based on the methods used. Brief descriptions of environmental concerns for some of the most common methods under development follow.

Electrolysis: The most obvious environmental concern with electrolysis is that it requires the use of electricity.³⁶ If a common commercial fossil-fueled electrical grid is used as the source of electrical power, the amount of fossil-fuel energy used to generate hydrogen and the corresponding atmospheric emissions may negate the environmental benefit of hydrogen power. Fossil-fueled electricity produces greenhouse gases and other pollutants. If the system is powered by the Pacific Gas and Electric power grid in California, for example, energy sources used to power the grid range from wind power to imported electricity from out-of-state coal power plants. The average percentage of power derived from renewable sources is 25% across the U.S., but up to 40-45% in

³⁵ "Hydrogen Production and Delivery." National Renewable Energy Laboratory, Department of Energy. http://www.nrel.gov/hydrogen/proj_production_delivery.html (accessed November 26, 2006).

³⁶ Philip Baxley, Cynthia Verdugo-Peralta, and Wolfgang Weiss. *Rollout Strategy Topic Team Report, California 2010 Hydrogen Highway Network*. Sacramento, CA: California Environmental Protection Agency, 2005.

California. There is, however, the option of powering the electrolysis system using a separate, dedicated grid powered purely by renewable sources, such as wind or solar energy. This may achieve hydrogen generation with zero emissions.³⁷

Reforming: This method most commonly uses fossil fuels as a feedstock; however, reforming methods using renewable liquid fuels, such as ethanol or methanol, are also under development. Reforming using fossil fuels does generate CO₂ emissions, but there is still a 40 to 50% reduction in these emissions when compared to gasoline-powered cars.³⁸ Greenhouse gas emissions from reforming renewable liquid fuels are predicted to be 60 to 85% lower.³⁹ When methanol is used as a feedstock, despite its benefits as a renewable energy source, there is an environmental downside that should be addressed. It is a known neurotoxin, even when ingested in small amounts, and it can be absorbed through skin. Special handling procedures are required to mitigate this risk, but methanol is not expected to put the general population at risk.⁴⁰

Cryogenic separation: The concern here is again emissions resulting from fuel consumption for an energy-intensive hydrogen generation process and greenhouse gases emitted by processing coal as a feedstock. Cryogenic separation methods that sequester greenhouse emissions and are powered by renewable sources are currently under development, but are not technologically mature and are costly.⁴¹

Other options for advanced gasification are being developed with the intention of reducing the need for fossil-fuel based energy inputs.⁴²

³⁷ Philip Baxley, Cynthia Verdugo-Peralta, and Wolfgang Weiss. *Rollout Strategy Topic Team Report, California 2010 Hydrogen Highway Network*. Sacramento, CA: California Environmental Protection Agency, 2005.

³⁸ Ibid.

³⁹ Ibid.

⁴⁰ John D Osterlch. "Study of the Neurological Effects of Low-Level Methanol in Normal Subjects and Subjects with Susceptibility to Folate Deficiency." California Air Resources Board. <http://www.arb.ca.gov/research/resnotes/notes/95-11.htm> (accessed December 8, 2007).

⁴¹ "Prospects for Hydrogen from Coal." Profiles no. PF 03-09 (December 2003): November 29, 2006, http://www.iea-coal.org.uk/publishor/system/component_view.asp?LogDocId=81106.

⁴² *Gasification Technologies: A Program to Deliver Clean, Secure, and Affordable Energy*. Washington, DC: Department of Energy, National Energy Technology Laboratory, 2001.

There are several other technologies under development that will reduce or eliminate emissions from hydrogen generation, although they are mostly in research and development. These include photobiological, photochemical, biomass gasification, coal gasification with sequestration of CO₂ emissions, and high temperature thermo-chemical hydrogen production. Environmental benefits and developmental state are outlined in Table 3.

Production Mode	Development Status / Industry Readiness	Technical Barriers	Environmental Considerations
Photobiological 1	Photobiological hydrogen production today is still at the basic R&D stage. Barring an unforeseen breakthrough, it is not likely to be commercially viable until after 2015. Two breakthroughs could move photobiological hydrogen production more rapidly to commercialization: (1) An acceptably high rate of hydrogen output, which depends upon solar-to-H ₂ conversion efficiency; and 2) lower photobioreactor costs.	In its early stage of development, the limitation to photobiological hydrogen production is inefficiency. Current solar-to-hydrogen conversion efficiency is only 0.5%. These systems are also constrained by “pond” depth and by diurnal operation limitations. Because they depend upon light, photolytic processes lose efficiency to varying degrees on cloudy days and at greater pond depths and of course are not operational at night without the presence of artificial light.	Carbon neutral process.
Photo-electrochemical 1	Like photobiological hydrogen production, PEC technology is still in the R&D stage. Two breakthroughs would move PEC hydrogen production rapidly to commercialization: (1) the discovery of new materials with a 2015 target efficiency of 14% and 20,000 hours demonstrated durability; and (2) more optimal engineering systems to lower cost of hydrogen produced.	PECs currently have low efficiency and durability. These appear to be mutually antagonistic in many of the materials investigated so far; that is, materials having greater efficiency have tended to be less durable and vice versa. Similarly, semiconductor materials that have more optimal band gaps to produce sufficient electricity for splitting water have had disappointingly low visible light spectrum absorption capability and vice versa. Like photo-biological processes, PEC needs light to function.	This technology is expected to be carbon-free, but that may depend upon the electrolyte that is used.

Production Mode	Development Status / Industry Readiness	Technical Barriers	Environmental Considerations
Coal Gasification with CO ₂ Capture and Sequestration Large, central option: not scalable (150-600 t/day H ₂) Delivered by Compressed Gas or LH ₂ Truck or Gas pipeline	Coal gasification is commercial technology; CO ₂ capture and sequestration demonstrations ongoing; could be developed in near term.	Technical barriers center on cost reduction rather than feasibility. CO ₂ sequestration is still being proven via large scale demos.	Impact of CO ₂ on underground storage reservoirs; need for long term monitoring to detect leaks.
Biomass Gasification (75-150 t/d) Midsize central option, smaller than coal H ₂ systems Delivered by Compressed Gas or LH ₂ Truck or Gas Pipeline	Demonstrated at pilot plant scale.	Technical barriers center on cost reduction rather than feasibility.	Land use Constraints (requires use of large land areas), depends on low cost biomass feedstocks.
High temperature Thermochemical H ₂ Production (Nuclear) Large, central Delivered by Compressed Gas or LH ₂ Truck or Gas Pipeline	Experimental, laboratory stage	Hydrogen production from these technologies has not been proven, and subsystems have not been evaluated; new cost-effective materials operating at high temperatures and temperature cycling need to be developed.	Same as nuclear power; serious public safety, environmental, and political issues.
Thermo-chemical H ₂ Production (Solar). Size not yet determined. Delivered by Compressed Gas or LH ₂ Truck or Gas Pipeline	Experimental, laboratory stage.	Hydrogen production from these technologies has not been proven, and subsystems have not been evaluated; new cost-effective materials operating at high temperatures and temperature cycling need to be developed.	Land use for solar Concentrators.

