Hydrogen Refueling Station

DESIGN PROPOSAL

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EXECUTIVE SUMMARY

A request for proposal was sent out by the National Hydrogen Association and the US Department of Energy to develop a public hydrogen refueling station. This report presents the proposed design developed by the University of Victoria Design Team.

The station is to be located in Vancouver, British Columbia, one of the prime centres of activity in the fuel cell technology and support industries. The station incorporates an ergonomic, space efficient layout with inherent safety benefits. It is designed around liquid hydrogen with a 2,700 kg Dewar, and energy efficient liquid compression to 9,500 psi. On-site storage with centralized production allows for great flexibility in the design and the simple fueling process results in fewer potential failure modes. The single dispenser can easily accommodate high customer demand with a four minute filling time, made possible by a low temperature hydrogen filling system.

The overall well to wheel pathway of this fueling process generates up to 95% less CO₂ and requires up to 42% less energy than gasoline. The proposed design requires a low capital investment, and uses components easily available from a proven supplier base. An economic analysis shows that the delivered hydrogen cost is between $0.11/mile and $0.18/mile, based on a ten year discounted cash flow analysis.

The design consists of mainly passive and static components, providing the station with a long life expectancy and safe operation with minimal required maintenance. The station includes effective leak detection and fire suppression systems, and the innovative component layout provides controlled access to process equipment.

One of the greatest benefits of this design is its flexibility. The station has the ability to accept liquid hydrogen from any source, and can easily adapt to future renewable hydrogen production sources. This design is also scaleable to accommodate future growth. It can easily accommodate liquid hydrogen fueling, or 10,000 psi on-board storage with few modifications and minimal additional investment. The station also has the capability of supplying liquid hydrogen directly to local users.

Along with all the built-in benefits of the station, an innovative public awareness campaign is planned to encourage the acceptance of hydrogen as a fuel. With the operation of this station to begin in 2006, it will be the first step in developing the commercial hydrogen infrastructure of tomorrow, here in Vancouver.
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1 TECHNICAL DESIGN

1.1 Problem Outline

A request for proposal was sent out by the National Hydrogen Association (NHA) and the US Department of Energy (DOE) to develop a design for a public hydrogen refueling station to be open for service by March 2006. Located on a footprint not exceeding 14,400 ft$^2$, this station must service a minimum daily capacity of 50 light-duty hydrogen fuel cell vehicles. Although the storage capacity of each vehicle is 4 kg, it can be assumed that the vehicles will enter the station with their tanks one-quarter full. Thus, 3 kg of gaseous hydrogen, compressed to 5,000 psig, must be supplied to each automobile. The station must be designed to handle a peak hourly fueling rate of 20 kg, or slightly less than 7 cars. The design may be based on any viable hydrogen production and distribution method.

1.2 Design Solution

1.2.1 Proposed Station Location

The station is to be located in Vancouver, a city of 1.8 million people located on the west coast of Canada, in the province of British Columbia (BC). British Columbia’s economy is largely based on its vast natural resources, constituting industries such as forestry, mining, and fishing. Its economy is gradually becoming more diversified, however. There have been notable expansions in the areas of electronics and other technology-based enterprises [1]. Vancouver, in particular, has established itself as one of the prime centres of activity in the fuel cell technology and support industries. The trend began in the early 1990’s when Ballard Power Systems, now a world leader in the development of PEM fuel cells, situated itself in the city of Vancouver. Today, there is a diverse group of fuel cell-related companies in the Vancouver area. This includes companies such as Cellex, QuestAir, Angstrom Power, Westport, and General Hydrogen. The focus of these companies ranges from the development of fuel cell replacement systems for electric forklifts, to hydrogen purification systems and miniaturized fuel cell systems. Important research institutions are also located in the Vancouver area. For instance, the National Research Council (NRC) Institute for Fuel Cell Innovation recently moved to Vancouver and the Integrated Energy Systems Institute of the University of Victoria (IESVic) is also nearby [2].

1.2.2 Hydrogen Production and Delivery Method

The proposed hydrogen refueling station was designed around liquid hydrogen (LH$_2$). LH$_2$ has superior volumetric density, which makes it cost effective to both store and transport. The hydrogen will be produced and liquefied off-site and then transported to the refueling station by LH$_2$ tanker. Transporting the equivalent amount of hydrogen in compressed form would require several transports compared to only one LH$_2$ tanker.
Two viable options have been identified for the centralized hydrogen production and liquefaction. The simpler, currently available option is to obtain the hydrogen from a steam-methane reforming and liquefaction plant in Sacramento, California. The second option is a more cost-effective and environmentally-friendly approach. The ERCO sodium chlorate plant in Vancouver currently releases 600 kg/h of gaseous hydrogen into the atmosphere as a by-product of a necessary chemical reaction. The plant is interested in storing this hydrogen, possibly as a liquid, and distributing it as a commodity. There is enough hydrogen production from this source for several refueling stations and since the plant is already financially viable, it will be able to sell this hydrogen at a very competitive price.

1.2.3 Fueling Process

The station fueling process begins with the bulk delivery of LH₂. There is a dedicated lane around the station for LH₂ tanker operation. The tanker will pull in to the station, park under the storage and distribution system, and connect its hoses to the LH₂ double-walled vacuum storage tank, or Dewar. When hydrogen is needed, it is drawn from the Dewar by a cryogenic pump. The pump increases the liquid hydrogen pressure up to approximately 9,500 psi. The hydrogen then passes through a vaporizer where its temperature is increased to about -30°C. The cold, compressed hydrogen is stored in buffer storage tanks at approximately 9,500 psi and -20 °C. This higher pressure allows for a largely passive fueling process to occur from that point on. The low temperature of the compressed hydrogen gas serves several important functions. First, the volume of buffer storage necessary is decreased due to the higher H₂ density at these conditions. More important, however, is that the filling time can be much shorter since the tank temperature will not rise as rapidly. In fact, calculations have shown that even if the filling rate is increased by over 50%, a tank temperature 20 K lower is still achieved (see Appendix B). A lower storage temperature also means that the car tank will not have to be overfilled to the same degree and this further decreases the necessary volume of the buffer tanks. This low-temperature filling system allows for a quick four minute fill time to be achieved safely and economically. The buffer storage tanks, thermally insulated in order to passively maintain the low hydrogen temperature, are connected to the dispenser system through an insulated piping line.

A fueling process schematic, including all the major components, is depicted in Figure 1. A summary of the hydrogen properties throughout the fueling process can also be seen in Table 1.

Table 1 – Refueling Process Hydrogen Parameters

<table>
<thead>
<tr>
<th>Location</th>
<th>Hydrogen Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>State</td>
</tr>
<tr>
<td>Dewar</td>
<td>Liquid</td>
</tr>
<tr>
<td>Cryopump Exit</td>
<td>Liquid</td>
</tr>
<tr>
<td>Vaporizer Exit</td>
<td>Gas</td>
</tr>
<tr>
<td>Buffer Storage (Filled/Empty)</td>
<td>Gas</td>
</tr>
<tr>
<td>Car Tank (Filled, Transient)</td>
<td>Gas</td>
</tr>
<tr>
<td>Car Tank (Filled, Steady State)</td>
<td>Gas</td>
</tr>
</tbody>
</table>
1.2.4 Component Layout

The station was designed on a square plot of maximum allowable area. It was assumed that it would be located on a high traffic, corner lot in Vancouver. A square plot was chosen with safety in mind since it allows for the Dewar to be situated as far away as possible from the property lines, and thus, any surrounding buildings. The station layout reflects the need to provide customers with easy access to the dispenser while having sufficient space for a large LH2 tanker truck to periodically fill the storage Dewar. As a result, the Dewar is located in an elevated storage area which also houses the cryogenic pump, the vaporizer, and the buffer storage tanks. The storage area is located behind the store, on top of a solid, well-ventilated concrete platform. There are many advantages to housing the majority of the process equipment in an elevated area, including:

- Convenient fueling tanker access: A tanker truck can easily drive into the station and fill the Dewar discretely, while being both at a safe distance from the customer service area and shielded from any poor weather.

