FEASIBILITY STUDY OF HYDROGEN POWERED HEAVY CONSTRUCTION EQUIPMENT

By

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To my family, for listening and supporting me in my wild endeavors

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I would like to express thanks to my family for always listening and enlightening me of the harsh realities of life. Over the years they have supported me, through what at times, had to be difficult. And most all, thanks to my parents for their unyielding support in my discovery of the sciences, without which I would not be where I am today.

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LIST OF ABBREVIATIONS

A	Amp
AC	Alternating Current
Ah	Amp-hour
dB(A)	Decibel
DoD	Depth of Charge
DOE	Department of Energy
EoE	Encyclopedia of Earth
EERE	Energy Efficiency and Renewable Energy
FTP	Federal Test Procedure
KE	Kinetic Energy
Kg	Kilogram
kJ	kilojoules
Kph	Kilometer/hour
kW	kilowatt
kWh	kilowatt-hour
kw/l	kilowatt/liters
l	liter
LVH	lower heating value
Lbs	pounds
m	mass
m	meters
m/kg	miles/kilogram
m/dge	miles/diesel gallon equivalent
mph	miles/hour

NEDC	New European Driving Cycle
NREL	National Renewable Energy Laboratory
PMI	Preventative Maintenance Inspection
PSI	Pounds/Square Inch
PEM	Polymer Electrolyte Membrane
s	seconds
SoC	State of Charge
v	velocity
V	Volt
W	watt

Abstract of Thesis Presented to the Graduate School
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Chair: Ian Flood
Cochair: Robert Ries
Major: Building Construction

The price of oil is more volatile than ever before and its use has unknown long term effects on the environment and human health. Adverse environmental and health conditions are more prominent in metropolitan areas due to the density of emissions producing vehicles. In order to help mitigate the effects of exhaust production and better estimate the cost of fuel, a hydrogen powered track-type tractor commonly referred to as a dozer was proposed.

In order to best determine feasibility of such a machine several steps were taken. First, the energy requirements of the fuel cell and battery were determined. From there, the volume of hydrogen required for a typical 8 hour shift was found and used to find the size of the hydrogen fuel cell. In order to reduce the space requirements of the fuel cell, a pressure of 10,000 PSI was used. Costs were divided into operating and non-operating costs. Maintenance costs were taken from the CTtransit Hydrogen Bus research project. Though the cost of replacement parts was not significant labor was.

Pricing of the hydrogen components were found using the U.S. Department of Energy, Energy Efficiency and Renewable Energy Laboratory 2010 and 2015 high

volume estimates. After analysis it was found that the current 2010 estimated total present value of the operating and non-operating costs of the hydrogen dozer were surprisingly inexpensive although more than the baseline comparison. However, the 2015 estimate values make the hydrogen dozer a cheaper machine to maintain and operate, and offers a quicker payback period.

What makes hydrogen power equipment so appealing is that the cost of hydrogen fuel is only expected to decrease with time rather than increase as with the cost of oil. An added benefit is the total elimination of pollution being generated by the equipment. With further research, hydrogen technology could expand to other equipment used throughout the construction industry.

CHAPTER 1
INTRODUCTION

Problem Statement

The vast majority of heavy construction equipment throughout the world is powered using diesel fuel. There will come a time in the future where the price of oil will reach the point where it no longer makes economic sense to use diesel fuel as a primary energy source. As the price of oil becomes more volatile, the need for energy that is both stable in price and can be reliably acquired in sufficient quantities will be increasingly important to the construction industry. When coupled with rising environmental criticism, concern with noise pollution and tightening emissions regulation, an alternate energy source to power the mass of heavy construction equipment must be identified. For this research hydrogen was chosen as the most suitable alternate energy source on which to focus. The associated heavy construction equipment type will be a track type tractor, commonly referred to as a dozer.

Background

Demand for oil has been on the rise for the past eighty years and is projected to continue doing so for the foreseeable future. Therein lay the problem, as demand for oil has increased the size and number of new discoveries have steadily declined. What new discoveries are made, require more complexity in obtaining the oil. On the following webpage http://www.peakoil.org.au/peakoil.htm can be found the figure The Growing Gap of our current situation and the troublesome state of affairs by comparing production to past and future oil discoveries. It was stated by William J. Cummings, Exxon Mobile company Spokesman, “All the easy oil and gas in the world has pretty much been found. Now comes the harder work in finding and producing oil from more challenging environments and work areas" Donnelly, John (2005). In a quote by Lord Ron Oxburgh, former chairman of Shell stated that "It is pretty clear that there is not much chance of finding any significant quantity of new cheap oil. Any new or unconventional oil is going to be expensive" Wheatcroft, Patience (2010). In this figure the paradigm is clearly identified, much of the oil that does exist has been discovered, and what is left will require great efforts to recover. Figure 1-1 shows the rising cost of oil production over the last decade and Figure 1-2 shows the rising cost of oil to the consumer over the same period. In order to justify the expense of such complex operations the price of oil must not fall below a certain point. Examples of this paradigm in recent years are the tar sands in Canada. When the price of oil fell in late 2008 mining of the tar sands declined with it (Oil Field Directory, 2009).

Future demand for oil is expected to increase on a global scale. Users such as China, in its industrial revolution, will see a dramatic increase in the consumption of oil at a rate of 7.5% increase a year, 7 times more than the U.S. (The Institute for the Analysis of Global Security, 2003). India too is increasing its annual rate of oil consumption by 5.5% (The Institute for the Analysis of Global Security, 2003).

Over the past few decades hydrogen has been considered by some to be the fuel of the future. That it could be the element that will shift the U.S. to hydrogen based economy and eliminate the dependence on foreign oil. In the past decade hydrogen fuel cell and hydrogen vehicle technologies research has seen an infusion of $1.7 billion from the U.S. government (Miller, 2005). Through the infusion of research funds advances to reduce the cost and energy required to manufacture and produce hydrogen fuel cells and hydrogen fuel have been made. In 1990 the high volume cost/kilowatt for a 50 kW hydrogen fuel cell was estimated to be $3000/kW due in part to the large amount of platinum used in construction of the catalyst (Miller, 2005). Through research the cost of an 80 kW fuel cell has been brought down to $61/kW in 2009 (DOE, Hydrogen Program Record, 2009). Extremely important to the future success of hydrogen is reducing the energy required to generate hydrogen gas through electrolysis. Today (2010) the required electrical energy to generate 1 kg of hydrogen has been reduced to 47 kilowatt-hour, resulting in 71% efficiency using a PEM fuel cell (Moulthrop, L., 2006). It has been estimated that the efficiency of hydrogen electrolysis can reach approximately 94% (Kruse, B., Grinna, S., & Buch C., 2002).

Many benefits stand to be had by using hydrogen fuel cells in place of internal combustion engines. One of the immediate benefits is reduced noise levels on the job site and noise pollution emitted to the surrounding area. Another benefit is the virtually unlimited supply of hydrogen gas via electrolysis of water. In the future much of the hydrogen fuel could be generated at the fill location reducing shipping cost and infrastructure construction and maintenance. Hydrogen used in a fuel cell generates no pollutants, only water is released which will help to eliminate pollution from vehicle exhaust.

With new technology comes refinement of not only the specific piece of technology but the understanding of how to maintain it as well. In the particular case of hydrogen construction equipment, technicians will have to be trained on how to understand, diagnose, and repair the equipment. In addition, study of how much maintenance and when to schedule preventative maintenance will also have to be determined. Not to mention, the infrastructure needed to distribute hydrogen must also be developed.

Further research aimed at identifying more durable and inexpensive materials to construction hydrogen fuel cells must also be conducted.

Operator skills will not likely change other than understanding safety procedures and how to fill the hydrogen fuel tank.

In the end, the most important aspect of introducing a new technology is cost. Hydrogen powered heavy construction equipment will have numerous hurdles before becoming the mainstay of the industry, especially from those who resist forward progress and see no reason for change. Not to mention the complexity involved in moving from a fuel source that people have grown accustomed, to one that is entirely different in its nature. As a result, this paper will seek to determine the cost of a hydrogen powered dozer, should it be bought tomorrow. This will include the cost of the individual equipment needed for refueling and in some remote locations, equipment needed to generate hydrogen fuel. Other costs include maintenance and retrofitting of existing work-shops to safely accept hydrogen equipment. The most important cost that will be identified is the life cycle cost and payback period.

A quote by Denis Simanaitis shares interesting insight on the situation, “The stone age didn’t end because of a lack of stones” (Simanaitis, D., 2004). It is not a question of, will the age of oil end? Rather, the question is, when? When will the cost of oil and the state of technology reach the point when oil no longer makes economic sense to continue to use at the current rate of consumption? It may not be that the price of oil must increase drastically over the next decade before the state of technology that will replace oil becomes equally or less expensive. If it were oil to be replaced tomorrow by hydrogen, what would it cost to transform our construction industry? is the question this study will seek to answer.

Purpose of Research

Today's technology will allow for a hydrogen fuel cell stack to be employed in many vehicular applications, yet it has not been explored in the field of heavy construction equipment. In such an application a hydrogen fuel cell stack is more than capable of supplying enough power to a medium sized dozer comparable in size to a Caterpillar D7R or D7E. There are several reasons why hydrogen was selected for this research. When considering what fuel was the best option, availability was of primary importance. This encompasses the ability to manufacture and produce the fuel source in sufficient quantities as to ensure no lag between the point when fuel is needed, and the point when it becomes available. With other alternative energy sources, availability cannot be ensured especially if demand were significant. The second criterion was to select an energy source that did not employ internal combustion as a means of energy conversion. This decision was based on the lower energy conversion efficiency of internal combustion engines. In using hydrogen to power a given equipment fleet, an estimator can better determine the actual costs of fuel needed to complete a project.

Benefits to the constructor and owner include the ability to produce hydrogen fuel on site. As with concrete production, a mobile hydrogen production plant can be transported from one site to another. By generating hydrogen fuel on-site the constructor can reduce complexity of fuel procurement, further reducing costs, especially in remote locations. Using hydrogen fuel cells to power equipment will reduce noise due to their nearly silent generation of power, thereby creating a healthier working environment and greatly reducing noise pollution. Compared to a mechanical driveline, there are fewer components comprising the power delivery system of a hydrogen fuel cell vehicle. Fewer mechanical components results in reduced potential for component failure, and will be realized with refinement of the technology.

What makes hydrogen such an attractive alternate fuel source is ease of conversion. The large, spacious chassis for mounting necessary equipment will allow the current generation of hydrogen fuel cells to be installed on current equipment models. For example, if converted to hydrogen power many of the electrical systems in the Caterpillar D7E diesel-electric dozer could be retained. Re-designing the diesel electric dozer would consist of removing the diesel engine, fuel tank and electrical generator and then sizing the appropriate hydrogen fuel cell, tank and system accessories.

Generating fuel on-site may be performed with the introduction of hydrogen fueled equipment. In total, three methods of hydrogen production will be considered, production of hydrogen via a centralized plant, locally delivered hydrogen, and on-site hydrogen production. There are also several methods of generating hydrogen. A common method is using steam reformers that require methane or propane undergoing a thermochemical reaction. For the purpose of this research, only hydrogen electrolysis will be considered.

Most important and the primary focus of this discussion, are issues pertaining to the cost of operating heavy equipment fueled by hydrogen. As with much of the construction industry cost is an important motivator. Based on the hypothetical design, estimates regarding initial, operating, and life cycle costs will be generated. Feasibility will be determined based on economic and physical design limitations.

Research Objectives

The objectives for this study will be to determine the following for a hydrogen fuel cell dozer:

- Estimated Initial Cost
- Hydrogen Fuel Cost
- Maintenance Costs
- Life Cycle Cost

Scope of Research

This research will investigate the cost of purchasing and owning hydrogen powered track-type tractor. Pricing will be found using the U.S. DOE EERE high volume estimates for fuel cells, hydrogen storage tanks, and the cost of hydrogen fuel. Hydrogen fuel requirements are determined by the duration of the work shift, which will be 8 hours and the size of the fuel cell. The typical production cycle is consistent with that of the Caterpillar D7E track-type tractor. Maintenance costs will cover the cost of performing routine maintenance and any unscheduled work that may arise. Life cycle costs include operating costs and non-operating costs. Operating costs are the costs associated with operating the equipment less the operator. Non-operating costs are the costs associated with purchasing a piece of equipment less tax.

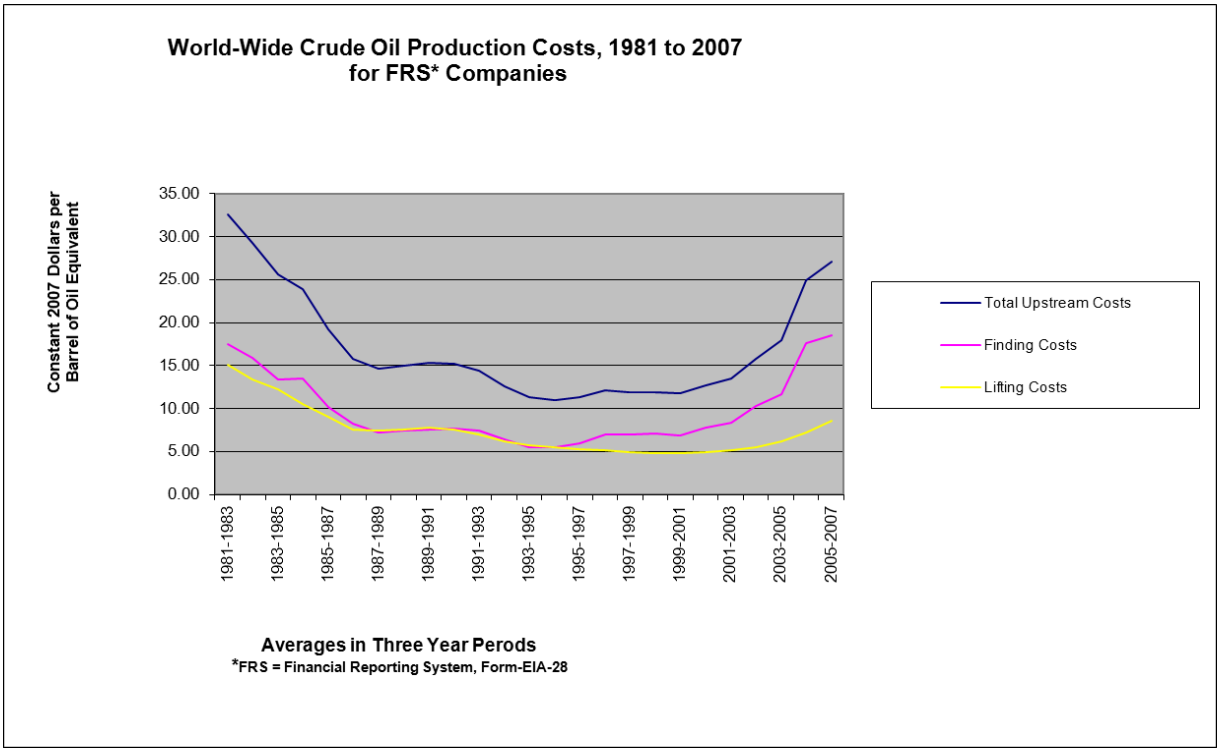

Figure 1-1. (U.S. Energy Information Administration, EIA 2007).