Table 3. Technical and Environmental Concerns for Developmental Extraction Technologies⁴³

⁴³ Philip Baxley, Cynthia Verdugo-Peralta, and Wolfgang Weiss. *Rollout Strategy Topic Team Report, California 2010 Hydrogen Highway Network*. Sacramento, CA: California Environmental Protection Agency, 2005.

E. MAINTENANCE AND LOGISTICS CONCERNS

In their current state of development, hydrogen fuel cells have multiple concerns. PEM fuel cells are sensitive to impurities in the hydrogen and the catalyst is precious metal (platinum) and thus relatively expensive to manufacture.⁴⁴ Fuel cells are currently very expensive and large-scale production is needed to reduce these costs. Fuel cell vehicle range is limited with current fuel storage options. Gasoline typically provides 300-400 miles of range while fuel cells provide 60-150 miles of range, with large vehicles (busses) able to get up to 250 miles by carrying larger storage tanks.

Fuel cells run on hydrogen fuel. A "reformer" reformulates non-hydrogen fuels such as gasoline, methane, etc., to turn them into hydrogen. A reformer is expensive and produces emissions that may offset the advantage of using hydrogen by itself.

Fuel cells are still in a relatively early stage of development and even the few commercially available models have limited fleet operating experience. This emerging technology requires risk-taking early adopters as end users to expose more consumers to the benefits of fuel cells.⁴⁵ In order to become widely accepted as clean distributed generators, fuel cells must prove their adaptability for a variety of applications. Certain fuel cell system components—like the cell stack, which can require a costly replacement every one to five years depending on the model—must be developed to have a longer lifespan or be easily and cheaply replaced.⁴⁶

Despite risks associated with technological immaturity, hydrogen-fueled GSE may have significant logistic benefits over diesel-powered GSE. Hydrogen fuel cells are inherently modular, and they operate at near constant efficiency, independent of size and load. The fuel cell power plant can be configured in a wide range of electrical outputs,

⁴⁴ *Fuel Cell Handbook, Seventh Edition*. Morgantown, WV: National Energy Technology Laboratory, Department of Energy, 2004.

⁴⁵ "Energy Information: Fuel Cells." Massachusetts Technology Collaborative. <http://www.mtpc.org/cleanenergy/cells.htm> (accessed November 25, 2006).

⁴⁶ *Ibid.*

ranging from single kilowatt sizes up to multi-megawatt systems.⁴⁷ The absence of combustion and moving parts means that fuel cell technologies have the potential for much improved reliability over traditional combustion engines in some vehicles.⁴⁸ Improved reliability is synonymous with a reduction in failures, and therefore may result in a reduction in maintenance requirements. Maintenance benefits are further evaluated in the analysis section of this report.

⁴⁷ "Fuel Cell Information: Fuel Cell Benefits." National Fuel Cell Research Center, University of California Irvine. http://www.nfcrc.uci.edu/fcresources/FCexplained/FC_benefits.htm (accessed November 23, 2006).

⁴⁸ "Advantages and Benefits of Fuel Cell and Hydrogen Technologies." Fuel Cell Markets, Ltd. http://www.fuelcellmarkets.com/article_flat.fcm?subsite=1&articleid=663 (accessed November 26, 2006).

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III. METHODOLOGY

A. QUALITATIVE SAFETY ASSESSMENT

In conducting a Cost Benefit Analysis, an organization must consider both qualitative and quantitative assessments. Particular to establishing a Hydrogen program are safety concerns, which should be considered and will be addressed in the analysis portion of this report. Key factors considered are safety hazards and hazard mitigation methods. The analysis is a comparison between hydrogen gas and diesel in these two areas of concern. The remainder of this methodology section will detail variables, distributional assumptions, and procedures used in the quantitative analysis.

B. QUANTITATIVE ANALYSIS

The Cost Benefit Analysis of Hydrogen Powered Ground Support Equipment is a simulation built on a Crystal Ball™ analysis driven by Microsoft Excel™ software. Key factors that are looked at are safety hazards and hazard mitigation methods. The analysis is a comparison between hydrogen gas and diesel in these two areas of concern. The remainder of this methodology section will detail variables, distributional assumptions, and procedures used in the quantitative analysis.

1. Assumptions

The simulation is in a spreadsheet, an analysis tool that quantifies the following costs and indirect benefits associated with establishing and operating a hydrogen processing operation (assumptions around key variables are explained in greater detail below):

a. Annual Recurring Costs

- Infrastructure expenditures
- Cost of refilling
- Transport cost of hydrogen
- Maintenance cost
- Labor cost
- Filter cost

- Waste disposal
- Hazmat cost

b. One Time Expenses

- Equipment conversion cost for A/S32A-42 Tow Tractor
- Equipment conversion cost for A/M27T-5/A Hydraulic Cart
- Equipment conversion cost for A/M32A-108 Electric Cart

c. Plant Costs

- Procuring the plant
- Leasing the plant

d. Indirect Benefits

- Training value realized through reduced I-Level training costs
- Reduced emissions

e. Usage and Inventory Assumptions

The model has been developed as a planning tool for decision makers to evaluate potential cost reductions and quantify indirect benefits that manifest themselves in reduced training costs at the organizational level and reduced emissions, providing an environmental benefit. Naval Air Station Lemoore is a notional site for the pilot project; thus usage and analysis data used in the model are derived from the Fleet Readiness Center (FRC) at that location.

f. Costs Overview

The following assumptions will be used in the analysis section, and serve to extrapolate predicted values and costs, ultimately justifying conclusive recommendations. These assumptions are based on data received from Dave Cook at Naval Facilities Engineering Service Center, Port Hueneme, California.

g. Recurring Costs

These are comprised of infrastructure expenditures, including the cost of refilling, with a uniform distribution valued between \$14,400 and \$17,600 per year and the hydrogen transportation cost, with a normal distribution and a mean of \$3,000 and standard deviation of \$300 per year.

h. Maintenance Costs

Maintenance costs include direct labor costs, with a normal distribution and a mean of \$7,000 and a standard deviation of \$700 per year, and filter costs, with a uniform distribution between \$3,600 and \$4,400 per year.

i. Annual HAZMAT Processing Costs

These costs have an associated value of \$6,000 per year.

j. One Time Expenses for Conversion of Individual GSE

These are based on data provided by representatives from General Hydrogen, Concurrent Technologies Corporation and Naval Air Systems Command and are all uniformly distributed.