Figure 1 – The Hydrogen Fueling Station Process Schematic above depicts the manner in which hydrogen flows through the system as it travels from the LH2 tanker to the dispenser and how each of the process components are interconnected in order for this to occur.
- Process component isolation: All the critical process equipment, piping and control devices are contained within a single, solid structure, isolated from the rest of the station. This allows for more control in the event of a process failure, minimizing the risk to the surrounding area.

- Limited accessibility: An elevated structure is not easily accessible. Important and potentially dangerous components are, therefore, less prone to malicious actions such as vandalism.

![Figure 2 – Fueling station component layout diagram.](image)

A concrete wall separates the storage area from the store, shielding the service area and store in the event of a failure. A four foot tall containment wall also surrounds the Dewar to contain the liquid hydrogen if a failure were to occur. In addition, the storage area is well ventilated to allow potential hydrogen leaks to escape quickly and harmlessly. In fact, the storage area is open on three sides and the canopy features a split design that allows gas leaks to vent straight up. The cryogenic pump and the vaporizer are located next to the LH$_2$ storage tank to minimize the length of vacuum-jacketed piping. This minimizes both expense and any potential heat flow into
the system. The compressed gas buffer storage and helium are also located on the platform. A venting manifold collects vent and purge lines from each component and connects to the vent stack, dispersing hydrogen above and away from any structure. For additional safety, the Dewar has its own venting line that connects directly to the stack, bypassing the manifold. The vent stack can be seen in Figure 4, serving a dual purpose as a flagpole.

The only process components not housed within the storage area are the dispenser, the control panel, and the air compressor. The dispenser interacts with the customer and interfaces with the vehicles. It is sheltered under the canopy which is designed to house two more units in the event of future expansion. The control panel is located inside the store, allowing gas attendants to monitor system performance in a convenient location. The air compressor, located at the corner of the plot, is used to power any the pneumatic valves within the system and supply air to the customers. The compressed air line and hydrogen line feeding the dispenser are the only piping lines not contained within the storage area platform.

**Figure 3** – A component layout diagram of the elevated storage area.
Due to its compact nature, the station design also features a large parking area in the rear. This space could be used for other business-related extensions, such as a repair shop or a carwash, however, these possibilities were not included at this time since the aim was to determine the unsubsidized selling price of compressed hydrogen fuel.

### 1.2.5 Major Component Description and Justification

The liquid hydrogen will either be obtained from Air Products or from the ERGO sodium chlorate plant in the Vancouver area. These cases will be discussed in more detail, however, it should be noted that the purity of the LH$_2$ available from Air Products is 99.999%. This level of purity is not easily attainable with on-site production. A 10,000 gallon Dewar, to be provided by Air Products, was selected for local storage [3]. A vessel of this size can store about 2,700 kg of hydrogen, providing enough hydrogen for approximately 18 days at the minimum 50 car/day capacity. This is not an excessive amount of storage, but still allows a large degree of flexibility for handling increased daily refueling capacities. Vacuum-jacketed piping, to be supplied by Acme Cryogenics, ensures the hydrogen stays in liquid form as it is drawn to the cryopump [4]. The hydrogen pressure is increased while it is in liquid form as this is a much more efficient process than gaseous compression. In fact, calculations show that pumping the hydrogen up to 10,000 psi while it is in liquid form requires about 71% less energy use than performing the same operation on gaseous hydrogen (see Appendix B). The cryopump, to be obtained from Cryo Canada Inc., can run at pressures as high as 10,000 psi and flow rates of up to 3 gpm (11.4 L/min) [5]. Its modular design also allows for the parallel addition of up to two more cylinders to double or triple the maximum flow rate.

The vaporizer, responsible for gasifying the compressed liquid hydrogen and raising its temperature to approximately -30 °C (-20 °F), is available from Cryogenic Experts. It is designed for a maximum operating pressure of 10,000 psi and a maximum pressure drop of 20-30 psig. It also has a maximum output temperature fluctuation of about 6.5 °C [6]. The mild and relatively stable year-round weather of the Vancouver area will also help ensure the vaporizer output temperature remains close to its design value. The buffer storage tanks, used to contain the high-pressure hydrogen until it is needed, will be obtained from CP Industries. They can each contain about 300 L of compressed hydrogen at pressures as high as 10,000 psi [7]. Calculations were performed to determine the volume of storage necessary to refuel one car passively (see Appendix B). As was mentioned in the Fueling Process section (1.2.3), this means that the buffer storage pressure cannot drop below 5,350 psi. The resultant value for buffer storage volume per car can then be scaled so that compressed hydrogen is available for a desired number of cars. It was decided that the station would be designed with two buffer storage tanks, or enough buffer storage volume to fuel two cars. However, each time the cryogenic pump is activated it will actually pump enough hydrogen to fuel a minimum of three cars. This is the case since the flow rate of the pump is great enough that the first fill can just pass through the buffer storage system. The pump will then continue running until the storage tanks have been filled. The buffer storage system is shrouded in insulation so that the output temperature can be maintained. Preliminary calculations have shown that the temperature will only increase by about 0.4 °C per hour if 8-inch thick fiberglass insulation is used.
Figure 4 – A 3-D model of the proposed hydrogen refueling station.

High pressure lines run underground to the dispenser system and a pressure regulator is used to control the pressure of the hydrogen stream entering the dispenser system. Available from Kraus Global, the selected dispenser system can accept hydrogen input pressures as high as 6,700 psi for flow rates up to 12 kg/min [8]. The dispenser also features an overfill protection system with electronic pressure and temperature compensation and a control system that can be customized to optimize fill rates. Fuel flow rate is controlled through an electronic solenoid valve. An overhead hose retractor, an in-line breakaway coupling, and a static grounding cable are also included.

1.2.6 Process Control System

The process control system, both for nominal operation and in the event of a process anomaly, is shown schematically and described in Appendix C. However, the technical portion of the process control system will be described in more detail. When first filling the hydrogen lines, all pneumatically actuated vent valves are in the closed position. All valves along the process path of the hydrogen are open to allow the system to pressurize. The cryopump is activated for this initial fill until the pressure transmitter on the buffer tanks reads the desired pressure of 9,500 psig. At this point, the control system deactivates the pump.

As hydrogen is taken from the buffer storage system to fill the car tanks, the pressure in the buffer tanks will drop. When the pressure in the buffer storage falls below 5,350 psig, the control system activates the pump to rebuild the system pressure. This will occur after two cars...
have been filled without the cryopump being activated. If at any time there is excessive pressure beyond the rated amount in the system, pressure transmitters will alert the control system and venting of the desired section will occur. Also, if the gas, fire or temperature sensors near the hydrogen storage or the dispenser are ever activated, then the control system will purge the hydrogen lines and vaporizer, and if necessary, the buffer storage. The system will be purged using high pressure helium gas and all gases will be vented out through the main vent manifold. Manual valves are located throughout the system to isolate and vent all individual components for safety reasons or maintenance.

1.2.7 Process Energy Use

The largely passive nature of the selected refueling process has an inherent advantage over on-site production. The process energy usage is, therefore, quite low. The largest component of this will be for the cryopump, as can be seen in the daily energy usage estimates of Table 2. A very large portion of the global system energy usage will be necessary for the production and liquefaction of the LH₂. This energy requirement will be taken into account in the environmental analysis.