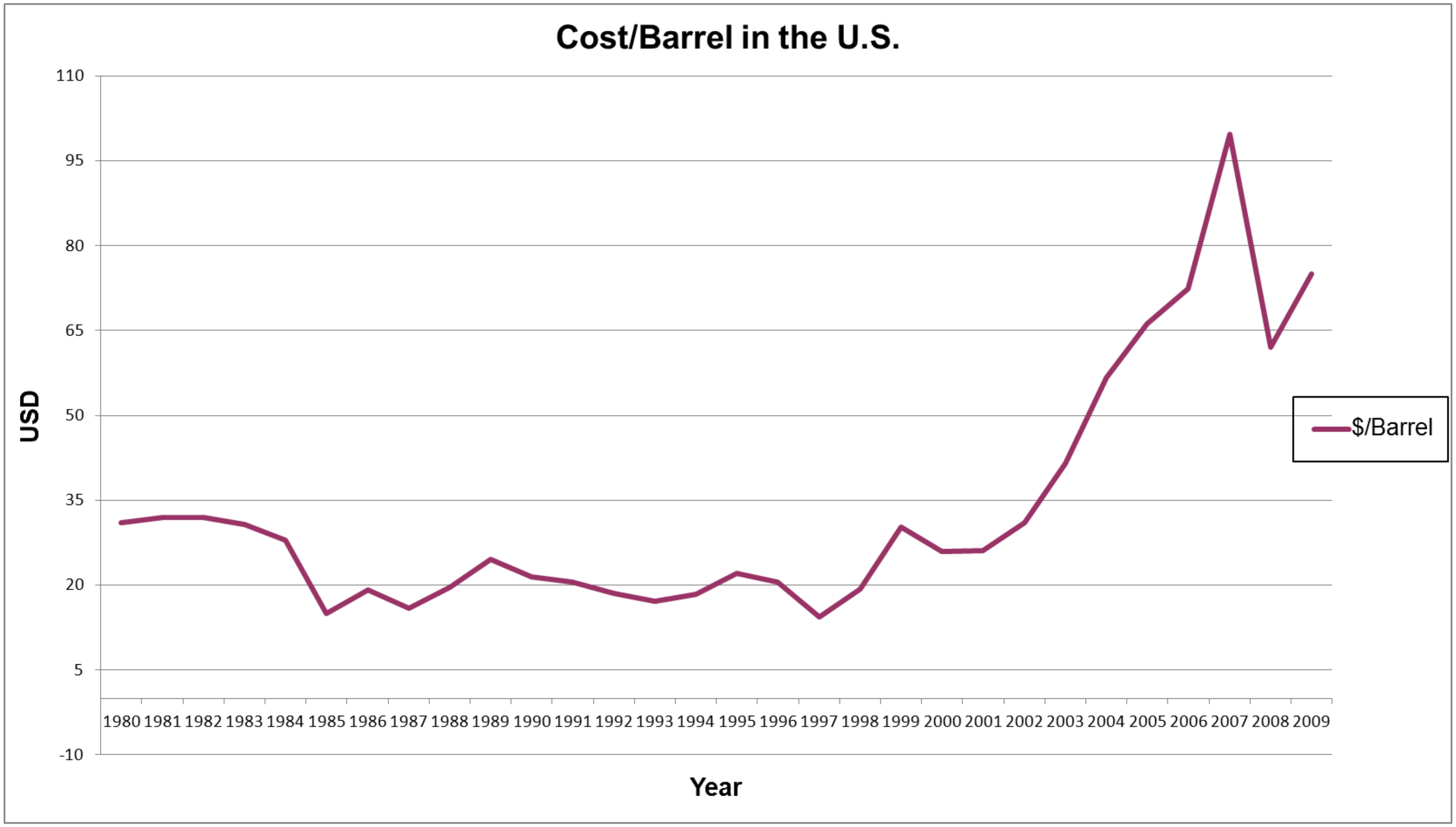

Figure 1-2. (Energy Information Administration, EIA). [Data File]

CHAPTER 2
LITERATURE REVIEW

About the Literature Review

For this study, the purpose of the literature review shall be to provide a foundation of knowledge that will allow further understanding of how the issues described in the problem statement may be resolved. The literature review will be divided into several sections, with each section reviewing current and future state hydrogen fuel cell related technology. The purpose for providing a review of future technology is to lend further support to the concept of a heavy construction industry powered by hydrogen, in the not so distant future. After extensive effort no research has been found on hydrogen fuel cell dozers, therefore an alternative review of a hydrogen fuel cell bus will make for the lack of existing research. Additionally, research on the following areas will also be included:

- Caterpillar D7E diesel electric hybrid
- Fuel cells
- Hydrogen electrolysis
- Hydrogen storage
- Energy recovery flywheel

Review of Hydrogen SCANIA Fuel Cell Bus Research Project

“Even though only a small percentage of all vehicles in the world are urban buses, they impact disproportionately on public health.” (Folkesson et al.)

This section begins with a review of a hydrogen fuel cell bus that was built and tested in Europe in the late 1990’s and the corresponding results published in 2003. The reason for such disproportionate impact of city buses on human health is that they operate in areas where populations are concentrated (Folkesson, Andersson, Alvfors, Alakula, & Overgaard, 2003). Heavy equipment too, often operate in highly populated locations. The density of heavy equipment on a particular site may be higher in fact than that of city buses. In effect, the same concern for health as it relates to exhaust emissions of city buses is the same for the heavy equipment industry. The primary emissions of concern from traditional compression ignition city buses are particulates and nitrogen oxides (Folkesson et al., 2003). Particulates are generally thought to be carcinogenic while nitrogen oxides are considered to be the most detrimental to the environment (Folkesson et al., 2003). Nitrogen oxide is one of the leading components of smog formation, acid rain, and also causes adverse health conditions (Folkesson et al., 2003). According to research by Folkesson et al. (2003) the city bus is an excellent candidate for hydrogen fuel cell propulsion for several reasons, including the following:

- City buses operate in polluted air
- Fleets are fuelled centrally
- Availability of space: including volume and space
- Produce little noise
- Longer lifetime as a result of fewer moving parts

Coincidentally, the same reasons that city buses make an excellent candidate for hydrogen propulsion, heavy equipment does as well.

However there are some drawbacks to using fuel cells according to Folkesson et al. (2003), as they are expensive and there is no hydrogen infrastructure. Other environmentally friendly city bus concepts using compression ignition are still in development (Folkesson et al., 2003). In light of the finitude of fossil fuel reserves according to Folkesson et al. (2003), hydrogen is thought to be an excellent alternative for the long term future.

Overview of Fuel Cell Bus Configuration

The bus used for this experiment was construction by SCANIA and primarily used for city transportation and airport traffic. The bus measures 9.2 m long, 2.5 m wide and 3.2 m high with a total capacity of fifty three passengers. The driveline of the bus is configured in series hybrid and is completely electric, receiving electricity from more than one source (Folkesson et al., 2003). In this particular experiment the buses driveline receives energy from both a hydrogen fuel cell and battery. Driving the rear wheels are two 50 kW brushless electric motors. Using brushless electric motors reduces friction thereby increasing efficiency (Folkesson et al., 2003). The battery can store and discharge large volumes of energy (Folkesson et al., 2003). Such a configuration allows for a smaller and correspondingly less expensive fuel cell (Folkesson et al., 2003). The battery is of the lead acid type and discharges at 528 V. The fuel cell used has a power output of 50 kW and fuel is compressed hydrogen. The oxygen is derived from compressed ambient air. A dc/dc converter adjusts voltage output of the electric driveline to match that of the SCANIA bus, in this case 600 V (Folkesson et al., 2003). The majority of the system fits in the rear of the bus, and can be easily removed for maintenance (Folkesson et al., 2003).

Overview of Fuel Cell System

In a fuel cell the chemical energy of hydrogen fuel is, through an electrochemical reaction not combustion, converted directly to electricity (Folkesson et al., 2003). There are a number of elements that make up the hydrogen fuel cell system and include the following:

- Fuel cell stack
- Hydrogen circuit
- Air circuit

- Primary and secondary cooling water loop

Voltage between the fuel cell system and bus are coupled by a dc/dc converter, ensuring smooth power delivery (Folkesson et al., 2003).

The fuel cell system is configured using two fuel cell stacks, and together creates what is called the fuel cell module (Folkesson et al., 2003). Each fuel cell stack contains 105 cells. In total the fuel cell module has a maximum power output of 50 kW (Folkesson et al., 2003). The fuel cell stacks are produced by Nuvera Fuel Cells Europe (Folkesson et al., 2003). The fuel cell module was developed by Air Liquide (Folkesson et al., 2003).

There are two types of fuel cell stack construction, ceramic and metallic; in this case the fuel cell stacks are of metallic construction (Folkesson et al., 2003). The fuel cell module measures: 58 cm height, 42 cm width, and 57 cm in length, subsequently total volume measures 139 l (Folkesson et al., 2003). The power density of the fuel cell module is 0.2 kW/liter (Folkesson et al., 2003). Power density is not a critical problem today, with considerably higher figures, the more important issue is size and weight of the auxiliary systems, and fuel storage systems according to Folkesson et al. (2003).

Heat generated by the fuel cell system must be managed in order to keep temperatures within the fuel cell stacks at the desired integer (Folkesson et al., 2003). According to Folkesson et al. (2003) much of the heat generated is transferred to the through the exhaust gases, however enough remains that additional measures must be taken. In the case of the SCANIA bus, pure water is injected directly into the stack, creating the primary water circuit (Folkesson et al., 2003). The primary water circuit is then heat exchanged with a secondary water circuit (Folkesson et al., 2003). Cabin heating is integrated into the secondary heating circuit (Folkesson et al., 2003). The secondary heating circuit travels through a fan and radiator system that is located on the roof of the bus (Folkesson et al., 2003). A minor amount of heat is handled by a compartment fan mounted in the rear of the bus (Folkesson et al., 2003).

The thermal and water management systems are integrated (Folkesson et al., 2003). In an effort to reduce complexity the system is desined to operate with no pre-humification system for reactant gases (Folkesson et al., 2003). Doing without such a device, reduces overall cost and size (Folkesson et al., 2003). Instead the water is directly injected into the fuel cell stack where it pre-humidifies and controls temperature (Folkesson et al., 2003). The exhaust exiting the fuel cell stack contains a considerable amount of water, a portion of which is captured and recirculated through the primary water cooling circuit (Folkesson et al., 2003).

Ambient air is compressed by an air compressor powered by an individual fuel cell stack (Folkesson et al., 2003). The compressor is outfitted with an air filter and silencer (Folkesson et al., 2003). The power for the compressor motor passes through an ac inverter (Folkesson et al., 2003). Hydrogen gas for fuel is stored at 200 bar in two stainless steel tanks that have been mounted on the roof (Folkesson et al., 2003). Total hydrogen storage capacity of the stainless steel tanks is 875 liter and is equal to 13.2 kilogram (Folkesson et al., 2003). In two stages the hydrogen gas pressure is lowered before reaching the fuel cell module (Folkesson et al., 2003). The first low pressure stage occurs on the roof, going from 200 bar to less than 10 (Folkesson et al., 2003). The second low pressure stage occurs just before the hydrogen gas reaches the fuel cell stack where it is reduced to the working pressure of the fuel cell stack (Folkesson et al., 2003).

Review of Test Results

The fuel cell bus was tested at the renown IDIADA proving ground in the North of Spain and is used by vehicle manufacturers the world over (Folkesson et al., 2003). The high regard of the testing ground is attributed to the plethora of facilities the track provides and according to Folkesson et al. (2003), the facilities include:

- High-speed circuit
- External noise test track
- Dynamic platforms
- Handling track
- General road circuit
- Accelerated fatigue track
- Test hills
- Straight line braking surfaces
- Comfort track
- Customer workshops

To better replicate real world operating conditions the bus was fitted with external weights amounting to 12,500 kg (Folkesson et al., 2003).

Acceleration tests were performed with the bus reaching 30 kilometers/hour in 7 seconds and 60 km/h in 25 s (Folkesson et al., 2003). The ability of the bus to climbs hills was also tested. The bus was able to drive 75 m along an 18% slope and had no trouble completing the 12% slope course (Folkesson et al., 2003). Performance of the bus was evaluated using two methods, the first being the Braunschweig city duty cycle and the FTP 75 duty cycle (Folkesson et al., 2003). The Braunschweigh city duty cycle is a simulation test bed that remains unchanged for each test and includes many stops and periods of acceleration (Folkesson et al., 2003). The purpose of each test is to measure performance of the fuel cell, battery, and regenerative braking systems

(Folkesson et al., 2003). Testing showed that the eficiency of the regenerative braking system which includes storing of energy in batteries and using energy from the battery averaged 85% (Folkesson et al., 2003).