(1) Conversion of one A/S32A-42 Tow Tractor ranges from \$30,000 to \$50,000.

(2) Conversion of one A/M 27T-5/A Hydraulic Cart ranges from \$10,000 to \$30,000

(3) Conversion of one A/M32A-108 Electric Cart iranges from \$10,000 to \$30,000.

k. Discount Rate

An 8% discount rate is based on the assumption that a project would run at least as long as the model's time analysis, which is five or ten years. The discount rate creates a conservative output, and can be adjusted up or down to meet decision makers' requirements, economic assumptions, and regulations.

l. Building and Leasing Costs

While the assumption to build or lease the hydrogen plant is discussed in the analysis section, these values are based on data received from Dave Cook at Naval Facilities Engineering Service Center, Port Hueneme, California.

(1) A constant value to procure one hydrogen plant is valued at \$350,000 with an annual 15% maintenance cost.

(2) Leasing a production plant is valued at \$100,000 annually.

m. Training Costs

Training values are set at current Chief of Naval Education and Training school duration and are annotated in Table 4.

	ATT (Required)	Diesel in hours	Hydrogen in hours
A/S32A-42 Tow Tractor	224	240	69
A/M 27T-5/A Hydraulic Cart	224	282	68
A/M32A-108 Electric Cart	224	171	82

Table 4. Training required for I level maintenance qualification. All maintainers require ATT, followed by training in either diesel or hydraulic systems.

n. Emission Levels

Emission levels are derived from the Environmental Protection Agency’s most recent issue of “Technical Support for development of Airport Ground Support Equipment Emission Reductions.”

C. ANALYSIS SCENARIOS

Analysis was conducted on three scenarios (set of input parameter values):

1. Scenario 1

Scenario 1 considers setting quantities of all recurring costs to one and setting the number for conversion for each piece of equipment to one, the minimum acceptable level in the model. Consideration was given to buying a plant with a time frame analysis of both five and ten years and with a leasing option for both five and ten years. Intermediate level training requirements were set to 10 personnel. This scenario is meant to represent a ‘minimum buy-in’ option, and is also included as a base case for the purposes of model validation.

2. Scenario 2

Scenario 2 considers setting quantities of all recurring costs to one, setting intermediate level training requirements to 15 personnel and setting the number for conversion for each piece of equipment as follows (based on 20% of Naval Air Station Lemoore's current inventory of 35, 40 and 25 respectively):

- A/S32A-42 Tow Tractor conversion at 7 units
- A/M 27T-5/A Hydraulic Cart conversion at 8 units
- A/M32A-108 Electric Cart conversion at 5 units

This scenario is meant to represent a smaller scale 'shake-down' pilot implementation, in which a significant portion (20%) of the equipment is converted, but the large majority remains diesel powered.

3. Scenario 3

Scenario 3 considers setting quantities for all recurring costs to one, and setting the number for conversion for each piece of equipment to fifteen, the maximum acceptable level in the model. Consideration was given to buying a plant with a time frame analysis of both five and ten years, and to a leasing option, again for both five and ten years. Intermediate level training requirements were set to 20 personnel, the model maximum. This report did not examine a 'total conversion' scenario in which all equipment was converted for the pilot, because that was considered unrealistic. Hence, this scenario is meant to represent the largest-scale pilot implementation is likely to be undertaken.

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IV. ANALYSIS

A. SAFETY HAZARDS OF GASEOUS HYDROGEN VS. LIQUID DIESEL FUEL

Table 5 shows a qualitative comparison of hydrogen fuel safety concerns to diesel fuel safety concerns. Hydrogen power has several safety benefits over diesel, but has high explosive potential.

	Hydrogen	Diesel/Fuels
Health hazards due to inhalation.	There is some risk of asphyxiation resulting from oxygen deprivation. ⁴⁹	Short term effects of inhalation include dizziness, headaches, ⁵⁰ nausea, and fatigue. ⁵¹ Long term effects. Long term effects include damage to blood, ⁵² liver, kidneys, heart, lungs, and nervous system. ⁵³
Health hazards due to ingestion.	Not applicable.	Same as those for prolonged inhalation. ⁵⁴ If swallowed, diesel may enter the lungs, resulting in injury and possibly death. ⁵⁵

⁴⁹ Safetygram #4: Gaseous Hydrogen. Allentown, PA: Air Products and Chemicals, Inc., 2004.

⁵⁰ OPNAV P-45-110-961996 : Hazardous Material User's Guide. 1996.

⁵¹ Roy J. Irwin, Mark Van Mouwerik, Lynette Stevens, Marion Dubler Seese, and Wendy Basham. "Diesel Oil." in Environmental Contaminants Encyclopedia. Fort Collins, CO: National Park Services, Water Resources Divisions, Water Operations Branch, 1997.

⁵² OPNAV P-45-110-961996 : Hazardous Material User's Guide. 1996.

⁵³ Roy J. Irwin, Mark Van Mouwerik, Lynette Stevens, Marion Dubler Seese, and Wendy Basham. "Diesel Oil." in Environmental Contaminants Encyclopedia. Fort Collins, CO: National Park Services, Water Resources Divisions, Water Operations Branch, 1997.

⁵⁴ Ibid.

⁵⁵ Material Safety Data Sheet, Diesel Fuel no. 2. Richmond, CA: Chevron Energy Technology Company, 2006.

	Hydrogen	Diesel/Fuels
Health Hazards due to skin contact	None. Hydrogen is non-toxic.	Short term effects include skin irritation, blistering, redness, and dryness. ⁵⁶ Prolonged contact may result in dermatitis.
Health Hazards due to eye contact	None. Hydrogen is non-toxic.	Eye contact with diesel can cause discomfort and irritation. ⁵⁷
Reproductive Hazards	None. Hydrogen is non-toxic.	Some immunological, reproductive, fetotoxic, and genotoxic effects have been associated with some of the compounds found in diesel fuel. ⁵⁸
Environmental Hazard (Leakage or Spillage)	None. Hydrogen gas dissipates into the atmosphere. Pure hydrogen is not a pollutant. ⁵⁹	In the event of a fuel spill, there is risk of contamination to the local water table, presenting health hazards to the general population and potential acute toxicity to aquatic life. ⁶⁰

⁵⁶ OPNAV P-45-110-961996: Hazardous Material User's Guide. 1996.