<table>
<thead>
<tr>
<th>Component</th>
<th>Running Time (hrs/day)</th>
<th>Energy Usage (kW)²</th>
<th>Daily Energy Usage (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryopump</td>
<td>3.0</td>
<td>44.00</td>
<td>132.00</td>
</tr>
<tr>
<td>Dispenser</td>
<td>5.0¹</td>
<td>2.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Control System</td>
<td>24.0</td>
<td>1.50</td>
<td>36.00</td>
</tr>
<tr>
<td>Safety Systems</td>
<td>24.0</td>
<td>0.25</td>
<td>6.00</td>
</tr>
<tr>
<td>Exterior Lighting</td>
<td>24.0</td>
<td>1.00</td>
<td>24.00</td>
</tr>
<tr>
<td>Interior Lighting</td>
<td>24.0</td>
<td>0.50</td>
<td>12.00</td>
</tr>
<tr>
<td>Interior Services</td>
<td>24.0</td>
<td>0.50</td>
<td>12.00</td>
</tr>
<tr>
<td><strong>Total Energy Usage</strong></td>
<td><strong>49.75</strong></td>
<td></td>
<td><strong>232.00</strong></td>
</tr>
</tbody>
</table>

¹ 50 cars x 0.1 hrs/car
² From component quotes [3-8].

1.2.8 Station Design Flexibility

This station design is very flexible in many respects. Since it was designed around a LH₂ storage system, there is the option of obtaining this fuel from any production site and method. In the future, LH₂ may be available from a more environmentally-friendly production and liquefaction method, such as the ERGO sodium chlorate plant. Also, as hydrogen becomes more widely available, LH₂ plants will appear near the Vancouver area, greatly reducing the transportation costs of the fuel. Because hydrogen is available at the site in liquid form, it will also be quite easy to supply LH₂ to vehicles if there is an increased demand. The high hydrogen pressure in the buffer storage system also allows for potential fueling of 10,000 psi storage tanks. This is an important consideration since companies such as Dynetek have been developing higher-pressure storage systems that may soon be commercially viable.
Another aspect of the station design’s flexibility is its ability to expand. Since hydrogen production is centralized, less space is required for the process components. This allows plenty of future expansion space to service an increasing number of fuel cell cars in the future. Space for two more dispensers, providing either LH₂ or compressed hydrogen at 5,000 or 10,000 psi, is available. More frequent filling of the Dewar will allow the daily capacity of the station to increase easily and the modular design of the cryogenic pump will allow for an increase in required flow rate by simply adding one or two more cylinders to the unit. The small size of the vaporizer relative to large storage area will also allow the addition of other equipment to handle increased flow rate. Furthermore, it is quite simple to increase the capacity of the buffer storage system, to allow for more car tanks to be filled while the cryopump is not active.

Yet another aspect of the design flexibility is the ability to supply LH₂ to some of the many local fuel cell-related organizations. Smaller mobile Dewars could be filled directly from the large Dewar if adaptations were made to the piping system. If the number of vehicles using the station was lower than expected, this source of revenue could maintain the financial viability of the proposed station design.

![An aerial view of the proposed hydrogen refueling station.](image-url)
2 FUELING STATION SAFETY ANALYSIS

Safety was a priority during the design of the hydrogen refueling station. It was a necessary consideration in order to ensure that the general public, the surrounding environment, and the station storage and process devices were adequately protected. It was deemed very important to produce a design that not only operated safely and consisted of safe processes, but at the same time did not present a heavily industrial atmosphere with heightened security. This would only fuel the public misconception that hydrogen is an unsafe fuel.

Several steps were taken in the process to gain confidence that the finalized design was safe; existing codes and standards were researched and examined where possible, a potential failure modes and effects analysis (FMEA) was carried out on the station design, and modifications were made to address the critical safety issues identified in the FMEA analysis.

2.1 Current Codes and Standards

Before the station design was initiated, research of the existing codes and standards relevant to the project was conducted. Numerous codes and standards for hydrogen production, delivery and storage, as well as refueling station process components and buildings were found. Many of the standards cover similar topics, and often overlap with different requirements. Some of the codes most relevant to the hydrogen fueling station are listed in Table 3 below [1][1-4]:

<table>
<thead>
<tr>
<th>Association</th>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGA</td>
<td>G-5</td>
<td>Properties, manufacturing, transportation, storage and use of gaseous H₂.</td>
</tr>
<tr>
<td></td>
<td>G-5.3</td>
<td>Requirements for commercially available gaseous and liquid H₂.</td>
</tr>
<tr>
<td></td>
<td>G-5.4</td>
<td>H₂ piping systems at consumer locations.</td>
</tr>
<tr>
<td></td>
<td>G-5.5</td>
<td>Guidelines for H₂ vent systems for gaseous and liquid H₂ installations at consumer sites.</td>
</tr>
<tr>
<td>NFPA</td>
<td>50A</td>
<td>Gaseous H₂ at consumer sites.</td>
</tr>
<tr>
<td></td>
<td>50B</td>
<td>Liquid H₂ at consumer sites.</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>Fuel gas piping installation (Fuel gas code).</td>
</tr>
<tr>
<td>SAE</td>
<td>J2600</td>
<td>Compressed H₂ vehicle fueling connection devices.</td>
</tr>
<tr>
<td></td>
<td>J2601</td>
<td>Compressed H₂ surface vehicle fueling communication devices.</td>
</tr>
<tr>
<td>BSR/CSA</td>
<td>HV4.1</td>
<td>H₂ dispensing systems.</td>
</tr>
<tr>
<td></td>
<td>HV4.2</td>
<td>Hoses for H₂ vehicles and dispensing systems.</td>
</tr>
<tr>
<td></td>
<td>HV4.3</td>
<td>Temperature compensation devices for H₂ dispensing systems.</td>
</tr>
<tr>
<td></td>
<td>HV4.4</td>
<td>Breakaway devices for H₂ dispensing systems.</td>
</tr>
<tr>
<td></td>
<td>HV4.5</td>
<td>Priority and sequencing for H₂ dispensing systems.</td>
</tr>
<tr>
<td></td>
<td>HV4.6</td>
<td>High pressure manually operated valves for H₂ dispensing systems.</td>
</tr>
<tr>
<td></td>
<td>HV4.7</td>
<td>Automatic high pressure operated valves for H₂ dispensing systems.</td>
</tr>
<tr>
<td></td>
<td>HV4.8</td>
<td>H₂ vehicle fueling station compressor guidelines.</td>
</tr>
</tbody>
</table>
The majority of the codes and standards were inaccessible since they were either only available for purchase or currently in development. As a result, the decision was made to conduct a safety analysis of the design instead of relying on the existing codes. This allowed the freedom to produce an innovative and safe design not constrained by the existing standards.

### 2.2 Station Design Safety Features

Safety considerations played a major role in the initial station layout decision-making process. A station based on centralized production is inherently safer than an on-site production facility due to fewer processes and components which result in fewer potential failure modes. Although this approach requires bulk liquid hydrogen storage on-site, it can easily be isolated.

Many safety features were incorporated into the station design as it was developed, as can be seen in Figure 6. The station was designed to reduce the exposure of the public to any of the process components. The design includes an elevated and isolated LH₂ storage area that also houses all of the process equipment. This design distances the storage, pumping and vaporization processes from the customer. As a result, the dispenser is the only hydrogen component accessible to the public. All liquid hydrogen is confined to the storage area and any spillage or release is fully contained within a controlled environment. The liquid storage Dewar is forty feet from neighbouring structures and buildings. Furthermore, any minor leak is very unlikely to combust because of the open-air design of the storage area. This allows hydrogen to easily disperse into the environment in a safe manner. Even in the unlikely occurrence of combustion, the storage area is isolated and elevated above public areas, which reduces the severity of that failure.