Energy consumption of the fuel cell bus during testing was converted to diesel equivalent and found to be 42 and 48% lower than the standard SCANIA city bus (Folkesson et al., 2003). The regenerative system provided 24-28% greater efficiency, while the efficiency without the regenerative braking system would have been 21-32% better than the standard SCANIA city bus (Folkesson et al., 2003).

The energy consumption of the bus's subsystems is 7% of total energy input (Folkesson et al., 2003). Power demand of the subsystems equates to 3-4 kW (Folkesson et al., 2003). The subsystems include those systems that operate the doors and vertical height of the bus (Folkesson et al., 2003). However no air conditioner was operated during the tests, as it would have consumed 15 kW at full operating power (Folkesson et al., 2003).

Temperature in the fuel cell stack during testing was between 50-75 °C (Folkesson et al., 2003). Excess air provided by the compressor was 1.5 bar and reached 4 bar during periods of low power demand (Folkesson et al., 2003).

Noise

During formal testing of the fuel cell bus, noise levels were also taken. The bus is accelerated to 50 km/h and held as it reaches the noise measuring area (Folkesson et al., 2003). Once entering the noise measuring area the bus accelerates fully for 20 m while noise levels are measured in accordance with the European regulation 70/157/EEC (Folkesson et al., 2003). The results of the noise tests are compared to the standard compression ignition SCANIA bus type (Folkesson et al., 2003). Under the same conditions the stand SCANIA city bus produces 80 dB(A) while the fuel cell bus noise level was measured at 70.3 dB(A) (Folkesson et al., 2003).

Research Results

All the components that make up the fuel cell system and corresponding driveline must be improved to increase durability and life time (Folkesson et al., 2003). Efficiency of the fuel cell was measured at 54.6% with 56 kW of hydrogen energy entering the fuel cell 30.9 kW of electrical energy was produced (Folkesson et al., 2003). Cost is a great concern and must be reduced and can be done by reducing complexity of the fuel cell system and standardization (Folkesson et al., 2003). Batteries are also expensive and the cost for which can be reduced by finding cheaper materials that are able to perform equally (Folkesson et al., 2003). Optimization of the fuel cell and battery must be done to increase longevity and robustness (Folkesson et al., 2003). Also beneficial is designing the vehicle from the start to operate on hydrogen fuel (Folkesson et al., 2003). Lastly, it is important that all systems that do not operate via electrical power be replaced with an optimized replacement (Folkesson et al., 2003).

Conclusion from SCANIA Fuel Cell Bus Research

The experiences of the SCANIA fuel cell bus research team will help guide the research of this thesis in several key areas:

- The use of batteries in the design of hydrogen fuel cell vehicles
- Incorporation of an energy capturing device
- Efficiency and optimization of the various types of systems needed to operate a fuel cell vehicle

Connecticut Transit Fuel Cell Bus Overview

In this particular hydrogen test bed, the Connecticut Transit Fuel Cell Transit Bus (CTtransit) began regular city bus operation in April 2007 and the ensuing synopsis follows the bus through October 2009. During this particular review period the CTtransit bus went through 3 fuel cell power systems with the fourth recently installed but not included in this analysis (National Renewable Energy Laboratory, 2010). In total the bus has operated for 38,461 miles equaling 5,940 hours of operation (NREL, 2010). This analysis will cover the time period for the bus's third fuel cell power system which occurred between December 2008 and October 2009 (NREL, 2010). Various costs for bus during this time period can be reviewed on page vi at the following website http://www.nrel.gov/hydrogen/pdfs/45670-1.pdf The high cost of maintenance of the fuel cell bus can be attributed to the considerable participation by the CTtransit technicians and was not back charged to the manufacturer as warranty work (NREL, 2010).

Background of CTtransit Bus

The fuel cell bus operates in a metropolitan environment in Hartford, Connecticut. In 2007 the bus was delivered to the city to begin testing. It was constructed by Van Hool and employs at UTC Power 120kW fuel cell and MES-DEA ZEBRA batteries make up the power system (NREL, 2010). Three new diesel buses operate in the same fleet and were used to create a baseline to compare the hydrogen fuel cell bus's performance. The baseline bus is a 40 ft. 2007 New Flyer that uses a Cummins diesel engine (NREL, 2010). CTtransit refuels the hydrogen bus at the UTC Power headquarters located 7 miles distant from the central bus yard (NREL, 2010). The fuel station stores hydrogen in liquid form and when refueling vaporizes the fuel to be stored as a gas onboard the bus (NREL, 2010). Hydrogen is provided by Praxair who obtains the hydrogen as a by-product of chemical process (NREL, 2010). The fuel cell bus operates on as a standard passenger bus for a metropolitan route with a bus arriving every 12 minutes (NREL, 2010). The route is 5.5 miles long and averages 10 mph along the route (NREL, 2010). Though the average speed of the route is 10 mph the fuel cell bus has seen and average of 6.5 mph, while the diesel buses are able to achieve 12 mph. This is attributed to the fuel cell not being shut down while idling between cycles (NREL, 2010).

During the bus's tenure with CTtransit it has achieved an average fuel economy of 4.79 m/kg over the entire 38,461 miles (NREL, 2010). It should be mentioned that this bus's fuel economy is lower than that of similar fuel cell buses in other states which have achieved over 7 m/kg (NREL, 2010). A lower m/kg can be attributed to the lower average speeds and greater idle time that the CTtransit fuel cell fuel bus realizes during operation. On a positive note, the CTtransit bus averaged 5.4 m/dge compared to the baseline diesel bus's 3.68 mpg resulting in 47% greater energy efficiency for the hydrogen powered bus (NREL, 2010).

The hydrogen used in this project was produced via a chemical process and provided by Praxair, who shipped the hydrogen from western New York (NREL, 2010). As a result the hydrogen is relatively inexpensive compared to other production methods (NREL, 2010). Total fueling needs over the life of the project has been almost 8,000 kg (NREL, 2010).

CTtransit specifically chose the route on which the fuel cell bus operates, called the Star Shuttle route (NREL, 2010). The route is free to all passengers and serves to increase public awareness of the project (NREL, 2010). In a survey of passengers who rode the Star Shuttle route showed that they thought that the performance of the bus higher than that of the baseline bus (NREL, 2010).

Maintenance Facility and Technical Training

Modifications to mechanic facility to allow for safe maintenance of the hydrogen fuel cell bus were surprisingly inexpensive. CTtransit hired a consultant to investigate the required modifications needed to for such a project. The consultant's subsequent recommendations led to $150,000 in modifications to the existing mechanic/maintenance facility (NREL, 2010). Since the bus is able to operate on batteries alone, the maintenance facility was not required to make drastic changes (NREL, 2010).

Prior to the bus's arrival CTtransit organized a training regime to familiarize the staff with appropriate knowledge, safety and maintenance information (NREL, 2010). Two senior level technicians are primarily responsible for the fuel cell bus's maintenance (NREL, 2010). No information on the cost of training was given.

CTtransit Fuel Cell Bus Challenges

Reliability is a major issue for new unproven technology. In the case of the CTtransit fuel cell bus manufacturers are working closely to identify problem areas and increase reliability and life of the product (NREL, 2010). Several issues have been encountered with the fuel cell system and traction batteries (NREL, 2010).

The traction batteries are built by MES-DEA using the ZEBRA battery line (NREL, 2010). They have created difficulty throughout the project (NREL, 2010). The difficulty with the ZEBRA batteries is that a cell will fail in short circuit (NREL, 2010). Even though the battery has failed cells it is still able to function though at reduced voltage (NREL, 2010). Three batteries created by a number of individual cells operate in direct parallel (NREL, 2010). When the number of shorted batteries becomes too great, an imbalance in the state of charge makes the batteries more difficult to operate within designed parameters (NREL, 2010). The imbalance may cause the battery management software to shut down the battery during operation (NREL, 2010). The failed cells have been linked to stress from use of the batteries and has been improved by making changes in the battery management software (NREL, 2010). As a secondary measure additional batteries are kept in stock (NREL, 2010). The batteries are kept around 50-60% State of Charge (NREL, 2010).

The manufacturer of the fuel cell, UTC Power has been active in monitoring the performance of their product measuring nominal versus actual (NREL, 2010). When the power output of the fuel cell falls between 90 and 100 kW, it is considered to be at the end of its functional life (NREL, 2010). The reduction of power output from the fuel cell is reportedly caused by contamination in turn resulting in premature failure around 800-1200 hours (NREL, 2010). After replacing the fuel cell with a newer version the problem was resolved (NREL, 2010).

Due to the comparatively quiet operation of fuel cell vehicles other noises not related to the power delivery system become more apparent. With the CTtransit fuel cell bus it was found that the air conditioning fans were rather loud (NREL, 2010). The issue was resolved by members UTC Power by adding baffles among other devices to quiet the system (NREL, 2010).

Since the fuel cell bus must travel off site to refuel this increases operating costs where the bus in not generating revenue (NREL, 2010). CTtransit staff must drive the bus off site, ensure appropriate personnel are available to open the fueling station, and wait for fueling to complete, before returning the bus back to the central bus yard (NREL, 2010).

Fueling the CTtransit Fuel Cell Bus

The fueling station is located at a UTC Power facility (NREL, 2010). The driver must call ahead before leaving to refuel in order to ensure that the appropriate personnel are available at the fueling site to operate the equipment (NREL, 2010). At the onset of the project fueling time was about an hour but has since been reduced to an average of about 30 minutes (NREL, 2010). This includes the time spent driving to the fueling station, safety procedures, and start-up time (NREL, 2010).

Evaluation of CTtransit Fuel Cell Bus

During the evaluation period the fuel cell bus acquired 13,862 miles and the fuel cell operated for 2,140 hours (NREL, 2010). Over the same period the baseline diesel bus accumulated 38,461 miles (NREL, 2010). Compared to the baseline diesel bus the average monthly miles were 3,420 and 1,260 for the fuel cell bus (NREL, 2010). Through the evaluation period the bus was available 62% of the time, due to issues with the traction batteries and fuel cell system (NREL, 2010).

Operating cost for hydrogen production and dispensing are unknown (NREL, 2010). On the other hand the cost of fuel charged by UTC Power was $5.29/kg (NREL, 2010). The cost for hydrogen resulted in $1.11/mile, whereas the cost of diesel for the baseline bus $0.70/mile (NREL, 2010).

When calculating the maintenance cost per mile warranty costs were not included. In order to provide consistency $50/hour labor rate was used (NREL, 2010). First discussed are the total maintenance costs and subsequently an analysis of the maintenance costs by system. Total maintenance costs comprise the labor and parts (NREL, 2010). The cost per mile was calculated as (($50/hour x number of labor hours) + cost of parts) / number of miles (NREL, 2010).

The fuel cell bus's cost for parts are 36% lower than the three baseline diesel buses for the same period (NREL, 2010). However, the fuel cell bus accrued 63% fewer miles than the baseline diesel buses. There was also an average of 84.3 or 40% more hours of maintenance for the fuel cell bus over the three baseline buses (NREL, 2010). The cost per mile of the fuel cell bus during the evaluation period arrived at $1.29, compared to an average of $0.41 per mile of the three diesel buses (NREL, 2010). Excluding warranty costs the fuel cell bus averaged about 3.2 times more to operate than the three baseline diesel buses (NREL, 2010).

Total maintenance hours are considerably higher than the three baseline buses and resulted in a cost of $2.14 per mile (NREL, 2010). Parts costs for the fuel cell bus was an average of just over $3,400 less than the fuel cell bus (NREL, 2010). Again the fuel cell bus traveled fewer miles over the same time period, an average of 48,000 less than the baseline buses (NREL, 2010). Much of the added cost of the fuel cell can be attributed to the issues with the traction batteries and the on board charger (NREL, 2010). Other maintenance problems were found with the wiring harness and a leak in the on board fuel storage tank (NREL, 2010). Maintenance costs for the baseline diesel buses were attributed to three brake relines, replacement of hydraulic lines, air conditioning system issues, body damage, and engine trouble (NREL, 2010). With time the total cost per mile has been reduced, which can be seen by comparing the total cost per mile and the cost per mile during the evaluation period (NREL, 2010).

During the evaluation period the most troublesome problem was propulsion related accounting for 87% or $1.12 of the total cost per mile (NREL, 2010). Propulsion related issues for the baseline buses only accounted for 18% or $0.07 of the cost per mile (NREL, 2010). PMI amounted to 4% or $0.05 of the cost per mile for the fuel cell bus whereas the 20% or $0.08 for the baseline buses (NREL, 2010). Looking at the Figure 2-3 it can be seen that many of the systems for the fuel cell bus cost less per mile than the baseline buses (NREL, 2010). In fact the total cost per mile excluding the propulsion system is $0.17 for the fuel cell bus (NREL, 2010). Interestingly the cost per mile for the baseline buses is $0.33 per mile excluding the propulsion system (NREL, 2010). Excluding the propulsion system the fuel cell bus costs 51% or $0.16 less than the baseline bus. Much of the additional costs can be attributed to Cab, Body, and Accessories which includes body, glass, and paint, cab and sheet metal repairs following an accident, along with seat and door repair (NREL, 2010). This amounts to $0.15 of the cost per mile for the baseline diesel buses, nearly all of the $0.16 (excluding the propulsion system) difference over the fuel cell bus. It is not known if the skill of the baseline bus drivers is less than that of the drivers of the fuel cell bus. The premium per mile cost for the fuel cell bus over the baseline bus is $0.89.

Route Reliability

Reliability is measured in part by the number of road calls due to component failure and necessitates replacement of the bus while performing assigned duties (NREL, 2010). If the bus is repaired in the field then it is not considered to be a road call (NREL, 2010). Any number of failures can constitute a road call, including safety issues, propulsion system preventing forward progress, or an inoperable door (NREL, 2010). The number of road calls for the fuel cell bus amounted to 12 during the evaluation period while the three baselines buses shared 7 (NREL, 2010). The number of propulsion related road calls was 11 for the fuel cell bus and a total of 6 between the three baseline buses (NREL, 2010). The traction batteries accounted for 3 of the road calls, the hybrid propulsion system 5, while the fuel cell system resulted in 2 (NREL, 2010). The fire suppression system is credited for the 1 remaining road call (NREL, 2010).