⁵⁷ Philip Baxley, Cynthia Verdugo-Peralta, and Wolfgang Weiss. Rollout Strategy Topic Team Report, California 2010 Hydrogen Highway Network. Sacramento, CA: California Environmental Protection Agency, 2005.

⁵⁸ Roy J. Irwin, Mark Van Mouwerik, Lynette Stevens, Marion Dubler Seese, and Wendy Basham. "Diesel Oil." in Environmental Contaminants Encyclopedia. Fort Collins, CO: National Park Services, Water Resources Divisions, Water Operations Branch, 1997.

⁵⁹ "Air Toxics Web Site: Original List of Hazardous Air Pollutants." US Environmental Protection Agency. <http://www.epa.gov/ttn/atw/orig189.html> (accessed December 12, 2006).

⁶⁰ Roy J. Irwin, Mark Van Mouwerik, Lynette Stevens, Marion Dubler Seese, and Wendy Basham. "Diesel Oil." in Environmental Contaminants Encyclopedia. Fort Collins, CO: National Park Services, Water Resources Divisions, Water Operations Branch, 1997.

	Hydrogen	Diesel/Fuels
Flammable/Explosive Hazard	Air is flammable with 4% to 74% hydrogen content, and requires very little energy for ignition within this range. ⁶¹ Hydrogen has the highest burning velocity of any gas. ⁶²	Diesel has a flash point 125 degrees Fahrenheit, with an external ignition source. Autoignition temperature is 494 Fahrenheit. Diesel is stable at normal temperatures and pressures. ⁶³
Noise Pollution Hazard	Hydrogen fuel cells have less moving parts than internal combustion engines; therefore they produce significantly less noise. ⁶⁴	Highways are currently a major source of noise pollution in US metropolitan areas. Noise is generated by vehicles powered by traditional internal combustion engines.

⁶¹ Safetygram #4: Gaseous Hydrogen. Allentown, PA: Air Products and Chemicals, Inc., 2004.

⁶² "Hydrogen (H2) Carrier Gas Safety Guide." Agilent Technologies.
<http://www.chem.agilent.com/cag/servsup/psnews/h2safety.html> (accessed December 11, 2006).

⁶³ Material Safety Data Sheet, Diesel Fuel no. 2. Richmond, CA: Chevron Energy Technology Company, 2006.

⁶⁴ Kate Figiel and James Rhodes. Transition to a Hydrogen-Based System: Next Ten Years. Department of Engineering and Public Policy, Heinz School of Public Policy and Management, Carnegie Mellon University, No year given.

	Hydrogen	Diesel/Fuels
Air Pollution Hazard	Hydrogen fuel produces no emissions other than water vapor when burned in a combustion engine. ⁶⁵	Diesel combustion generates greenhouse gases and other pollutants, including sulfur. ⁶⁶ Typically, one gallon of diesel produces 10,084 grams of CO ₂ . ⁶⁷
Equipment Damage	Metals exposed to hydrogen at elevated temperatures and pressures may suffer embrittlement. Vessels and piping used for transportation and storage of hydrogen must be designed to American Society of Mechanical Engineers and the Department of Transportation to mitigate this risk. Hydrogen is non-corrosive. ⁶⁸	During the combustion process, diesel fuel produces corrosive gases, such as sulfur and nitrous oxide. ⁶⁹

Table 5. Safety Hazards of Gaseous Hydrogen vs. Liquid Diesel Fuel

Hydrogen's high explosive risk can be mitigated by using appropriate protective gear, instructing handlers in safety precautions and proper procedures for transportation, storage, and usage, and ensuring facilities are designed to prevent incidents. Recommended measures are in Table 6.

⁶⁵ Philip Baxley, Cynthia Verdugo-Peralta, and Wolfgang Weiss. Rollout Strategy Topic Team Report, California 2010 Hydrogen Highway Network. Sacramento, CA: California Environmental Protection Agency, 2005.

⁶⁶ "Diesel." Wikimedia Foundation. <http://en.wikipedia.org/wiki/Diesel> (accessed December 11, 2006).

⁶⁷ Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel. Washington, DC: US Environmental Protection Agency, 2005.

⁶⁸ Safetygram #4: Gaseous Hydrogen. Allentown, PA: Air Products and Chemicals, Inc., 2004.

<p>Safe hydrogen facility design:</p> <ul style="list-style-type: none"> ○ Remove ignition sources (sources of electrical spark or static, high heat, or flame) from the operating environment wherever possible. ○ Provide adequate ventilation. Forced ventilation may be necessary in some facilities. ○ Design gaseous hydrogen system for thorough purging (purged of all oxygen, air, or other oxidizers prior to introduction of hydrogen, and purged of all hydrogen prior to opening the system to atmosphere). In systems with extensive piping, purge first with an inert gas between evacuations. ○ Use flammable gas analyzer (portable or continuous). ○ Buildings and all electrical equipment should be electrically grounded to avoid sparking. Building material should be noncombustible. ○ Protect cylinders from extreme weather conditions, electrical, and heat sources. ○ Cylinders should not be stored near oxidents. ○ System must be located above ground; if possible, on higher ground than other flammable liquids and oxygen, including storage and piping. If not possible to place on higher grounds, proper protection should be provided for the hydrogen storage facility (diking, grading, diversion curbs). ○ Post “no smoking” and “open flame” signs.
<p>Mitigate risk in storage and handling.</p> <ul style="list-style-type: none"> ○ Ensure personnel are properly trained and practice prescribed handling techniques for hydrogen cylinders (e.g. never drag or slide cylinders along the floor, never tamper with valve safety devices). ○ Personnel should wear appropriate PPE when handling hydrogen cylinders; safety glasses, safety shoes, and leather gloves are recommended.

Table 6. Precautionary Measures for Handling and Storing Hydrogen.⁷⁰

B. COST BENEFIT ANALYSIS

The methodologies, information, and assumptions given earlier in this report drive the hydrogen power cost benefit analysis. It is built around GSE usage, inventory, and cost information from Naval Air Station Lemoore, coupled with best-available emissions data from reports published by the Environmental Protection Agency, including tracking pollutants which fall under the Clean Air Act (CAA). Various seed values were used to

⁶⁹ Fuels, Engines, and Emissions: Assessment of Corrosion Potential in Diesel Exhaust via Application of a Specialized Probe. Oak Ridge, TN: US Department of Energy, Oak Ridge National Laboratory, Freedom Car and Vehicle Technologies Program, 2003.