The station will be operated with an integrated safety control system. The control schematic and algorithm are available in Appendix C. The control system will monitor all process variables, such as pressure, temperature and flow rate, for extremes and take corrective actions as required. Gaseous hydrogen, temperature and flame detectors placed in the storage and customer area will also be connected to the control system. The system can give warning and take action to prevent or reduce the effect of failures. For instance, the system can vent process gas by purging process lines with helium or activate water deluge sprinklers to extinguish flames or cool possible ignition sources. Rupture disks and pressure relief valves were included in parallel to the control system to vent the process gas in the case of excess pressure and a malfunction of the control system. The vent stack and all process components are also grounded to reduce the chance of
ignition due to electrical discharge. In addition, pneumatic actuators are used on process control valves to minimize possible ignition sources.

Finally, in addition to the built-in safety systems, a strict maintenance and inspection procedure will be carried out on a regular basis. As a result of these procedures, access to the storage area will be restricted to essential services performed by trained operators.

![Diagram of safety features](image)

**Figure 6** – The various safety features included in the design of the process equipment storage area.

### 2.3 Potential Failure Modes and Effects Analysis (FMEA)

An FMEA analysis helps identify every possible failure mode of a process to determine its effect on other sub-items and on the required function of the process [5]. It is also used to rank and prioritize each possible cause, as well as develop and implement preventative actions [5]. A summary FMEA style safety analysis was conducted on the preliminary station design to
The FMEA was carried out as follows:
- All process components were listed, along with their function.
- A brainstorming session was conducted to determine every conceivable way in which a component could fail to perform each of its functions.
- The potential effects of each failure mode were listed and ranked based on the degree of severity; 1: little or no effect, 10: very severe effect.
- All conceivable causes of the failure modes were then listed and ranked based on their probability of occurrence; 1: remote probability, 10: certain failure.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LH2 Storage (Dewar)</td>
<td>Contain LH2 @~30psi? Leakage/Rupture</td>
<td>Spill to Storage Area and Dissipation of H2</td>
<td>H2 Embrittlement</td>
<td>Specification: Supplier</td>
<td>4 160</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spill to Storage Area and Combustion of Vapour</td>
<td>Corrosion</td>
<td>Specification: Supplier</td>
<td>4 100</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spill to Storage Area and Pooling of LH2</td>
<td>Stress Cycling/Fatigue</td>
<td>Specification: Supplier</td>
<td>4 120</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical damage (collision)</td>
<td>Design: Barrier, Procedure: Restricted Access</td>
<td>6 120</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical damage (impact)</td>
<td>6</td>
<td>10</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical damage (structural)</td>
<td>6</td>
<td>10</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operator Error</td>
<td>4</td>
<td>Procedure: Operator Training</td>
<td>4 150</td>
<td></td>
</tr>
<tr>
<td>Isolate LH2 from Environment</td>
<td>Allow Excess Heat Conduction</td>
<td>Excess Vapour Pressure</td>
<td>Vacuum Jacket Failure</td>
<td>Specification: Supplier</td>
<td>6 72</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical damage (impact)</td>
<td>Procedure/Design: Restricted Access, Procedure: Operator Training</td>
<td>6 216</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vent Excessive Vapour Pressure</td>
<td>PRD Fails</td>
<td>Excess Pressure Buildup</td>
<td>H2 Embrittlement</td>
<td>Specification: Supplier, Design: Rupture Disk - Vent to Stack</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Corrosion</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mechanical damage (impact)</td>
<td>Procedure/Design: Restricted Access, Procedure: Operator Training</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Datra</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vent Line Blockage</td>
<td>Excess Pressure Buildup</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Corrosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Datra</td>
</tr>
<tr>
<td>Provide Vapour Pressure Signal to Controller</td>
<td>No signal</td>
<td>System Fault</td>
<td>Electrical Damage (shock)</td>
<td>Control: Shutdown</td>
<td>7 120</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Out of Range</td>
<td>Specification: Supplier</td>
<td>3 60</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Power Failure</td>
<td>4</td>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Calibration Error</td>
<td>Procedure: Supplier Calibration</td>
<td>7 105</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electrical Damage (shock)</td>
<td>6</td>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Calibration Error</td>
<td>Procedure: Supplier Calibration</td>
<td>7 9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Signal Bias High</td>
<td></td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Signal Bias Low</td>
<td>Excess Vapour Pressure</td>
<td>Electrical Damage (shock)</td>
<td>Design: Rupture Disk - Vent to Stack</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Calibration Error</td>
<td>6</td>
</tr>
</tbody>
</table>

**Figure 7** – A portion of the fueling station FMEA analysis.
• Existing controls and procedures that prevented either the cause or failure mode were documented and ranked based on their ability to detect each failure mode; 1: failure will be detected or prevented, 10: failure will not be detected.
• Finally, Risk Priority Numbers (RPN’s) were calculated for each failure mode as the multiplication of the severity, occurrence and detection rankings. High RPN numbers represent the most critical safety concerns.

Only failures affecting the customer, operator or public safety were considered. Failures affecting other design requirements such as efficiency and customer satisfaction were not included.

For the hydrogen fueling station design, some of the potential failures considered were:
- Rupture/Leakage (both of the liquid and compressed hydrogen)
- Blockage of process lines or components resulting in pressure build-up
- Process failures (excessively high or low pressure/temperature/flow)
- Component failures (tanks, pumps, valves, etc.)
- Electrical failure (sensors and controls)

2.4 Analysis Results

Numerous potential failure modes, effects and causes were brainstormed during the FMEA process carried out on the fueling station design. Once ranked, the most critical safety issues were distinguished. The three highest RPN numbers, representing the greatest safety risks, were:

1. Structural failure of the vent stack: The vent system is a very crucial component of the stations safety system; this failure had a high RPN because damage could cripple the stations ability to safely manage potentially dangerous failures.

2. Impact on the storage area, specifically the LH2 Dewar: With high vehicular traffic at the station, there is a moderate probability that a vehicle will collide with the storage area support structure.

3. Structural failure of the storage area: Vancouver is located on a known fault line zone, and so, the storage area support structure may have to withstand large- scale earthquakes in addition to the usual structural, shock and thermal expansion and contraction stresses.

As well as the three highest RPN numbers, the following were also potential safety risks, which will most likely require further consideration:
- Attacks on the storage area: Malicious acts such as vandalism could pose a serious safety concern as with any other commercial fueling station.
- Attack on the vent stack: Similar acts could be carried out on the vent system.
- Contamination and debris: Debris in the process components could result in mechanical wear, blockage and system pressure build-up.
• Electrical failure: Any electrical damage or failure could cripple the control and safety equipment. The mechanical back-up system (rupture disks) would safely vent excess pressure, but all other process and safety control would be lost.

• Malfunction of the safety control system: Potential problems in the control algorithm, software and/or hardware are also a concern due to the reliance on safety system to reduce the effect of failures.

The three greatest safety risks were analyzed and design, control or process modifications were implemented to reduce the overall risk they posed. This was accomplished by either reducing the severity of the effect or the likelihood of occurrence or increasing the probability of detection. The following modifications were made to the preliminary design:

• The elevated storage area was moved further from the property lines so that any surrounding structures would be safer in the event of a process anomaly. This was especially important for the Dewar since it houses such a large volume of LH2.

• A concrete wall was placed between the storage area and the store to ensure the customer service area was safer in the event of a failure. A shorter wall was also built around the Dewar to contain spills.