Results from CTtransit Fuel Cell Bus Project

This particular project has tremendous to offer primarily what to expect when looking to assign costs of a fuel cell vehicle. The results of this project will indirectly help to estimate life cycle costs and costs per hour. One of the most helpful results from this project is the cost of retrofitting the existing maintenance facility. Surprisingly it was found to be $150,000. Further discussion on this particular will be included and how it relates to the cost of introducing new technology, more specifically can the facility modification cost be justified? What is not known are the costs to purchase and maintain the hydrogen refueling station located at UTC Power. It would have been helpful for future research in knowing what to expect the costs of a working hydrogen fueling station to be.

Overview of the Caterpillar D7E Dozer

In researching the track type tractor commonly referred to as a dozer the discovery of the Caterpillar D7E was incremental in lending support to the concept of hydrogen powered heavy construction equipment. The Caterpillar is D7E according to Caterpillar, Inc., (2009a) is not considered to be a hybrid by the automotive definition in that it does not collect and store energy in a battery for later use. However, by general definition of the term the D7E is a hybrid due simply to the nature of using a diesel engine to turn a generator and creating electrical energy (Caterpillar, Inc., 2009a). The basic technology has been around for decades, most commonly found in train engines and referred to as a diesel electric hybrid. Inventively, yet so simple the D7E captures mechanical energy during braking, sending it to the flywheel (Caterpillar, Inc., 2009a). It is surprising that novel thinking is just now making its way to being used in such an application (Caterpillar, Inc., 2009a).

According to Caterpillar, Inc., (2009a) the purpose for going electric was to improve maneuverability in situations with limited maneuvering area, as with residential applications (Caterpillar, Inc., 2009a). The primary role for the D7E is site development (Caterpillar, Inc., 2009a). This is essential to clarify as it is common for dozers to assist scrapers by pushing during the cut segment of a cycle. Though the D7E may be capable of serving in such a capacity, acting as a pusher is not its primary function according to Caterpillar, Inc. (2009a) literature. The importance of this will become clearer with discussion of the conceptual hydrogen dozer.

There are a number of benefits publicized by Caterpillar that mark the D7E as a better product according to the company. Moving to an electric drive as it is claimed reduces the number of moving parts in the electric drive train by 60% over the standard model (Caterpillar, Inc., 2009). One of the most interesting credits of the D7E is 10-30% greater fuel efficiency (Caterpillar, Inc., 2009a). This is in part achieved by running the diesel engine in a tighter revolutions/minute range resulting in 6.2 gallons/hour for the D7E versus 7.7 gallons/hour for the outgoing D7R II (Caterpillar, Inc., 2009a). This can also be translated as 330 cubic yards/hour for the D7E and 300 cubic yards/hour for the D7R II (Caterpillar, 2010). Lifetime operating costs are said to decrease by 10% with the D7E (Caterpillar, Inc., 2009a). Contributing to reduced lifetime costs are reduced fuel consumption per yard of material moved, increased parts durability, elimination of drive belts, fewer maintenance services are required, and finally using a modular design for components helps to facilitate maintenance and repair, reducing the number of labor hours (Caterpillar, Inc., 2009a). The life time D7E electric drive train is expected to be much better than the D7R series 2 dozer it replaces, lasting up to 50% longer (Caterpillar, Inc., 2009a). The electric drive line is also expected to extend the service life of the machine as well (Caterpillar, Inc., 2009a). Total life time costs are expected to be 10% less than the D7R II and take around two and a half years to make up the cost premium over the D7R II (iBi, 2009).

D7E Specifications

Electrical energy is produced by operating a diesel engine which turns an Alternating Current generator (Caterpillar, Inc., 2009b). System voltage is 480 for the propulsion motors, 320 for the water pump and Compressor (Caterpillar, Inc., 2009b). Amps at the compressor are 12 and 5 for the electric water pump (Caterpillar, Inc., 2009b). The engine used is the C9.3 producing a gross output of 252 hp and 188kW (Caterpillar, Inc., 2009b). Net power is rated at 235 horsepower and 175kW (Caterpillar, Inc., 2009). Fuel tank capacity is 126 gallons for high fill (Caterpillar, Inc., 2009b). Standard operating weight is approximately 57,000 lbs (Caterpillar, Inc., 2009b). Torque delivery of the electric will provide enough drawbar force to exceed tractive effort (Caterpillar, Inc., 2009). Operating in wet and even submerged conditions, to a point, are on par with the outgoing D7R series 2.

Hydrogen Fuel Cells

Several types of fuel cells used today in vehicular applications. Only PEM (Polymer Electrolyte Membrane or Proton Exchange Membrane, both are interchangeable) fuel cells will be considered. This is due in part to the volume of manufacturers of PEM fuel cells. PEM fuel cells are a desirable technology because they generate higher power densities than other fuel cell technologies; they also weigh less and require less volume than other fuel cell technologies of equal output (DoE, 2009a). PEM fuel cells consist of a solid polymer used as an electrolyte and porous carbon electrode (DoE, 2009a). The catalyst is fashioned from platinum (DoE, 2009a). One of the drawbacks to current PEM technology is that the volume of platinum needed for construction of the catalyst accounts for a considerable portion of the cost of the fuel cell. Research aimed at reducing or finding a replacement to the necessary platinum are underway. Requirements for operation are a hydrogen fuel source, oxygen from the air, and water as a cooling medium (DoE, 2009a). Unlike other fuel cells no corrosive materials are used with PEM fuel cell (DoE, 2009a). Operating temperature is low in comparison, typically around 80°C (DoE, 2009a). Lower operating temperatures require less time to start and result in longer life of the fuel cell due to less wear (DoE, 2009a).

Hydrogen Electrolysis

Electrolysis is the process of splitting water into hydrogen and oxygen by introducing an electrical current (DoE, 2008b). Electrolysis is usually used in smaller scale applications however research is being conducted to allow for larger scale applications (DoE, 2008b). For example, research is being conducted to manufacture an electrolyzer that is large enough to be stationed at a wind farm and use green energy to produce hydrogen with zero emissions (DoE, 2008b). The type of electrolyzer used for this research is a PEM electrolyzer and operates the same a PEM fuel cell albeit in reverse, and was selected for many of the same reasons. There are two important components, an anode and a cathode (DoE, 2008b). Submerged in water the anode generates a positive charge to form oxygen and positively charged hydrogen called protons (DoE, 2008b). The positively charged ions then flow in turn to the cathode while electrons are flow through an external circuit (DoE, 2008b). Upon reaching the cathode positively charged hydrogen combines with the electrons where hydrogen gas is formed (DoE, 2008b).

Hydrogen Storage

Numerous methods exist or are in various stages of research to store hydrogen both on the vehicle and as it is produced by the electroyzer. Three of the storage methods compressed, liquid, and materials-based will be discussed. Each of these methods of hydrogen storage are in various stages of development and mentioned to produce a complete review of potential technology.

Compressed Hydrogen Gas Storage

10,000 psi tanks have been a recent advancement in the hydrogen fuel cell industry. A novel technology that has led to their introduction to the market is carbon-fiber epoxy resin shell construction (Encyclopedia of Earth, 2008). This material has led to reducing the weight of the tank, making it more suitable for vehicular applications. For safety measures the tank regulator has been mounted inside the tank (EoE, 2008). In addition a temperature gauge has also been mounted on the interior of the tank to measure gas temperature while filling with hydrogen (EoE, 2008). Volume needed for 1 kg of hydrogen at 10,000 is approximately 27 l (EoE, 2008).

Liquid Storage

To increase the energy density of hydrogen it can be stored in liquid form (EoE, 2008). Several problems need to be addressed in order to increase the efficiency of liquid storage including the energy used for liquefaction, weight, volume, and cost for the tank (EoE, 2008). The most important issue for this study concerns the amount of energy required to liquefy hydrogen gas, which is around 30% of the lower heating value (EoE, 2008).

Materials-Based Storage

Materials-based storage is an interesting subject and may one day prove to be the best method for storing hydrogen gas. Three physical methods are used to store hydrogen in materials, absorption, adsorption, and chemical reaction (EoE, 2008). When using absorptive technology the hydrogen is stored directly in the material (EoE, 2008). When using adsorption hydrogen is energetically bonded to a material surface (EoE, 2008). To increase surface area porous materials are used (EoE, 2008). Chemical storage works like a battery, pressure and temperature are applied reversing the chemical reaction and releasing hydrogen (EoE, 2008). Weight for all materials-based storage methods is a major problem and is currently under investigation (EoE, 2008).

Energy Recovery Flywheel

A simple method for increasing efficiency is to incorporate flywheel designs into the vehicle. Using a flywheel has the potential to reduce the size of a particular hybrid system or reduce the energy input. The concept of the flywheel has been around for millennia. Flywheels can recover kinetic energy that is normally lost during braking. Two common methods of energy recovery and storage are electric and mechanical

(Flybrid Systems, 2010). One particular system will allow for a total of 530 kJ of energy storage at a rate of 60 kW (Flybrid Systems, 2010). The system weighs 27 kg (Flybrid Systems, 2010). Fuel consumption savings have been measured at 20% on the NEDC cycle and said to achieve over 30% for real world conditions (Flybrid Systems, 2010).

CHAPTER 3
METHODOLOGY

Introduction

The research in this thesis is meant to investigate the feasibility of constructing and operating hydrogen powered heavy construction equipment as discussed in the introduction and problem statement. The methodology followed for this research was determined by the objectives of the study. The methodology consists of the following:

- A literature review consisting of several different topic areas was performed for the purpose of providing background knowledge pertaining to the study objective.
- The data required for analysis was identified.
- The sources to provide the data were identified.
- Estimates of initial and life cycle costs were performed as a primary means of determining feasibility.
- Fuel costs were determined as a means of calculating life cycle cost and payback period.

Overview of Cost Estimates

The initial cost estimate will be determined by comparing the Caterpillar D7E to a machine equipped with a fuel cell and storage tank. To arrive at an estimated cost for the hydrogen dozer, the caterpillar D7E purchase price will be used less any unnecessary equipment such as the diesel engine and replaced with the cost of the fuel cell and components. Life cycle costing will be conducted using manufacturer's data and data from the CTtransit hydrogen bus research project.

Life cycle costing is broken into operating and non-operating costs. Operating costs include parts used for maintenance and labor, while non-operating costs cover the cost associated with the purchase of equipment and a 6% discount rate. Operator cost is not included because it is assumed in the data analysis that both machines are equal in their production volume. What will be analyzed is the cost of purchasing and maintaining the equipment.

Determining Hydrogen Fuel Costs

Hydrogen fuel costs greatly depends on the size of the fuel cell used, which directly affects the volume of hydrogen consumed. Determining the size of the fuel cell is discussed in chapter 4. Originally two methods of hydrogen production were considered. However on-site hydrogen production was dropped due to overwhelming cost, and is instead briefly discussed in chapter 5. The second method of determining hydrogen costs involves off-site hydrogen production and on-site delivery. Hydrogen costs are measured by the kg. Because cost/kg varies greatly around the country, the U.S. DOE EERE 2010 and 2015 estimates are used.

Hydrogen produced sustainably via solar and wind electrolysis was also considered. Using 71% electrolyzer efficiency and a 125 kW fuel cell approximately 2.9 megawatts of electricity must be generated using either method of electricity generation. With 30% capacity of a given wind turbine, a 400 kW unit would have to be used. Due to the complexity and enormous initial investment, it was concluded that these methods were not relevant to this analysis for two primary reasons. First, hydrogen produced in such a way will benefit from a large wind farm scenario and is outside the scope of this analysis. The second is that large scale energy production is not the business of a construction company.

Battery Analysis

Incorporating batteries into the design of the hydrogen dozer has the potential to reduce the size of the fuel cell, and subsequently the volume of hydrogen fuel. The battery design used for this research will use two separate battery systems comprised of battery modules and individual cells. To maximize the life of the battery, one battery system will discharge while the other charges. However the size of the battery will vary depending on the duration of the charge and discharge cycles. So, in keeping with the intended operating conditions of the Caterpillar D7E, a cycle will be developed and discussed in chapter 4.

Storage Tank

Cost of the storage tank is determined by the size of the tank and using the U.S. DOE EERE 2010 and 2015 estimate. U.S. DOE EERE estimates high volume hydrogen storage tank production costs by first determining the kWh of energy stored. The mathematical analysis is discussed in depth in chapter 4.

Hydrogen Fuel Cell

The cost of the hydrogen fuel cell is found using a similar method of analyzing the maximum kW of energy produced. Fuel cell life cycle is assessed using 4,000 hours of operation before replacement. Cost associated with the replacement of the fuel cell is separate from maintenance work.

Dozer Platform

Both the diesel and hydrogen dozer configurations will be assessed using a 10,000 total operating life. After researching the salvage value of similar equipment, it was determined that it would not be worth the time for a construction company to try and sell the equipment other than for scrap. Since this number would not have much effect on the overall life cycle analysis and cannot be accurately predicted, it will therefore not be included.

CHAPTER 4
DATA ANALYSIS

Introduction

The analysis was divided into three different size fuel cells and accompanying battery. This was done to understand the effect each component has on the cost of the equipment. Cost was derived using various sources and will be explained in each related section. Once equipment costs have been determined, feasibility analysis and life cycle costing can be performed. This will help to provide a better understanding of the current state of fuel cell technology and identify areas of further improvement.

Fuel Cell, Batteries and Kinetics

For this research a typical earthwork cycle was developed that closely follows what a machine of this type would see in the field. The cycle consists of an 80 foot doze segment where full power from the fuel cell and battery are being discharged to the electric drive motors. The doze segment takes 0.45 minutes to complete. The return segment requires 0.20 minutes with 0.05 minutes for maneuvering and repositioning for the next cycle. During these two key segment totaling 0.25 minutes, the fuel cell is driving the electric motors while excess energy is charging the batteries. During this period where the operator changes direction, energy from the braking track is captured by a set of flywheels and reused. The implementation of such simple technology displaces a portion of the required number batteries. Total time for to complete one cycle is 0.70 minutes.