⁷⁰ Safetygram #4: Gaseous Hydrogen. Allentown, PA: Air Products and Chemicals, Inc., 2004.

populate the model and draw comparisons between relevant decision points in the process. Results will show not only the mean expected cost or benefit, but also the fifth and 95th percentiles of the forecast distribution given by Crystal Ball (that is, a 90% certainty interval). Note that these intervals are not the same as confidence intervals around the mean. Assuming the model has been specified correctly, certainty intervals represent the outcomes that might be realized within the given probability range. They do not address the likelihood that the mean is correct, but rather address the risk (upside and downside) of achieving values different from the mean. Several of the graphs output from Crystal Ball are given in addition to the key output values as examples to aid in building decision makers' intuitions about outcome risks.

1. Scenario 1: Minimum Buy-In

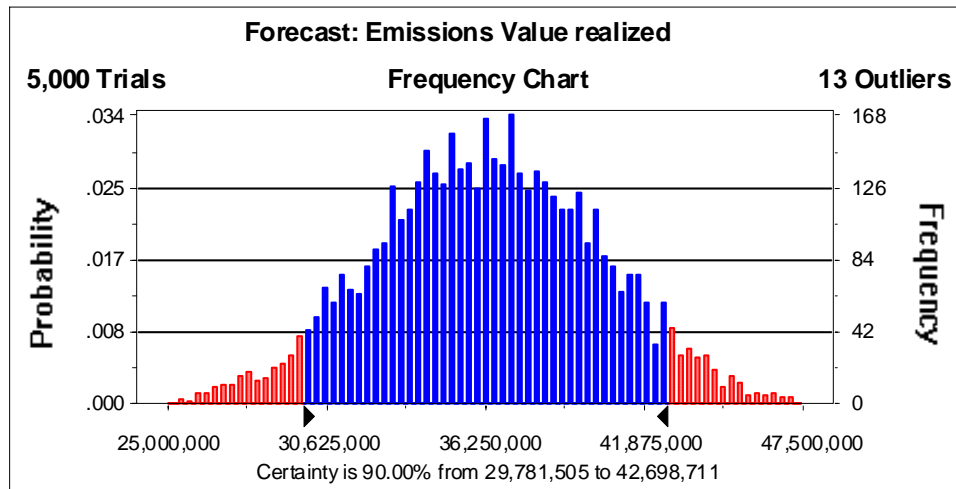


Figure 1. Indirect benefit emission reduction value realized in assumption 1

Scenario 1 results in an indirect annual benefit of emission reduction in grams of pollutants between 29,781,505 grams and 42,698,711 grams, based on a certainty interval between 5 and 95 percentile with a mean reduction of 36,348,339 grams. See Figure 1. Another indirect benefit is a reduced cost of Intermediate Level Maintenance Training between \$80,055 and \$297,213, with a mean of \$192,972. In sum, these results indicate that significant indirect benefits can be obtained even with a 'minimum buy-in'.

One-time costs (excluding plant) are estimated between \$62,690 and \$96,103, with a mean of \$80,063. Recurring costs (excluding plant) are estimated between \$33,707 and \$38,258 with a mean of \$35,983.

Total project costs (including plant) are analyzed in four separate sub-scenarios: Buy vs. Lease, and 5 vs. 10 year decision horizons.

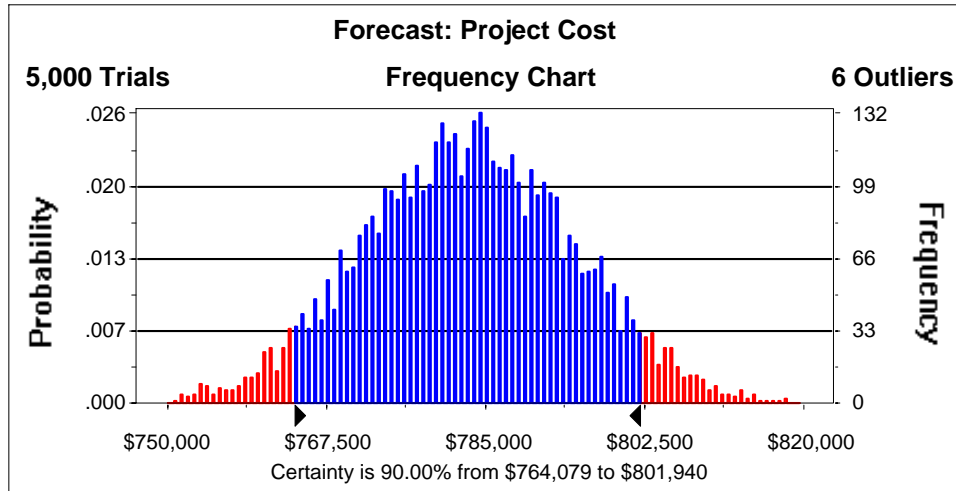


Figure 2. Project cost in assumption 1A, Buy, 5-year horizon

Overall project costs for analysis 1A assume a plant cost summary with a buy option spanning 5 years and an overall project cost between \$767,500 and \$802,500, and a mean of \$783,351 (See Figure 2). Overall project cost 1B assumes a plant cost summary with a lease option spanning 5 years and an overall project cost between \$603,385 and \$640,057, and a mean of \$623,063 (See Figure 3). Overall project cost 1C assumes a plant cost summary with a buy option spanning 10 years and an overall project cost between \$1,001,503 and \$1,045,352, and a mean of \$1,023,788. Overall project cost 1D assumes a plant cost summary with a lease option spanning 10 years and an overall project cost between \$970,538 and \$1,015,521, with a mean of \$992,823. For both horizons, the lease option has a lower expected cost, and a lower ‘downside risk’ of high costs (i.e., those high costs seen no more than 5% of the time in the simulation were lower in the ‘lease’ options).