• A sprinkler system and multiple leak, temperature, and flame sensors were placed within the storage area. A helium purge system and a vent stack were included to flush out certain sections of the piping upon detection of a malfunction.

• The vent stack design was modified to ensure that it was structurally sound and inaccessible to impact. This reduced the likelihood of failure.

• Vehicular access to the storage area was restricted to the supply truck and maintenance vehicles only. In a further design iteration, a structural assessment of the storage area will be conducted to ensure that it could survive an impact if one were to occur. A Seismic assessment of the storage area platform will also be carried out to ensure the structure would withstand a major earthquake if one were to occur.

Several measures were taken to ensure that the hydrogen refueling station was safe; existing codes and standards relating to hydrogen production, delivery, storage and commercial dispensing were researched, numerous design solutions and an integrated control system were included in the station, and a summary FMEA safety analysis was carried out to identify the greatest safety concerns of the preliminary station design. Modifications were also made to the design to address the top three failures modes. As a result, an innovative and safe concept for a hydrogen refueling station was produced.
3 ECONOMIC ANALYSIS

The economic analysis is divided into two subsections. The first section presents the calculated selling price of hydrogen while the next one describes the cost estimates used in the discounted cash flow analysis.

3.1 Selling Price of Hydrogen

Three demand scenarios were considered for the economic analysis; a base case, a high demand case, and a low cost alternative. The base case scenario assumes that the demand for the hydrogen refueling station will be 50 cars per day over the ten year forecasted period, while the high demand scenario assumes that 100 vehicles will be fueled per day. In these cases, the LH₂ is to be obtained from an Air Products distribution center in Sacramento, California. The low cost scenario was developed to showcase the design’s flexibility to obtain fuels from various sources. In this scheme, it was assumed that the station fuel would be available from an LH₂ supplier in the Vancouver area by 2006. A potential supplier was also identified. ERCO Worldwide, a manufacturer of industrial grade sodium chlorate in North Vancouver, currently expels 600 kg of hydrogen per hour as a by-product of its production process and there is currently an interest in capturing and selling it. It has been demonstrated that this source of fuel is significantly cheaper than that obtainable from suppliers such as Air Products. Although this case has many advantages over the other two schemes, it was only considered as a secondary case since the idea is still in the development stage. There is also no guarantee that the plant would be ready to supply LH₂ by 2006.

The base case scenario’s selling price of hydrogen is $10.83/kg or $0.18/mile\(^1\). As can be seen in Table 4, this cost is 3.1 times higher than the cost of travelling a mile in a conventional vehicle. The cost of hydrogen in the high demand scenario is somewhat better, at $9.13/kg or $0.152/mile, but the low cost case provides the most competitive selling price of $6.75/kg or $0.112/mile. However, this is still 1.93 times greater than the cost of travelling in a conventional internal combustion-powered vehicle.

Table 4 – Comparison Of Calculated Costs With Conventional Vehicles

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cost ($/kg)</th>
<th>Cost ($/mile)</th>
<th>Increase Over Conventional (Factor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>N/A</td>
<td>0.058</td>
<td>-</td>
</tr>
<tr>
<td>Base Case</td>
<td>10.83</td>
<td>0.180</td>
<td>3.10</td>
</tr>
<tr>
<td>High Demand</td>
<td>9.13</td>
<td>0.152</td>
<td>2.62</td>
</tr>
<tr>
<td>Low Cost</td>
<td>6.75</td>
<td>0.112</td>
<td>1.93</td>
</tr>
</tbody>
</table>

\(^1\) All price and cost values presented in this document are in US dollars. Any costs that were quoted in Canadian dollars were converted to US dollars using an exchange rate of $1.00 CAD = $0.75 USD.
The selling price of hydrogen is calculated using a 10-year discounted cash flow analysis based on a ten year analysis (see Appendix E for cash flow statements). A large portion of the price of hydrogen in the base case and high demand scenarios is due to the cost of purchasing hydrogen. As would be expected, the cost of fuel in the low cost scenario is much less.

**Price Breakdown by Scenario**

![Price Breakdown by Scenario](image)

Figure 8 – The costs for each scenario are broken down into their components in the bar graph above.

Some important points should be reiterated; other business opportunities, such as incorporating a convenience store or car wash were not considered in the economic analysis. Clearly, these important aspects of gasoline stations improve their profitability and would similarly add to the desirability of the business plan. In addition, other potential markets were not explored in detail. For instance, hydrogen could be sold to some of the numerous small-scale fuel cell companies based in Vancouver. Many of these companies currently have LH$_2$ trucked in. These business opportunities were purposefully left out of the analysis in order to better focus in on the actual, unsubsidised selling price of hydrogen to fuel cell vehicles.
3.2 Cost Estimates

This section provides some detail on the cost estimates that were used in the economic analysis.

3.2.1 Capital Costs

The capital cost of the fuel station equipment is summarised in Table 5. The cost of the capital equipment reflects the purchase price, Canadian sales tax (14.5%), and assumed transportation costs (1% of capital costs). Since the purchase prices of capital equipment were quoted in 2004, they were inflated by 2% to reflect the fact the capital equipment will not be purchased until 2005. Throughout the analysis, an inflation rate of 2% per year was used. This is consistent with Canada’s ten year inflation rate average calculated from 1993 to 2003 and the Bank of Canada’s announced inflation rate target policy [1].

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Cost, Including Taxes &amp; Shipping ($K)</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenic LH2 pump</td>
<td>62.0</td>
<td>Cyro Canada (ACD)</td>
</tr>
<tr>
<td>Vaporizer</td>
<td>10.3</td>
<td>Cryogenic Experts</td>
</tr>
<tr>
<td>Buffer tanks (2)</td>
<td>35.3</td>
<td>CP Industries</td>
</tr>
<tr>
<td>Dispenser</td>
<td>58.3</td>
<td>Kraus Global</td>
</tr>
<tr>
<td>Vacuum jacketed piping &amp; connectors</td>
<td>8.0</td>
<td>Acme Cryogenics</td>
</tr>
<tr>
<td>Leak detection sensors</td>
<td>2.3</td>
<td>Estimate</td>
</tr>
<tr>
<td>Heat &amp; smoke detectors</td>
<td>2.3</td>
<td>Estimate</td>
</tr>
<tr>
<td>Controller</td>
<td>34.7</td>
<td>Estimate</td>
</tr>
<tr>
<td>Valves</td>
<td>8.7</td>
<td>Estimate</td>
</tr>
</tbody>
</table>

The cost of the LH2 storage Dewar is considered under operating costs since it is leased from Air Products as part of the hydrogen supply contract. Other capital costs include the cost of the Canadian registration for the vaporizer and the cost of station construction. This was assumed to be $31.30 per square foot based on Invest British Columbia’s estimated cost of the construction of a light manufacturing building in Vancouver [2].

3.2.2 Operating Costs

The operating costs that were considered include the cost of purchasing hydrogen (cost of goods sold), the rental of the LH2 storage tank, repairs and maintenance, electricity, advertising, labour, insurance, and space rental.

The cost of LH2 in the base case and high demand scenario, as quoted by Air Products, is $5.89/kg plus an additional $1.03/kg natural gas surcharge. Therefore, the total cost is $6.92/kg.

---

1 [Technical Design, 3-8]

2 This inflation rate is lower than the US 10 year inflation rate average of 2.7%.
The future price of LH$_2$ and the natural gas surcharge were assumed to increase by 2% each year. The cost of liquid hydrogen in the low cost scenario is $3.00/kg. This was estimated by assuming that the ERCO sodium chlorate plant would want to price hydrogen 50% higher than it would cost to produce. The production costs were estimated to be $2.00/kg, based on work completed by Syed et al. regarding the cost of hydrogen liquefaction systems [3]. The future price of hydrogen in this scenario was also assumed to increase by 2% each year. In all three scenarios, the amount of boil-off in the storage Dewar would be sufficiently low, given the rate at which hydrogen would be used, that it can be assumed that the quantity of hydrogen purchased would be equal to the quantity sold.