Selecting the Battery

The battery used for this research project is manufactured by Toshiba, called the Super Charge Ion Battery or SCiB, and is intended to be used in both hybrid electric vehicles and electric vehicles. Battery chemistry is lithium however the technology allows for utilizing 85% of the battery capacity (DoD), whiling realizing 82% discharge capacity retention after 6000 cycles. The fast charge time is approximately 4 minutes, at 95% SoC. Cost for the battery is estimated to be $0.3/Wh compared to $0.63/Wh for similar technology from comparably smaller companies. This can be attributed to Toshiba's larger manufacturing base and ability to recapture a smaller return on investment/Wh/cell.

Each cell has a capacity of 4.2 Amp-hour at 2.4 Volts and 45 Amp discharge current.

$$4.2 \text{ Ah} \times 2.4 \text{ V} = \text{Wh}$$

Wh capacity amounts to 10 Wh/cell.

The charging rate is 50 Amp current at 2.9 Volts.

$$50 \text{ A} \times 2.9 \text{ V} = \text{W}$$

Total watts needed for charging amounts to 145 W/cell.

Given that the operating voltage will drop to approximately 2V and DoD of 85% at 82% retention, only 5.562 Wh of energy in each cell can be used. This will be used in determining the total number of cells making up the battery system.

Explanation of the Fuel Cell, Battery and Flywheel Systems

The power output of the hydrogen fuel cell dozer is designed to match that of the Caterpillar D7E for ease of comparison. A portion of the power will be provided by the fuel cell, battery, and energy recovering flywheel.

Sizing the fuel cell is an important factor to consider as it will directly affect the size of the battery. In order to compare cost of the fuel cell dozer in as fair a manner as possible, the high volume estimate provided by EERE will be used in determining the price of the fuel cell. The 2010 EERE estimate places the cost at 45/kW. Maintenance costs will be derived using the NREL CTTransit report. First, in order to determine the size of the fuel cell an analysis of the ability of the fuel cell to charge the battery must be performed. There are several methods that can be used to size a battery.

First the energy requirements must be identified. The total energy required while dozing = 1313 Wh. Energy required while on the return cycle is more complex. Tangible data for accurately finding the basic energy requirements to move the dozer is considered to be proprietary information. A formula does exist to find the rolling resistance of a vehicle travelling over a particular surface. However, since track mounted vehicles along their own surface they considered to have no rolling resistance. Instead grade resistance will be used in place of rolling resistance for this purpose of this research. Grade resistance can be found using the following formula:

Grade Resistance = (20 pounds / ton per % slope) x (% slope)

In this case grade resistance = (20 lbs X 28.5 tons) x (5% slope) = 2850 lbs. Therefore a minimum of 2850 lbs drawbar pull is required.

From here the drawbar pull can be used to determine the minimum engine power to generate the necessary drawbar pull using the following formula:

Drawbar pull = ((375) x (HP) x (Gear Train Efficiency)) / (Velocity)

In this case drawbar pull = ((375) x (HP) x (90%)) / (5 mph) = 42.2 HP or about 32 kW.

The kinetic flywheel is able to store 111- 222 Wh or 400 – 800 kJ of energy. Efficiency of the flywheel is 90% in both directions and an estimated life of 1 million hours. Energy can be added or released at 60 - 120 kW per flywheel. The amount of recoverable kinetic energy can be found by using the following formula:

Kinetic Energy = ½ mass x velocity^2

In this case m = 57000 lbs v = 2.5 mph doze velocity and 5 mph return velocity.

This equates to 13 kJ of recoverable energy on the doze cycle and 52.4 kJ on the return, for a total of 65.4 kJ of recoverable energy. Given that 1 kJ = 3.6 Wh a total of 235.4 Wh can be recovered/cycle. Each flywheel weighs 70 kg and is relatively small. Energy from the flywheel will be managed by on board computer and simply displaces the energy that would otherwise need to be accounted for; either by providing a larger battery, fuel cell or both.

There are two methods that may be used in designing the battery the first, used by the U.S. Navy allows for the battery to run through a complete discharge cycle while a second battery is charged. The second method uses the same principle but splits each battery into smaller partitions, in doing so a larger battery can be employed.

Sizing the battery is rather complex in that the amount of energy needed to charge must be provided by the fuel cell and still have sufficient power (32 kW) to move along uninterrupted and without running out of energy. Three criteria must be considered. The first, is that the Wh produced by the fuel cell for charging must exceed the energy to charge the battery, each battery requires of 12.2 Wh (2.9 V x 4.2 A) of energy input. The second criterion is that the watt output generated by the fuel cell at any given point must exceed the necessary watt input required for charging. This is found by taking the watts per cell, 50 A x 2.9 V = 145 Watts x the number of cells. Lastly, the battery must be large enough that it provides sufficient energy (Wh), before becoming depleted. This may call for an over sizing factor to be applied to the battery.

Sizing the Propulsion System

Three different configurations will be analyzed and discussed as means of determining feasibility and the state of technology. In the CTTransit fuel cell bus experiment energy output was found to degrade by approximately 10% over the life of the fuel cell. In order to make up for the power loss the fuel cell will be oversized by 10%.

Starting with the first battery system type, where two equally sized batteries are used, the largest battery output based on the parameters described is 50000 W or 50 k. With over capacity of 1.1 a 50 kW battery will provide just over 6 minutes of charging time. The size of the battery is limited by the watt output of the fuel cell. The fuel cell will be sized to meet the energy output at end of life so a 137.5 kW fuel cell with 10% output degradation will produce 125 kW. Available power for charging is 93 kW (= 175 kW – 50 kW Battery - 32 kW Return) . The wattage needed for charging is 145 W/cell x 612 cells = 88.74 kW. The remaining wattage is therefore 4.26 kW. The required Wh in this scenario is 612 cells x 12.2 Wh/cell = 7.5 kWh. Wh output from the fuel cell during the 6 minutes charging period totals 93 kW/60 Minutes = 1550 Wh/Minute X 6 minutes = 9.3 kWh, leaving 1.8 kWh unused.

If a larger battery were to installed partitions would have to be created in order to allow for a smaller portion of cells to be charged at a time. With a 4 minute minimum charge time an over capacity factor of 1.25 per battery would have to be used (a total of 2.5 times larger for the full battery system). The reason for this as seen in figure 4-1 is that as one partition is depleted and begins to charge another must sit idle. With increased Wh capacity of each partition, fewer idle partitions are required. For example, if each partition ran for 4 minutes and was sized to discharge ½ of the required power, no fewer than 4 partitions may be used. However if the running time per partition were increased to 8 minutes, 3 partitions may be used. Increasing the running time also decreases the number of discharge cycles experienced each day which in turn affects the life cycle of the battery system. However increasing the running time will equally affect the required Wh of each battery and therefore increase the number of cells and subsequently the total weight of the battery system.

If a larger battery is used partitions will have to be created to allow for sufficient charge energy. For example if a 125 kW battery were used, the standard method of charging the entire battery would result in 1,221,263 W needed for charging. The available charging energy is only 18 kW (175 kW – 125 kW – 32 kW). By creating individual partitions as small as 1/100 of the required output power, sufficient charging energy can be generated. This results in 11,100 W required and 18,000 W available. Still, the total size the battery remains the same if there were only 5 partitions. In the end cost of the implementing a particular configuration will determine how the propulsion system is organized.

Analyzing Cost

The base cost with no attachments or upgrades of the D7E track-type tracker is for this research $530,000. A new replacement engine is $30,000. The D7E uses an average of 6.2 gallons of diesel fuel per hour, so for an 8 hour shift would consume 49.6 gallons of fuel. The operating of the D7E used for this research will be 10,000 hours. If a machine were to operate an average of 2,000 hours a year, regular maintenance costs would amount to $6,034.00.

The cost of the hydrogen dozer will depend on the configuration of the propulsion system and corresponding battery. Four difference configurations have been developed to analyze the initial cost and life cycle of the dozer. In figure 4-8 the cost of a 50 kW fuel cell equipped dozer would cost around the same price as the diesel alternative, about $900 less. A larger 125 kW fuel cell equipped dozer is estimated to cost $518,000, saving $12,000 over the diesel counterpart.

From here estimating maintenance costs are not as simple. This can be primarily attributed to the lack of data on the cost of replacement parts. Since no system is in place extrapolating the cost for replacement parts will be extrapolated from the NREL CTTransit report. Since the technology is not in wide spread production a limited number of replacement parts are in circulation. It can be said with a fair degree of certainty that the high volume cost for parts will be less than what is to be estimated here. As technicians and engineers become more proficient with the technology maintenance costs will also decrease. The learning curve of the CTTransit mechanics was considerable. Over the course of the project labor hours averaged 3 times that of the diesel buses. In the latest CTTransit report the number of labor hours attributed to maintenance on the hydrogen bus had been reduced to 1.5 times that of the diesel counterpart. At an hourly rate of $50 the fuel cell bus cost over $76,000.

Life Cycle Analysis

In analyzing the life cycle cost, 10,000-hour operational life was used for both machines. No salvage value was used for two reasons. Both machines are designed to be rebuilt and the salvage value would most likely be similar. In researching used machinery with more than a few thousand operating hours, asking prices were not worth the time investment. 2,000 operating hours a year was used in determining life cycle costs of each machine.

Figure 4-2 shows the life cycle assessment of each machine. Figure 4-2 also shows the cost for the propulsion components used in determining life cycle costs. The initial cost of the hydrogen machines is less than the diesel counterpart Figure 4-2, however it is the maintenance and replacement costs of the hydrogen dozer that drive up the total present value. If the cost of hydrogen fuel were to decrease from $5 to $3/kg the difference in owning and operating costs of the hydrogen dozer compared to the diesel dozer would break even after 6.4 years Figure 4-10, 1.4 years beyond the operational life of the machine. However if the cost of hydrogen fuel were $3/kg and the cost of diesel rose to $5/g then the break-even point would occur at exactly 3 years Figure 4-10. Adjusting the energy output of the battery for the 125 kW fuel cell increases the lifecycle of the battery but also increases the maintenance and operating costs. This means that the life cycle of the battery is not extended long enough to offset the additional cost of the added batteries.

Feasibility Analysis

Since cost can be seen as one of the major contributors to change and in this case determining feasibility, the 50kW fuel cell dozer can be considered feasible in a high volume market. The conditions of this market would be such that diesel would cost $3/gallon and hydrogen $3/kg. The weight, size and volume of the respective battery systems shown in figures 4-3 and 4-4 may present some concern if it were in a road going vehicle, however the nearly 2900 pound weight of the 125 kW battery should not pose a problem for the dozer. Volume of the battery is less than 23 cubic feet amounting to 2.8 feet on a side. The volume of the engine used in the D7E is approximately 32.6 cubic feet or 3.2 feet on a side. This means there should not be a problem with installing the battery on the chassis of the dozer. No one of the fuel cell configurations is larger than 3.5 cubic feet. In the remaining 9.6 cubic feet of space provided by the now removed diesel engine, the fuel cell can be installed. Not to mention, a sizeable volume can be freed by removing the electric generator coupled to the engine of the D7E, no dimensions for piece of equipment have been found.

Estimated cost of the fuel cell propulsion system is shown in figure 4-6. As hydrogen fuel cell technology becomes more refined the cost will decrease as predicted by U.S. DoE and compared in figure 4-6. The cost is considerably less than the diesel alternative, however the diesel engine does not have to be replaced and incurs less maintenance costs associated with replacement tasks.

The cost of the fuel tank used for storage of hydrogen fuel shown in figure 4-5 accounts for only a small portion of the total cost of the hydrogen dozer. The same is true for storage technology as with other hydrogen related technologies, as time passes cost decreases dramatically. The weight of hydrogen fuel is also noticeably less than that of the required diesel fuel for an 8 hour shift. This is shown in figure 4-7. More important is the volume required to store the required fuel as mentioned earlier.

Using this scenario the objective statement originally set out is answered, by providing a means to cull the ever volatile cost of fossil fuels, specifically diesel. Estimators can pinpoint with certainty that the cost of fuel will not increase, but is expected to decrease with time. As a secondary benefit the cost of the hydrogen specific components should also decrease with time.

As for on-site production of hydrogen, no estimates at this point can be generated. In researching the cost of such systems many interviewees were hesitant to even name the potential cost. However it can be said that the price of these systems should not exceed $275,000 if diesel costs remain at $3/gallon. This was found by taking the cost of diesel per year at $3/gallon = $162.5 X 250 days = $40,625. The cost to generate hydrogen on site would be around $21,050 using off peak electricity over the course of a year. Similar systems installed in the last 10 years are still operational. So we can say the fuel savings by generating hydrogen on-site is $19,575 over 10 years amounts to $195,750. If an on-site system were produced in large quantities it should not cost more than the fuel savings of $195,750. If diesel fuel prices were to rise to $5/gallon, the fuel savings would then be $466,583. Systems in production today, capable of producing the required quantities are priced between $1,025,000 and $1,600,000.