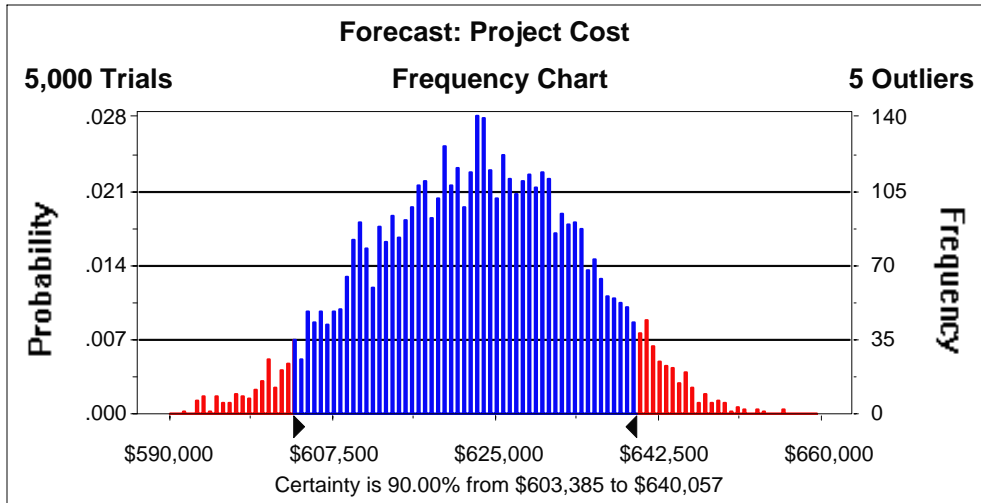


Figure 3. Project cost in assumption 1B, Lease, 5-year horizon

2. Scenario 2: Small Scale Pilot

Analysis of Scenario 2 assumptions result in an indirect annual benefit of emission reductions between 30,409,202 and 41,565,232 grams of pollutants, with an expected mean reduction of 36,400,106 (see Figure 4). Another indirect benefit is a reduced cost of Intermediate Level Maintenance Training costs between \$131,499 and \$456,336, with an expected reduction of \$290,294.

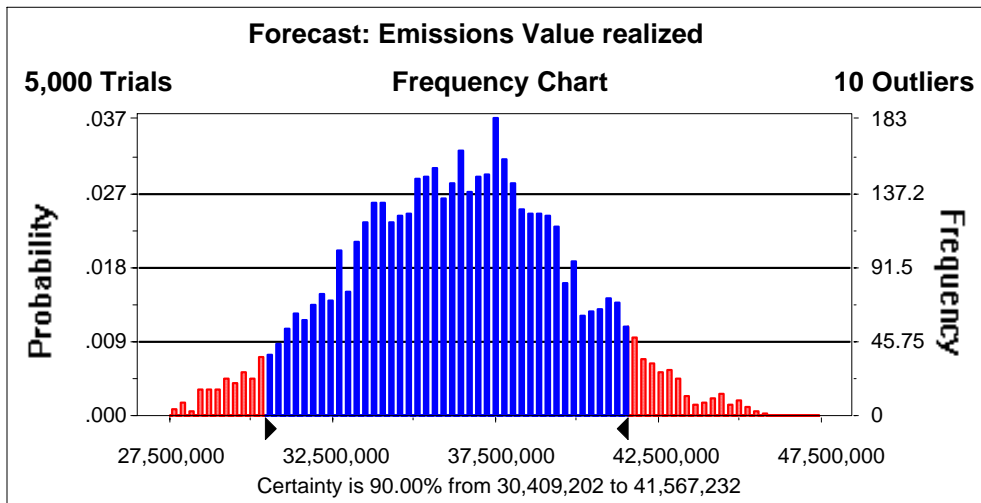


Figure 4. Indirect benefit emission reduction value realized in Scenario 2

One-time costs (excluding plant) is estimated between \$498,213 and \$583,143 with a mean of \$539,907, while the recurring costs (excluding plant) are estimated

between \$33,797 and \$38,321 with a mean of \$35,998. Overall project cost 2A assumes a plant cost summary with a buy option spanning 5 years and an overall project cost between \$1,200,626 and \$1,286,717, with a mean of \$1,243,253 (see Figure 5).

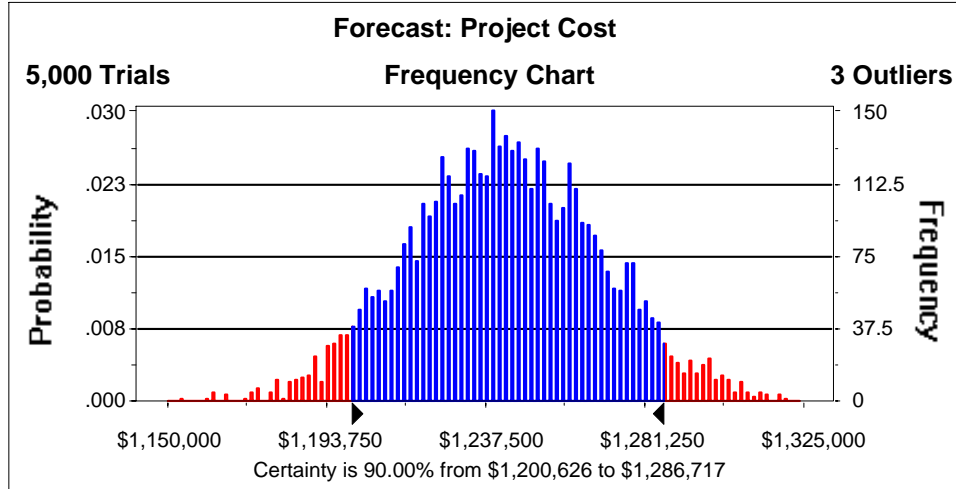


Figure 5. Project cost in assumption 2A, Buy option, 5-year horizon

Overall project cost 2B assumes a plant cost summary with a lease option spanning 5 years and an overall project cost between \$1,038,828 and \$1,125,617 and a mean of \$1,082,874 (see Figure 6). Note that the lease option is still more attractive for the short time horizon, even with the commitment to convert additional equipment.

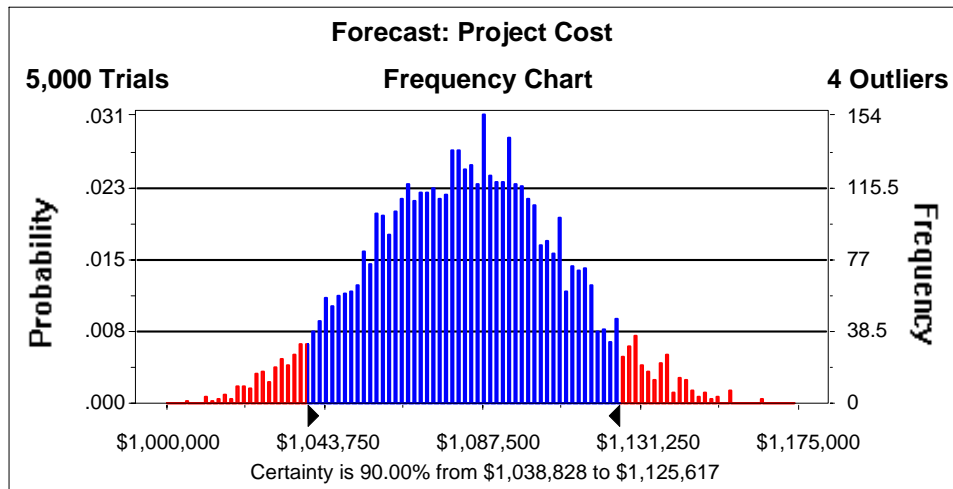


Figure 6. Project cost in assumption 2B, Lease Option, 5-year horizon

Overall project cost 2C assumes a plant cost summary with a buy option spanning 10 years and an overall project cost between \$1,439,290 and \$1,528,348, with a mean of \$1,483,341 (See Figure 7).