In addition to supplying hydrogen in the base case and high demand scenarios, Air Products will provide a 10,000 gallon LH$_2$ storage tank and all necessary ancillary equipment to ensure proper operation at a monthly service charge of $1,756 per month. The future price of the tank rental was estimated to increase with the assumed rate of inflation. It was also assumed that Air Products would provide the LH$_2$ tank in the low cost scenario but would charge double the rent since the hydrogen fuel would not be purchased from them.

The expected repairs and maintenance required each year are servicing of the dispenser and pump and regular inspections to ensure the station is in good working order. The cost of yearly maintenance is assumed to be 3% of capital equipment, increasing each year by the rate of inflation.

The electricity costs in the base case and low cost scenario, and the high demand scenario were estimated to be $5,700 and $8,300 per year, respectively. These values were calculated using the estimated energy requirements of the fueling stations and the price of BC Hydro electricity. The peak power demand was assumed to be 1.5 times the nominal amounts for transients, or 75 kW (see Table 2).

The monthly energy requirements were estimated to be 7,192 kWh per month in the base case and low cost scenario and 11,954 kWh per month in the high demand scenario. These values are based on the assumptions that the pump will be in operation 3 hours per day in the base case and 6 hours per day in the high demand scenario. It was also assumed that the dispenser will be used by either 50 or 100 cars per day depending on the scenario and each car will use 0.1 hours of dispenser time. The controller, safety systems, exterior and interior lighting, and interior services will be required 24 hours per day and are the same for both scenarios. These assumptions are also summarised in Table 2.

Since the fueling station will require more than 35 kW of energy to operate, it is classified as a medium power commercial consumer by BC hydro. The price of electricity is made up of three components; a basic charge, a demand charge and an energy charge. The basic charge is $3.11 per month while the demand charge is based on the peak demand required during the month. The first 35 kW of demand are not charged, however, the next 115 kW are charged $2.49/kW and any additional demand is charged $4.78/kW. The energy charge is based on the total monthly electricity consumption. The price of the first 14,400 kWh is 4.89 cents and the price of all additional kWh is 2.34 cents [4]. Once again, these prices were assumed to rise with inflation.
The yearly cost of advertising was estimated to be $6,000. The marketing plan is described in detail in the marketing and education analysis section.

Yearly labour, rent, and insurance values were estimated using Statistics Canada 1997 small business profiles for gasoline service stations in British Columbia [5]. This is a good estimate since the proposed design is safe and consumer friendly. This means that the station will not require any additional labour or insurance than a traditional gas station. The number of employees required was estimated to be 3.1 and the cost of this labour in 2006 will be $46,500. The estimated cost of insurance is $3,900 and the estimated cost of rent is $12,800. The costs were assumed to increase with inflation. The costs of labour, rent and insurance were assumed to be identical for the three scenarios.

A miscellaneous operating expense was included to take into account the various unconsidered expenses that would be incurred in the operation of the station and incidental costs that were not foreseen. This was assumed to be 2% of all other operating expenses. Income tax was charged at the estimated rate of 25.5%. The provincial corporate income tax rate is 13.5% and the federal corporate income tax rate for small businesses is 12% [6,7]. Depreciation was applied to capital equipment over 10 years at a rate of 20% using the declining balance method.
4 ENVIRONMENTAL ANALYSIS

In this section, the hydrogen delivery pathways described thus far are compared to a traditional gasoline fueling pathway in terms of carbon dioxide output and energy use. It should be noted that the analysis for the hydrogen produced at the ERCO plant in Vancouver is broken down into two scenarios. In the first, the hydrogen is considered to have no marginal cost to the company in terms of basic production electrical input. This is assumed since the hydrogen is currently vented to atmosphere. In the second scenario, it was assumed that 10% of the process electrical input was allocated for hydrogen production. The well-to-wheel analysis is performed using a spreadsheet program known as GREET [1].

4.1 Analysis Methodology

The request for proposal calls for an analysis showing both carbon dioxide emissions and energy associated with each stage of the fueling pathway. Each pathway is made up of a number of different steps associated with the production, delivery, storage, dispensing and use of the hydrogen fuel. Each of these processes has a number of operational variables associated with energy use and carbon dioxide production. Each functional block can be treated as a transfer function making use of certain inputs and creating certain outputs.

**Hydrogen**

![Hydrogen Diagram]

**Gasoline**

![Gasoline Diagram]

**Figure 9 – Fuel Pathways for Hydrogen and Gasoline Fuels**

The fueling pathways for liquid hydrogen and gasoline are shown in Figure 9. The pathway for hydrogen production is similar both for hydrogen produced using Steam Methane Reforming (SMR) and as a by-product of sodium chlorate electrolysis. The two pathways differ in that the SMR process relies on natural gas as the primary energy source and chemical feedstock while the chlorate process makes use of electrical power for both hydrogen production and liquefaction.
In order to accurately determine the energy usage and carbon dioxide emissions at each step in
the fueling process, both the process variables and the properties of the input energy and
feedstock need to be determined. In addition, upstream energy input and carbon dioxide
emissions must be accounted for. All calculations were performed in SI units. Throughout the
analysis, energy input and carbon dioxide emissions were expressed as a proportion of fuel
energy content in MJ.

4.2 Development of Analysis

The Argonne National Laboratories GREET software package was used extensively in this
analysis. GREET is an Excel based software package used to model various transportation fuel
pathways, from feedstock to wheel. While GREET has the functionality to calculate most of the
key process values for energy use and carbon dioxide emissions, these values are abstracted in
the GREET graphical user interface. It was necessary to build an analytical framework using the
GREET Excel backbone as a basis to access intermediate process values needed for the analysis.

It was also necessary to define the input variables for the GREET model. The default input
variables for the GREET model were found to be generally acceptable. A description of
parametric assumptions used in the GREET model is available on the software website [1].
Appendix D contains an explanation of input variables used in this analysis. It is important to
note that GREET calculates conventional gasoline fuel pathways based on current conditions and
hydrogen based pathways on expected future conditions. It was necessary to set the future
variables to currently accepted values to ensure a fair comparison of the various pathways.

4.3 Independent Calculation of Key Values

Using GREET, the energy component and emissions of BC based electrical power were
calculated based on generation mix information from BC and Alberta utilities [2],[3]. For
electricity generation in BC, 1.22 MJ of energy is used for every MJ of electricity delivered.
This translates to an energy efficiency of 82.2%. There are also 17.6 g of carbon dioxide emitted
per MJ of electricity delivered. This small emission is largely due to BC’s heavy reliance on
hydroelectric power. In fact, approximately 90% of the electricity is generated in this manner
[2].

A few sections of the hydrogen pathways could not be calculated using GREET. All hydrogen
pathways examined employed LH₂ compression at the station as a means of providing
compressed gaseous hydrogen in a more energy efficient manner than traditional gas
compression. Based on pump specifications [4], it was determined that the worst case electrical
requirement for the cryogenic pump would be 22,500 J/MJ of hydrogen. Accounting for the
energy efficiency and carbon dioxide output of the delivered electricity, this translates to
27,350 J/MJ of hydrogen, with CO₂ emissions of 0.395 g/MJ of hydrogen. This constitutes the
on-site portion of each of the hydrogen pathways.
Electricity is the key input for the hydrogen produced as a sodium chlorate by-product. Both scenarios make use of the liquefaction electrical energy requirement supplied by GREET, taking into account the energy and emission factors of electricity in British Columbia. For the scenario that assumes 10% of the process energy is allocated to production of hydrogen, the electrical requirement was found to be 0.313 MJ/MJ of hydrogen. This was based on industry norms of 5,000–6,000 kWh per metric ton of sodium chlorate produced, where 57 kg of hydrogen is produced for every ton of sodium chlorate produced [5]. This resulted in a total energy input of 0.380 MJ/MJ of hydrogen, with CO₂ emissions of 4.54 g/MJ of hydrogen.