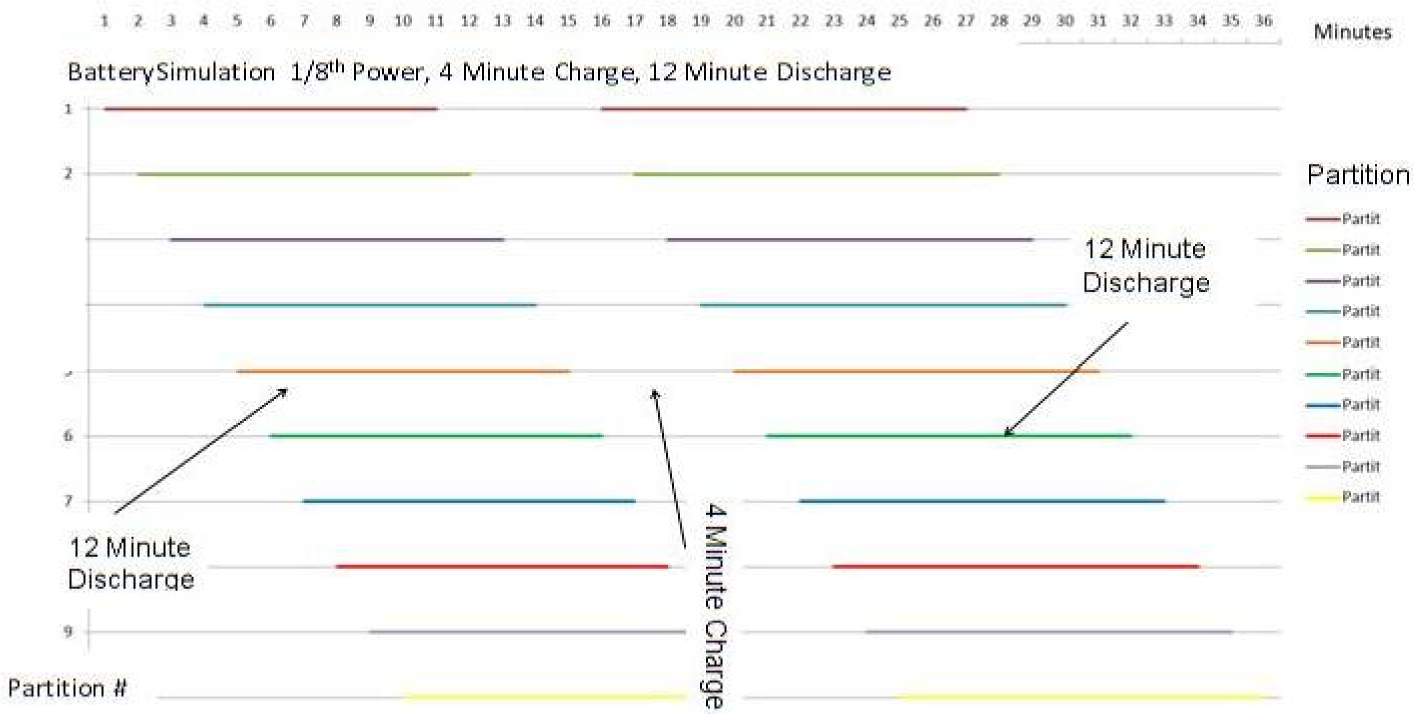

Figure 4-1. Battery Partition Simulation

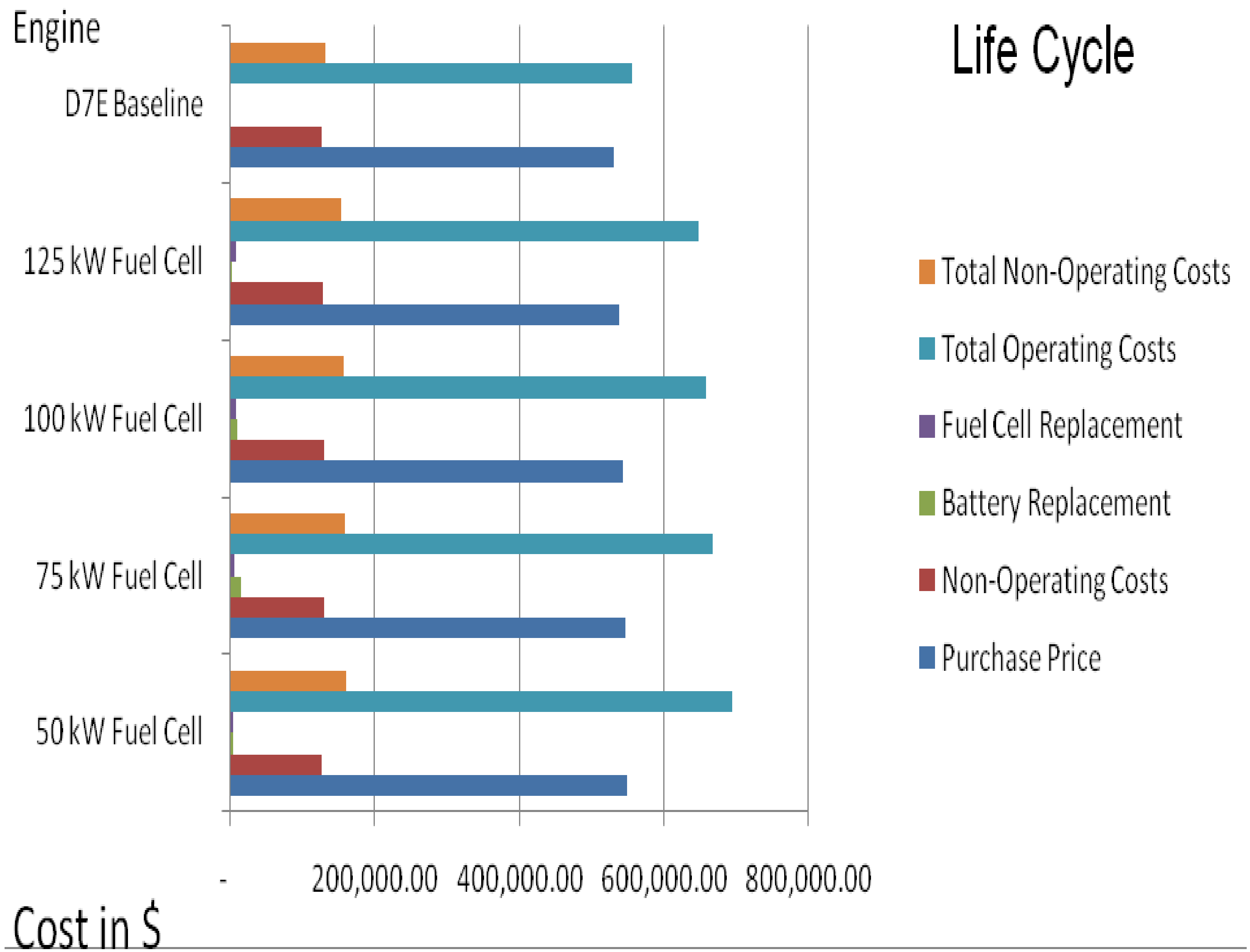

Figure 4-2. Life Cycle Assessment

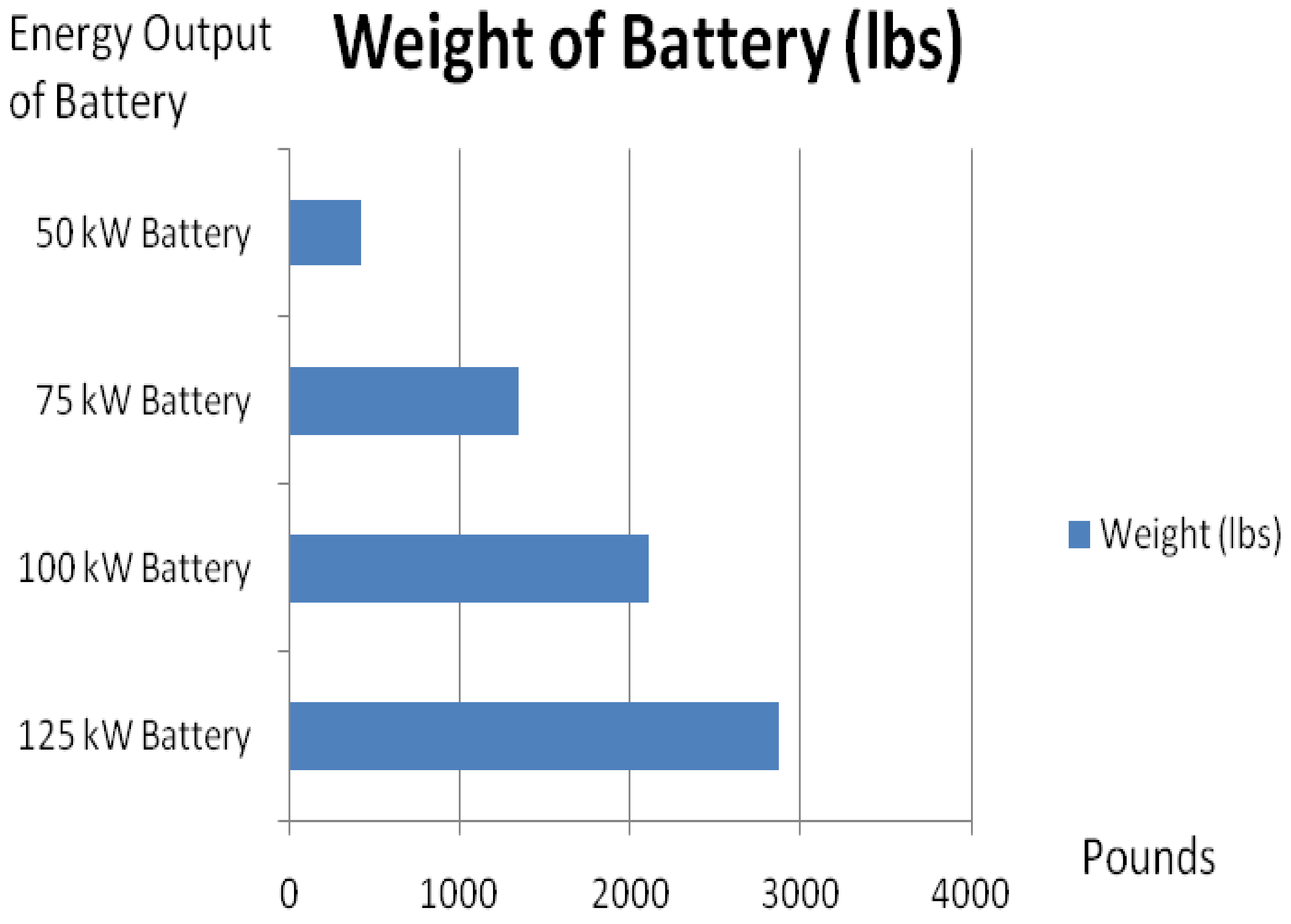

Figure 4-3. Battery System Weight Analysis