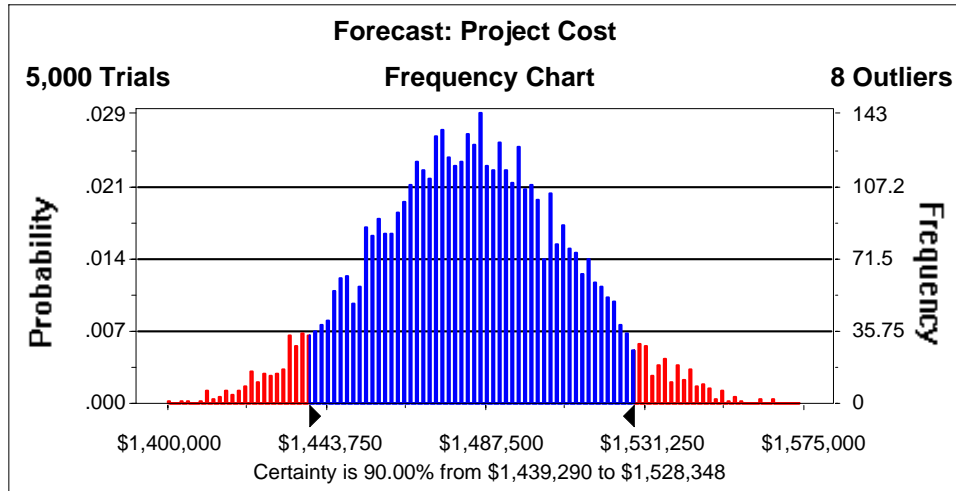


Figure 7. Project cost in assumption 2C, Buy Option, 10 year horizon

Overall project cost 2D assumes a plant cost summary with a lease option spanning 10 years and an overall project cost between \$1,407,109 and \$1,496,416, with a mean of \$1,453,025 (See Figure 8). With a 10-year time horizon and a commitment to convert 20% of the vehicles, the buy option begins to be economically attractive, but the lease option remains preferable.

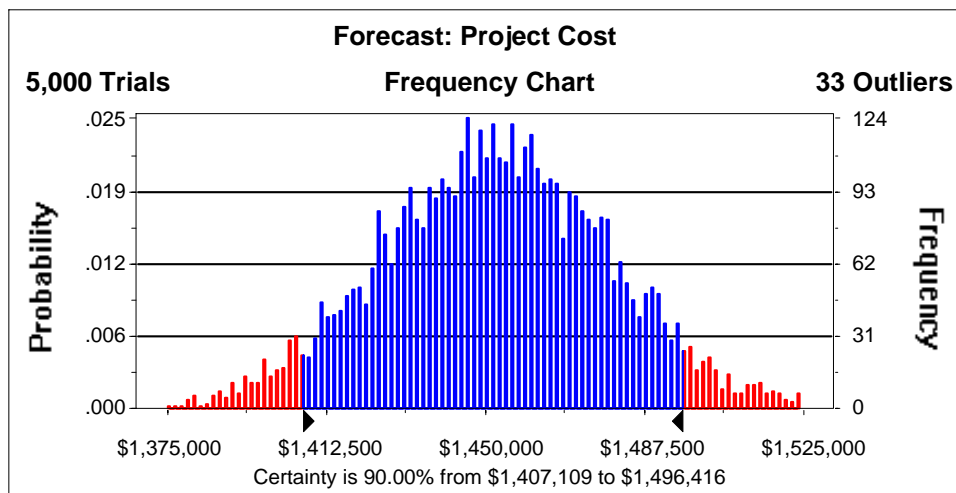


Figure 8. Project cost in assumption 2D, Lease Option, 10 year horizon

3. Scenario 3: Large Scale Pilot

Scenario 3 assumptions result in an indirect benefit of emission reduction in grams of pollutants annually between 30,930,174 and 41,641,841 with a mean of 36,309,819 (see Figure 9), and a reduced cost of Intermediate Level Maintenance training costs between \$345,194 and \$423,610 with a mean of \$384,869. All values were determined with a 90% certainty.

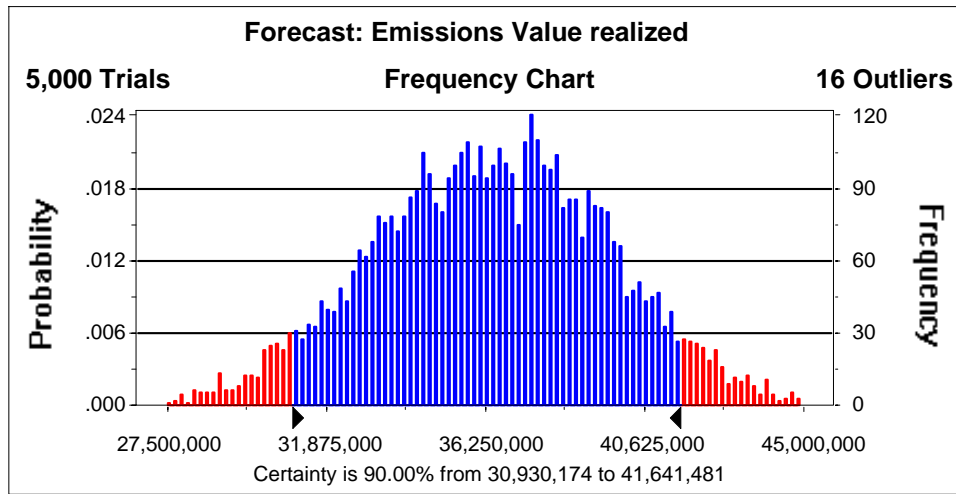


Figure 9. Indirect benefit emission reduction value realized in Scenario 3

One-time costs are estimated between \$1,134,611 and \$1,262,149, with a mean of \$1,199,484, while recurring costs are estimated between \$33,759 and \$38,204, with a mean of \$35,978. Overall project cost 3A assumes a plant cost summary with a buy option spanning 5 years and an overall project cost between \$1,836,727 and \$1,965,491, with a mean of \$1,902,751. Overall project cost 3B assumes a plant cost summary with a lease option spanning 5 years and an overall project cost between \$1,680,062 and \$1,810,635, with a mean of \$1,743,133. Note that even with a large-scale pilot, the buy option is not attractive for a five-year decision horizon.