4.4 Environmental Analysis Results

4.4.1 Well to Pump Analysis

The results of the well to pump analysis have been included to highlight the differences in inputs between the processes. These results can be seen in Table 6. While the fuel cell options end up better on a well to wheel analysis, it is interesting to note that the energy input is significantly higher at the front end of the process.

<table>
<thead>
<tr>
<th>Fuel Pathway</th>
<th>Feedstock</th>
<th>Fuel Production</th>
<th>Liquefaction</th>
<th>Transport</th>
<th>Storage</th>
<th>On site</th>
<th>Total</th>
<th>% of Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>2318</td>
<td>8432</td>
<td>-</td>
<td>263</td>
<td>-</td>
<td>-</td>
<td>11012</td>
<td>-</td>
</tr>
<tr>
<td>SMR</td>
<td>2971</td>
<td>56628</td>
<td>31222</td>
<td>6681</td>
<td>-</td>
<td>267</td>
<td>97769</td>
<td>888</td>
</tr>
<tr>
<td>ERCO - 10%</td>
<td>-</td>
<td>6177</td>
<td>4904</td>
<td>112</td>
<td>-</td>
<td>259</td>
<td>9114</td>
<td>83</td>
</tr>
<tr>
<td>ERCO - NMC</td>
<td>-</td>
<td>-</td>
<td>4904</td>
<td>112</td>
<td>-</td>
<td>259</td>
<td>5275</td>
<td>48</td>
</tr>
</tbody>
</table>

Table 6 – Well To Pump Analysis Results.

4.4.2 Well to Wheel Analysis

The well to wheel analysis was performed based on a mileage of 27.5 mpg for the conventional vehicle and 60 miles/kg for the fuel cell-powered vehicle, as specified in the request for proposal. The carbon dioxide output of the hydrogen powered vehicle is negligible while the gasoline vehicle will produce approximately 19.6 lbs (8.9 kg) of CO₂ per gallon of gas consumed [6]. This translates to an emission rate of approximately 323 g/mile (201 g/km). The results of this analysis are shown in Table 7.
### Table 7 – Well To Wheel Analysis Results

<table>
<thead>
<tr>
<th>Fuel Pathway</th>
<th>CO₂ Emissions (g/km)</th>
<th>Energy Input (MJ/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feedstock</td>
<td>Fuel Production</td>
</tr>
<tr>
<td>Gas</td>
<td>9.73</td>
<td>35.41</td>
</tr>
<tr>
<td>SMR</td>
<td>5.70</td>
<td>108.54</td>
</tr>
<tr>
<td>ERCO - 10%</td>
<td>-</td>
<td>7.36</td>
</tr>
<tr>
<td>ERCO – NMC</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 10 displays the carbon dioxide emissions for the various pathways. While the SMR option shows some reduction in carbon dioxide emission, the sodium chlorate options reduce carbon dioxide emissions quite significantly. This reduction is largely due to the low energy input necessary to create the hydrogen and because most of British Columbia’s electricity is generated at hydroelectric power stations.
Figure 11 shows the energy usage for the fuel pathways in question. It is interesting to note that while the gasoline pathway uses much less energy input during the well to pump portion, the reduced efficiency of the ICE engine leads to a higher overall energy use. The sodium-chlorate plant pathways benefit from the low input energy due to hydrogen being an industrial by-product. It should be noted that while the electrical requirement for liquefaction is the same in all cases, the total energy input is reduced in the ERCO scenarios due to the higher energy efficiency of the electricity available in BC.

![Energy Inputs for Various Fuel Pathways](image)

**Figure 11** – The energy input requirements of various fueling pathways.

### 4.4.3 Fleet Savings

The fleet savings results are based on a fleet of 50 cars with an average annual mileage of 12,500 miles (20,000 km) [7]. The results of this analysis can be seen in Table 8.

**Table 8** – Fleet Emissions Of Various Fueling Pathways

<table>
<thead>
<tr>
<th>Fuel Pathway</th>
<th>CO₂ Emissions (tons)</th>
<th>Savings (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>248.20</td>
<td>-</td>
</tr>
<tr>
<td>SMR</td>
<td>188.44</td>
<td>59.76</td>
</tr>
<tr>
<td>Sodium Chlorate - 10% energy</td>
<td>17.57</td>
<td>230.63</td>
</tr>
<tr>
<td>Sodium Chlorate - No energy</td>
<td>10.17</td>
<td>238.03</td>
</tr>
</tbody>
</table>

The steam methane reforming option offers modest CO₂ emissions savings, while the two sodium chlorate plant options offer large savings. This is due, in large part, to the fact that hydroelectric power makes up approximately 90% of the electrical mix in British Columbia [2].
5 MARKETING AND EDUCATION

A transition to a hydrogen economy requires the general acceptance of both business and the public. This section describes a marketing and educational plan to promote the fueling station and hydrogen in general.

5.1 The Target Market

Ultimately, the target market for the hydrogen refueling station will be the members of the general public who own hydrogen-fueled vehicles. However, as there are very few such vehicles currently in existence, the marketing will be targeted in two specific directions:

1. Public awareness campaign for the general public.
2. Marketing the refueling station as a source of hydrogen for Vancouver companies that currently require small amounts of hydrogen.

Each of these markets has different needs. The general public, for example, lacks awareness of hydrogen as a potential fuel, and harbours misconceptions about hydrogen safety [1]. Before viewing the public as potential customers, it will be necessary to develop an education program about the advantages of hydrogen as a fuel. This is the most important barrier to overcome if the hydrogen refueling station is to become profitable. On the other hand, the companies already using hydrogen do not need to be sold on the idea of its use; rather, they need to become aware of the existence of the hydrogen source in Vancouver and see the potential benefit of acquiring the hydrogen from the refueling station.

5.2 Marketing Environment Analysis - Opportunities and Threats

The marketing environment surrounding a potential hydrogen refueling station in Vancouver, BC is quite unique. Since the announcement of Vancouver’s winning bid for the 2010 Olympics, a $23 million proposal is being put together by BC Hydro and associates for the construction of a “hydrogen highway” extending from the U.S. border, through Vancouver, to Whistler [2]. BC Premier Gordon Campbell has also shown strong support for hydrogen and fuel cell ventures throughout BC, and US President George Bush has been encouraging the hydrogen economy in the United States. Coupled with the lack of competing hydrogen refueling stations in the Vancouver area, opportunities for both education of the public and growth of the hydrogen refueling business abound.

Many opportunities exist to aid in public education. A survey done by Natural Resources Canada (NRCan) showed that 30% of Canadians are concerned about the environmental impact of energy production and consumption, and a growing number of Canadians are becoming concerned about the available supply of energy resources [3]. The fact that hydrogen can be obtained from a wide variety of sources using a variety of methods, and that hydrogen fuels produce little or no CO₂ will be key in the promotion of hydrogen.

www.h2fuelstation.com
However, a few factors also threaten the viability of a hydrogen refueling station venture. Currently, Vancouver has no commercial hydrogen production facilities, little hydrogen infrastructure, and very few hydrogen cars. Oil and gas companies have a strong competitive advantage in the small vehicle fueling industry. There is also a lack of cohesive standards which could apply in the design of a hydrogen refueling station.