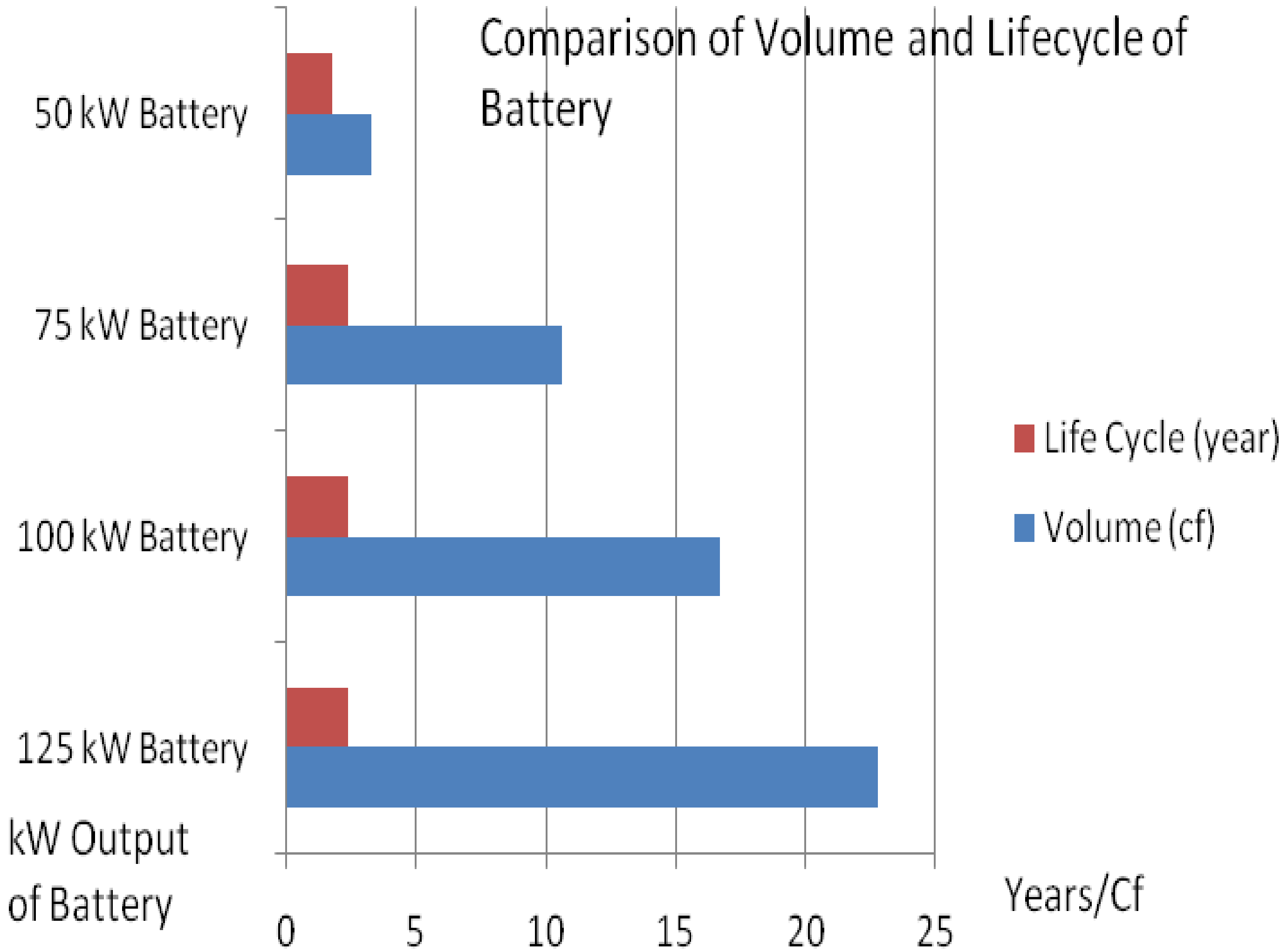

Figure 4-4. Battery Volume and Life Cycle Comparison

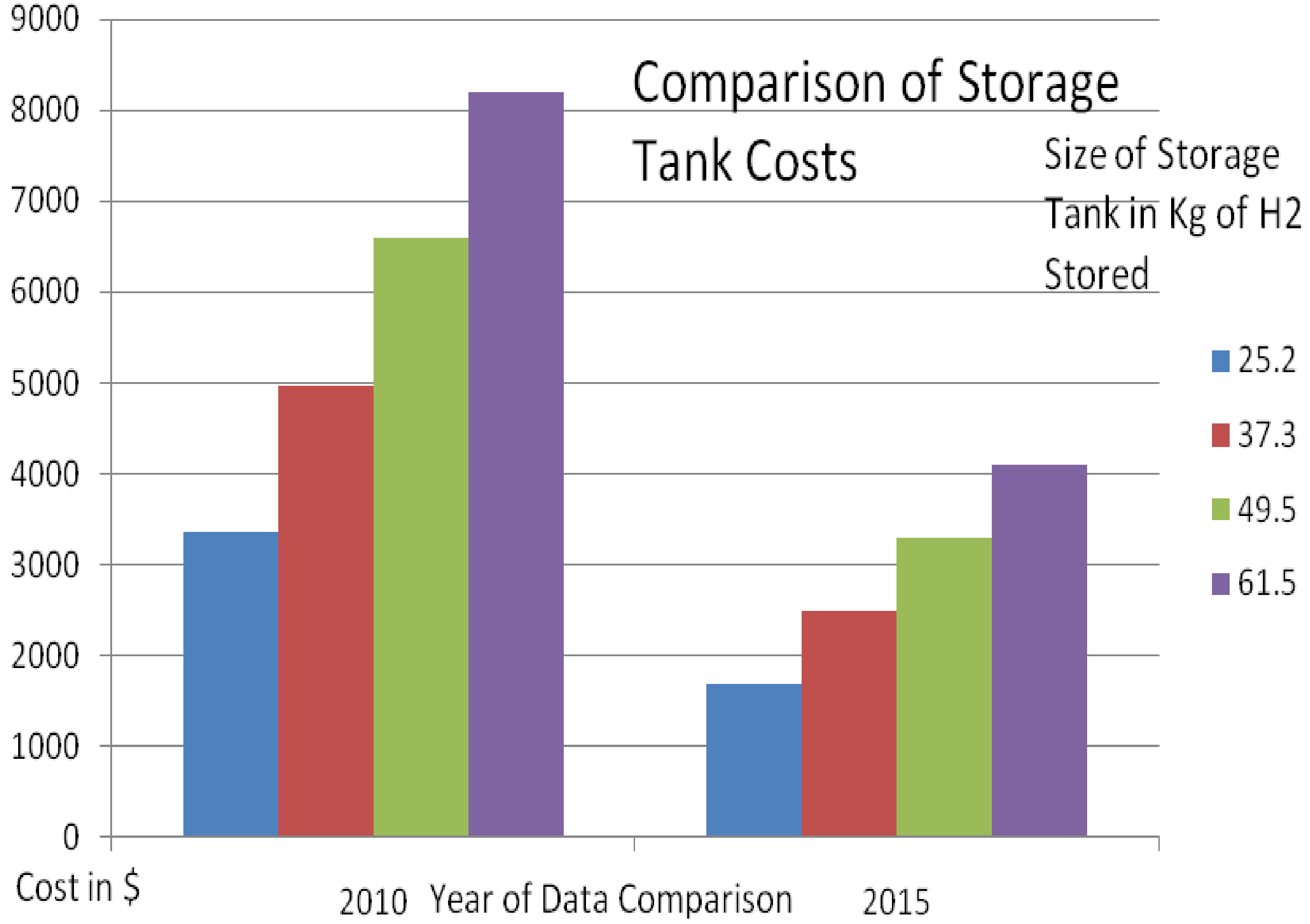

Figure 4-5. Cost of Storage Tank

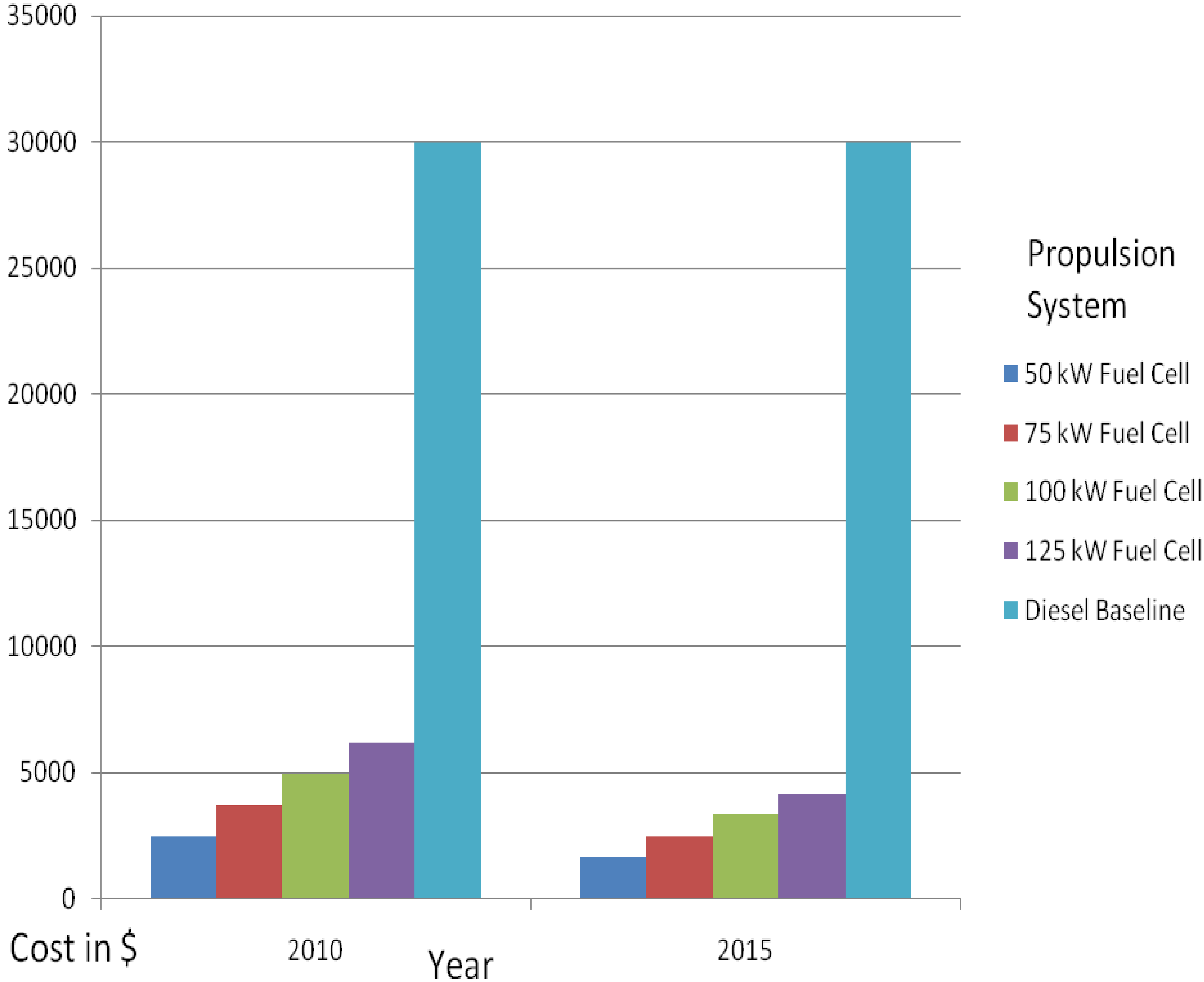

Figure 4-6. (DOE Hydrogen Program Record, 2009)