Overall project cost 3C assumes a plant cost summary with a buy option spanning 10 years and an overall project cost between \$2,075,218 and \$2,207,970, with a mean of \$2,144,165 (See Figure 10).

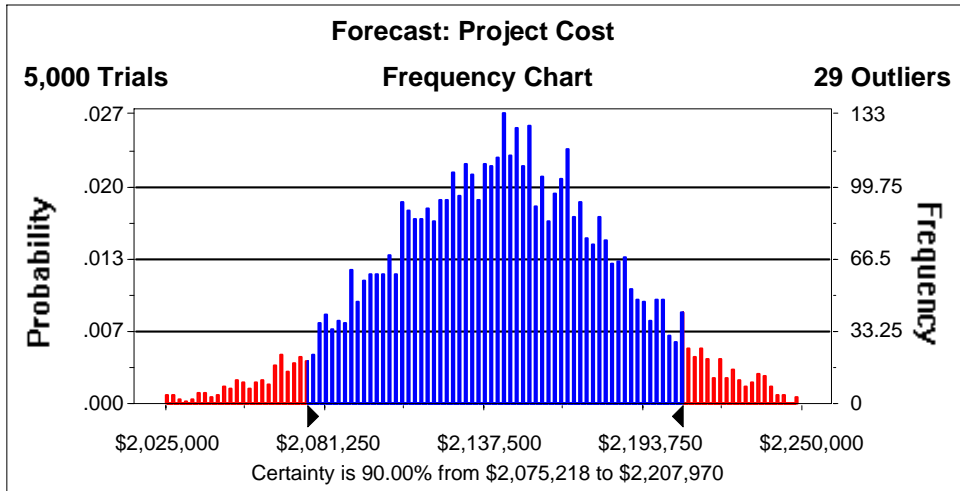


Figure 10. Project cost in assumption 3C, buy option, 10 year horizon

Overall project cost 3D assumes a plant cost summary with a lease option spanning 10 years and an overall project cost between \$2,046,490 and \$2,178,364, with a mean of \$2,112,384 (see Figure 11). At the 10-year horizon, the buy option is again more attractive than at the 5-year horizon – but not markedly more attractive in scenario 3 than it was in scenario 2. In sum, the scale of the pilot may be less important—in deciding whether to lease or buy plant capacity—than the time frame over which the commitment is made to pursue the pilot, and a time frame longer than 10 years may be necessary in order to justify the decision to build.

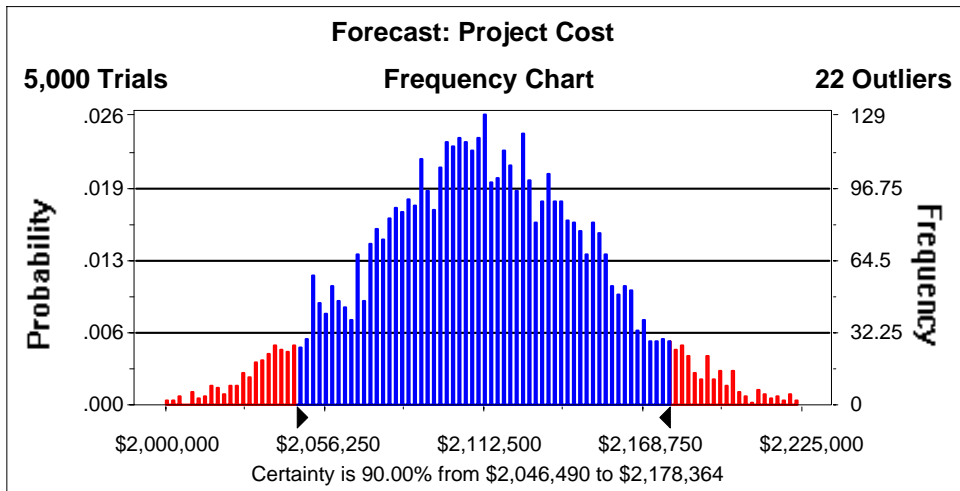


Figure 11. Project cost in assumption 3D, Lease option, 10-year horizon

Based on the three scenarios analyzed, the indirect benefits of both training and emission reduction should be considered by the organization in addition to any direct impact to local funding caused by a reduction in the recurring expenses associated with running hydrogen versus diesel vehicles.

As with any analysis tool, the output computed by the model is derived from the assumptions and deliverables, and therefore produces a result with the inherent limitations of the assumptions. For example, a key assumption that has been made is that plant maintenance expense can be reduced to zero at the end of the decision horizon. However, plant capacity that has been built (rather than leased) may continue to require operational expense, even if the pilot project is abandoned.

The incremental recurring expense of hydrogen fuel cell vehicles versus diesel vehicles is not considered to be within the scope of this project. An analysis of that type requires examining the cost distribution of operating diesel vehicles. The recurring costs reported here should be compared to the recurring costs of operating diesel vehicles in order to obtain a complete picture of the potential benefits of a pilot project.

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V. CONCLUSION

Hydrogen power opportunities present benefits to be realized across multiple spectrums. Reduced levels of pollutants coupled with lower training and maintenance costs make evaluating hydrogen power opportunities essential to satisfying future power requirements. This analysis demonstrates the qualitative and quantitative benefits of creating a hydrogen power plant and providing hydrogen power to aviation ground support equipment. Command-level decision makers can personalize their assumptions and variables by modifying the model to reflect both their current GSE inventories and their financial constraints. Additionally, they can interpret and assign an internal value to two indirect benefits being captured in the model based on equipment usage statistics. By comparing usage levels with training requirements and emission data, decision makers can assign a value to these indirect benefits. A final aspect addressed in the analysis section is the consideration of safety impacts. Although not quantitative, considering safety aspects of a program is proven to have significant impact to the success of a program.

The ability to apply the model to a unique situation will permit the user to validate existing costs, forecast expenses and draw conclusions about the applicability and benefit of establishing a hydrogen program, the number of vehicles to convert to hydrogen power, and whether to purchase or lease a plant. All of these considerations can be placed across a varying timeframe to determine breakeven points. By examining recurring and one-time costs and comparing those to current costs with diesel vehicles, sound business decisions can be made about the feasibility, affordability and expected return on investment.

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