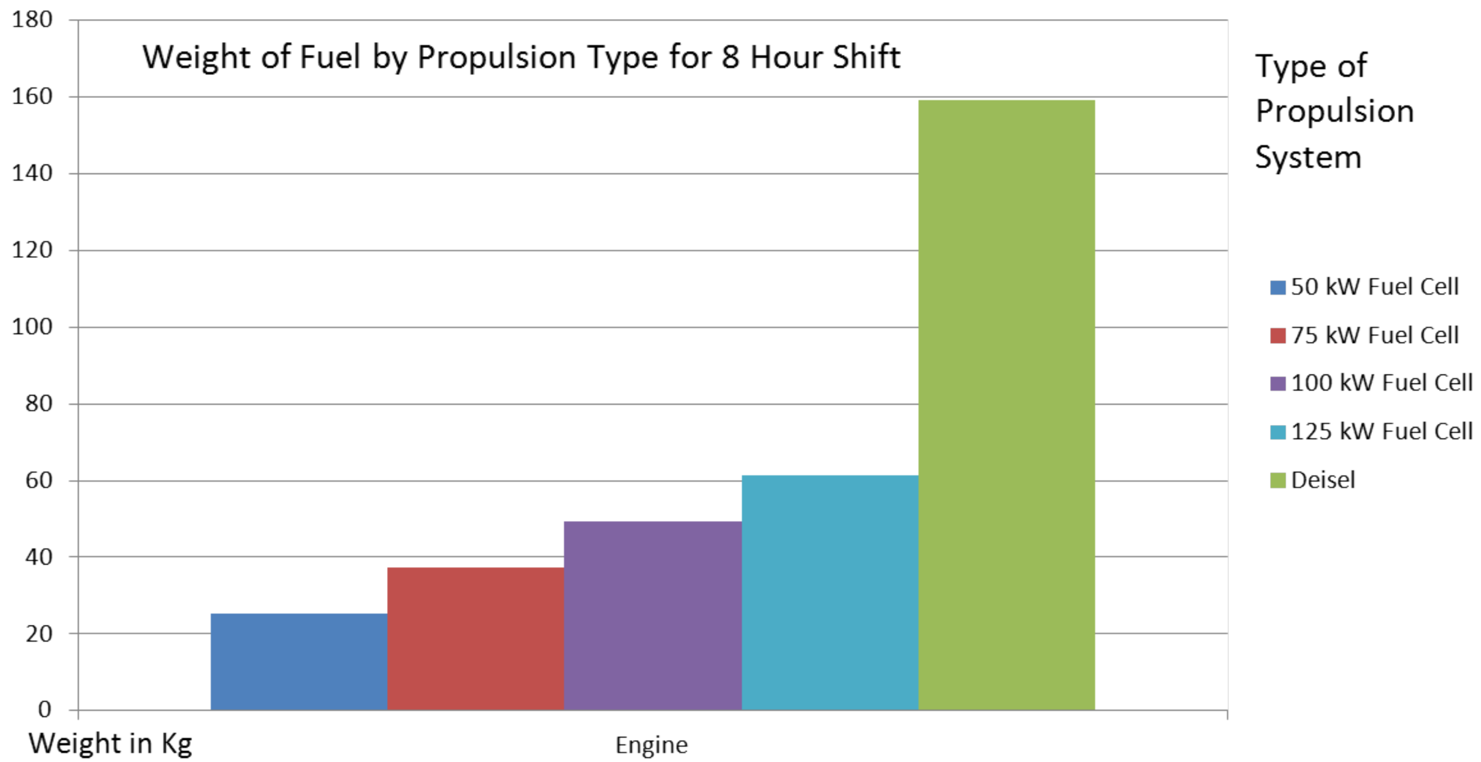

Figure 4-7. Comparison of Weight of Fuel for 8 Hour Shift by Propulsion Type

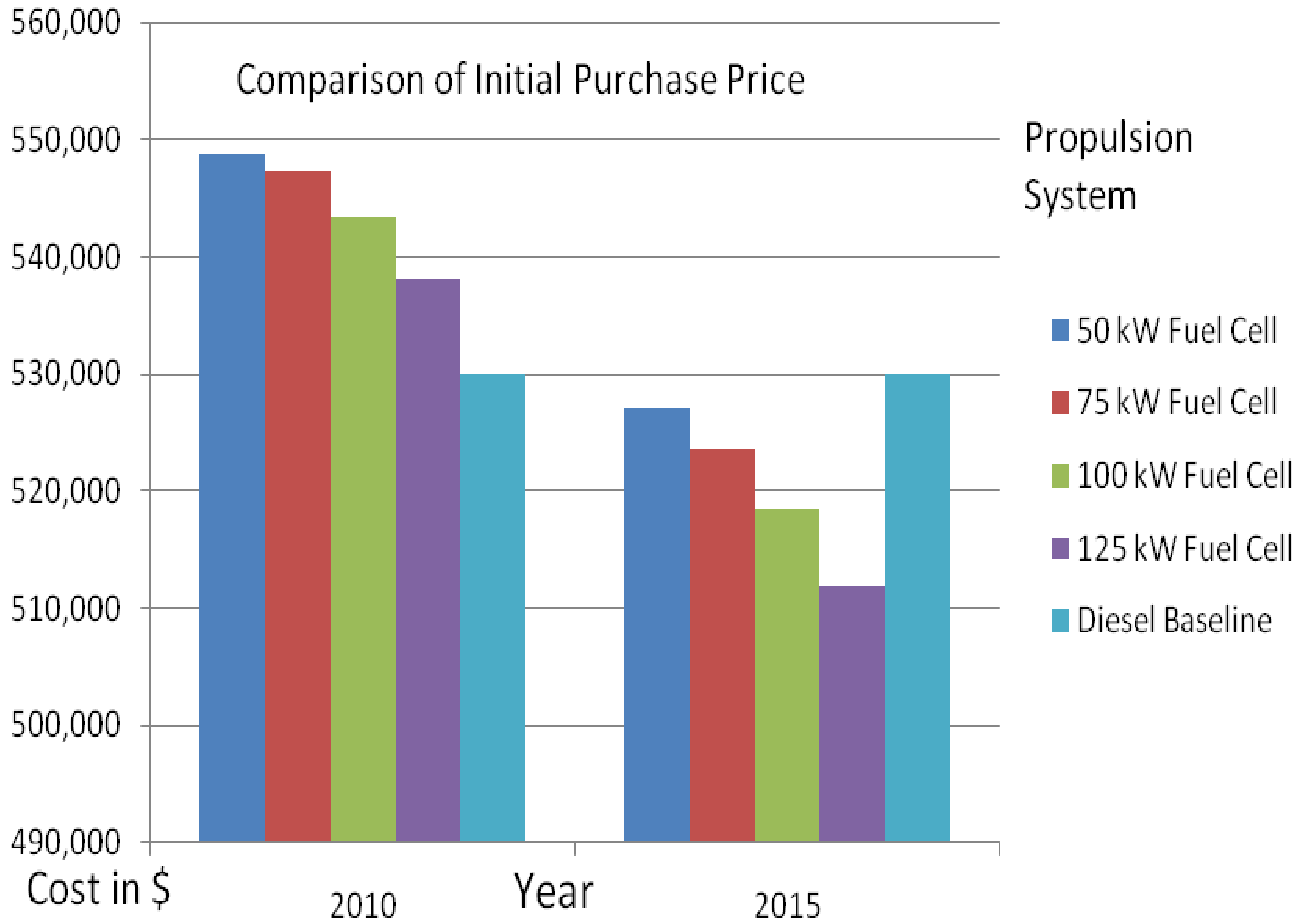

Figure 4-8. Initial Purchase Price Comparison

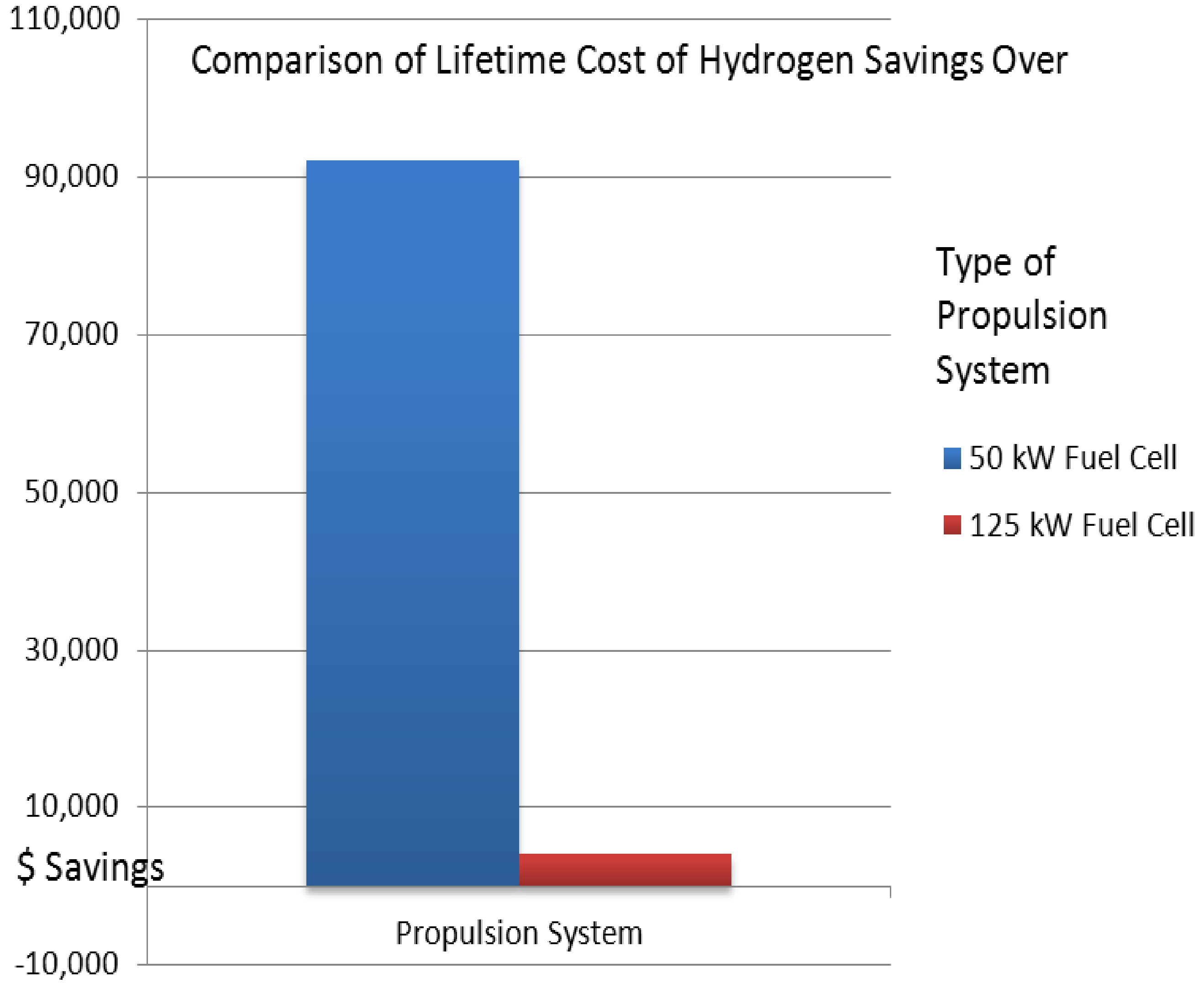

Figure 4-9. Lifetime Hydrogen Fuel Savings over Diesel Powered Dozer

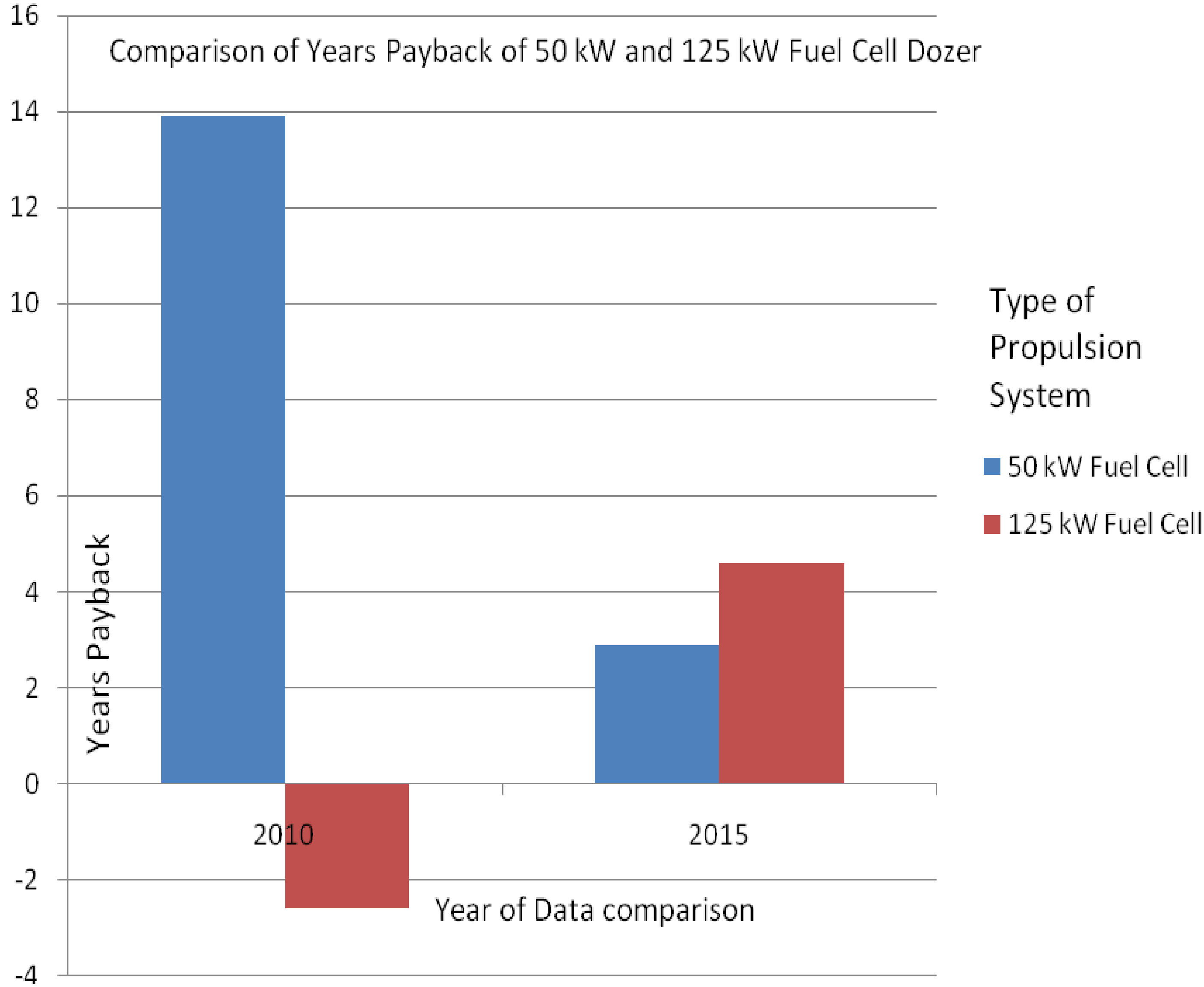

Figure 4-10. Payback Periods on Premium for Hydrogen Dozer

CHAPTER 5
CONCLUSIONS

Conclusions and Future Consideration

Despite the higher cost of building and owning a hydrogen dozer, there comes a point where cost is superseded by the health our fellow man and the environment. Though construction equipment represents only a small part of the total production of harmful pollutants, the industry must be held accountable and accepts responsibility for its part. It is an industry that in the past has resisted change. But hydrogen has many positive benefits going for it, and will ultimately make a tremendous impact on how our mobile world moves.

In analyzing the life cycle cost of the hydrogen dozer it appears that it is feasible. The question that remains, is at what point will production volume of the various fuel cell related components reach production levels greater than 500,000 units/year. The cost of the hydrogen dozer is not feasible at current production levels. For example, the hydrogen storage tank would cost over $600,000, exceeding the cost of the D7E by $70,000.

Even using the high volume cost estimates, the hydrogen equipment needs refinement to increase robustness. The fuel cell needs to have an operational life of over 10,000 hours while keeping cost similar. Individual fuel cell parts need to be better designed to reduce failure and subsequently maintenance and labor costs. Since many of these systems are being tested to help determine areas of improvement, with time, operational life will improve.

Arguably the most important element is the cost of hydrogen fuel and ensuring that it can be acquired in necessary volumes. Currently hydrogen can be purchased at just over $5/kg delivered on site. However in cases where on-site delivery is not an option, such as a remote location, on-site generation must be used. The current price of $1.6 million for 65kg/day hydrogen generation is excessive. Included in the cost are the electrolyzer, 10,000 psi storage tanks, and compressor, dispenser and replacement parts. Energy requirements for producing hydrogen via electrolysis are approximately 70% efficient; a good number must needs to be improved. It is estimated that hydrogen electrolysis can reach a level of 96% efficiency. A problem that may arise in the years to come with increased levels of hydrogen electrolysis around the country is the ability of the national power grid to keep up with demand. Much of the energy used for transportation today is generated from energy sources off the grid.

Currently research is underway to develop an on-demand hydrogen fuel cell. An on-demand hydrogen fuel cell would work much like an internal combustion engine. As the work energy demand increased the volume of hydrogen injected into the system would be adjusted to match. Whereas built on current technology are generating full power at all times. With such a device, wasted energy would be kept to a minimum and potentially eliminate the need for battery assist. An on-demand system would make hydrogen a much more appealing, especially in stationary equipment, such as cranes and shovels, or where the available charging time is fractionally smaller the discharge time.

Future Research

In order to better determine hydrogen energy demands, in depth analysis of the doze cycle could be reviewed. For this research the highest energy output was used in estimating energy requirements. However, actual energy output would be more gradual.

The energy demand and efficiency of the sub-systems (air compressor, etc.) on the hydrogen fuel cell dozer need to be analyzed. This research took into account that the energy demand would remain the same for these sub-systems. It may be of interest to examine other production cycles. It was important to consider how the machine would be used and to analyze the energy demand based on the equipment's intended use. But applying a hydrogen propulsion system to other dozing machines or even different pieces of heavy construction equipment may have a significant effect on feasibility.

Moving towards greener energy has been of rising interest in the last decade, it may be beneficial to analyze the potential cost of producing hydrogen energy from electricity sourced from wind, solar, hydro and nuclear. It may be that the hydrogen is produced locally by at the wind far or miles away from a nuclear reactor. The price of the hydrogen produced will be affected by the electrical transmission cost and amount the available wind. Large capacity flywheel may be used in addition to wind power. Doing so may reduce the cost of a potential hydrogen generating facility. A larger electrolyzer will have to be built to take advantage of peak energy production of the wind turbine, while a flywheel can smooth the power delivery and allow for a smaller electrolyzer.

Feasibility of extending hydrogen propulsion throughout the heavy equipment industry should be evaluated in depth. This research has shown that the topic is worth considering and will at some point become mainstream. What equipment would benefit from hydrogen technology would help guide research efforts.

Thankfully weight is not as much of an issue with heavy construction equipment as it is with light duty automobiles. Weight will have an affect of fuel consumption and could be a topic of future research. It was very helpful to have discovered the batteries used in this research. With the low comparable cost and energy density, without the SCiB batteries cost and weight would have been much higher. An alternative battery considered for this research would have weighed as much as 6,000 pounds and cost would have been well over two times the price. Additional research into battery technology that will increase the energy density and the Wh/kg needs to be conducted. Simultaneously, the cost/Wh needs to remain competitive with existing technology. Part of this can only be achieved by reducing or eliminating the amount of exotic or precious metals used in battery design.

It would be of interest to build and test a hydrogen powered dozer, to determine real world results. For example the actual energy use on the return cycle could be measured, allowing for more refinement of the propulsion system. Noise testing could be performed, where the dozer performs several complete cycles. Such a test may provide additional data on systems that produce excessive noise, as was found on the CTTransit hydrogen bus. These systems may not be heard over the roar of the diesel engine, but with the nearly silent operation of a hydrogen fuel cell, the smallest squeak may show itself. Not to mention that reduced noise levels will be beneficial in sensitive locations.

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National Renewable Energy Laboratory, NREL. (2010) *Connecticut Transit (CTTRANSIT) Fuel Cell Transit Bus: Third Evaluation Report.* Chandler, K., Eudy, B. L. [Figure 2-1] Table ES-1 Summary of Evaluation Period Results

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BIOGRAPHICAL SKETCH

Micah Lockwood Whitlow grew up in the small rural town of Holly Springs, North Carolina. After graduating from high school, he attended Western Carolina University where he studied construction management. It was Micah's long term goal to attend graduate school, which led him to the University of Florida. His career aspirations are to focus on international construction, especially developing countries.