5.3 Design Strengths and Weaknesses

The most important strength of this hydrogen refueling station is its flexibility from many standpoints – possible methods of production, possible sources, and methods of delivery. Another advantage of the proposed station design is its environmental benefit. The large-scale production of hydrogen off-site has an efficiency advantage over small-scale onsite hydrogen production. Along with the flexibility and environmental benefit, this station has also been designed to be aesthetically appealing to the general public. While previous hydrogen refueling stations have tended to look very industrial, this station has been designed to be pleasing to the eye and as approachable as a conventional gasoline refueling station.

A weakness of the proposed design is that both the reforming process and the trucking of the hydrogen will be sources of CO₂ emissions which will offset the benefits of hydrogen fueled vehicles. Another weakness is that the hydrogen station will be located in Vancouver, where there is little to no hydrogen infrastructure and no hydrogen corridor.

5.4 Marketing Objectives

Given the marketing environment surrounding this venture, the main objective of the marketing for this hydrogen refueling station will be the education of the public, both to reduce the uneasiness associated with hydrogen use, and to improve public awareness of the benefits of hydrogen and associated technologies.

5.5 Marketing and Education Strategies and Evaluation

The marketing mix targeted to the general public will consist of both awareness campaigns and educational tools. The awareness campaign will include:

- Newspaper ad in the Vancouver Sun ($3,106.80 for 1/8 page [4])
- Transit/SkyTrain banners (27 Interior cards for $1,000 [5])
- Coverage by the local media

Once the public is interested in knowing more about hydrogen technologies, educational tools will include:

- One or more open houses at the refueling station location
- An informative website
- Brochures detailing the benefits of hydrogen technology ($2,600 for 5,000 brochures).

At defined intervals throughout the implementation of the marketing strategy, evaluations such as polls and audits may be performed to assess the effectiveness of the public awareness and educational campaigns. Modifications may then be made in order to improve the success of the overall marketing and education strategy.
5.6 Hydrogen Refueling Station Advertisement

“I think there is a world market for maybe five computers.”
- Thomas Watson Sr., 1943

“Heavier-than-air flying machines are impossible.”
- Lord Kelvin, 1895

“Everything that can be invented has been invented.”
- Charles H. Duell, 1899

“This ‘telephone’ has too many shortcomings to be seriously considered as a means of communication. The device is inherently of no use to us.”
- Western Union internal memo, 1876

... Care to tell us hydrogen isn’t better than gasoline?

Worried about the harmful emissions that cars and trucks produce every day? Think hydrogen as a fuel is far off in the future?

Welcome to the future. Hydrogen is ready, right here in Vancouver. Even if your car does not run on hydrogen, we are more than happy to provide information and answer your questions about hydrogen - in plain English.

We’re ready when you are!

1234 Pretend St., Vancouver | (604) 555-5678 | www.h2fuelstation.com
APPENDICES

Appendix A – Additional Station Drawings

Figure 12 – In the rear view of the proposed station shown above, the LH$_2$ Dewar are vaporizer are visible in the elevated storage area. The LH$_2$ refueling tanker is also clearly visible.

Figure 13 – The split roof concept of the elevated storage area can be seen in the side view of the proposed station. This design allows for leaked hydrogen to readily escape.
Appendix B – Technical Design Calculations

Filling Process Temperature Increase Calculations

Automobile compressed hydrogen storage tanks are generally made of composite materials that can be adversely affected if their temperature goes above about 80 °C. Since work is done on hydrogen as it is pumped into the tank, its temperature will increase. This also necessitates a procedure termed “over-filling” since the hydrogen pressure inside the tank will decrease as it comes into equilibrium with the surrounding environment. Cylinders typically used for automobile hydrogen storage allow a maximum fill rate of only 8 g/s. Calculations were performed to determine the effect of pumping lower-temperature hydrogen into car tanks. The fill rates are very sensitive to the cylinder mass, specific heat and thermal diffusivity. The figures below show the results of the analysis. It was assumed that:

- The cylinders are thermally insulated.
- The car cylinder has a mass of 90 kg that is equally distributed.
- The car cylinder is composed of aluminum liner with carbon fiber reinforcement.
- The cylinder temperatures rise at the same rate as the gas temperature.

Figure 14 – The results of the filling process temperature increase calculations for the buffer storage tank show that a temperature increase of less than 10 °C would be seen after almost 10 minutes at a fill rate of 12.5 g/s with a -20 °C H2 flow.

Figure 15 – Calculations for the buffer storage system show that a car tank filled with a 20 °C H2 stream at 8 g/s (a 375s or 6m15s fill time) would warm to about 333K (60 °C) while a tank filled with a -20 °C H2 stream at 12.5 g/s (a 240s or 4m fill time) would only warm up to about 313 (40 °C).
Buffer Storage Tank Dynamic Pressure Calculations
(Using Redlich/Kwong)

<table>
<thead>
<tr>
<th>Density, ( \rho ) (kg/m(^3))</th>
<th>Spec. Volume, ( v ) (m(^3)/mol)</th>
<th>Pressure, ( P ) (MPaa)</th>
<th>Cars Refueled</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.98</td>
<td>4.92E-05</td>
<td>65.58</td>
<td>9500</td>
</tr>
<tr>
<td>38.29</td>
<td>5.27E-05</td>
<td>58.98</td>
<td>8543</td>
</tr>
<tr>
<td>35.59</td>
<td>5.66E-05</td>
<td>52.87</td>
<td>7656</td>
</tr>
<tr>
<td>32.90</td>
<td>6.13E-05</td>
<td>57.20</td>
<td>6833</td>
</tr>
<tr>
<td>30.21</td>
<td>6.67E-05</td>
<td>61.91</td>
<td>6066</td>
</tr>
<tr>
<td>27.51</td>
<td>7.33E-05</td>
<td>65.98</td>
<td>5350</td>
</tr>
</tbody>
</table>

Figure 16 – The amount of buffer storage necessary per car to be fueled can be determined using the above spreadsheet. Note that hydrogen properties such as temperature and pressure can be varied.

Compression @ 298K (25\(^\circ\)C), 1atm to 10000psig (680atm)

Ideal Work, \( W_i \) = 8550 kJ/kg H\(_2\)
Comp. Efficiency, \( \varepsilon_c \) = 75 %

Energy Required, \( E_1 \) = 11400 kJ/kg H\(_2\)

LH2 Compression @ 20K, 6 atm to 10000psig (680atm)

LH2 Density, \( \rho_{LH2} \) = 70.8 kg/m\(^3\)
Power Requirement, \( P \) = 44 kW
Flow Rate, \( m \) = 3 gpm
\( = 0.81 \) kg H\(_2\)/min
\( = 1.24 \) min/kg H\(_2\)

Energy Required, \( E_2 \) = 3271 kJ/kg H\(_2\)

Relative Energy Use = 28.7 %
% Improvement = 71.3 %

Figure 17 – The available process efficiency advantage as a result of utilizing a liquid cryopump instead of a gas compressor (to compress a liquid instead of a gas) is shown in this set of calculations.
Appendix C – Station Safety and Nominal Control Algorithm

Normal Operation (no safety is triggered):
- Flow valves A, D, F, G, H and I are normally closed
- Flow valves B, C and E are normally open

Pump Operation:
- If pressure transmitter A reads less than 5,350 psig
  - Power controller A activates the cryopump
- If pressure transmitter A reads more than or equal to 9,700 psig
  - Power controller A deactivates the cryopump

Hydrogen Gas Leak or Combustion Detection:
- If hydrogen gas sensor A detects hydrogen gas, combustion sensor A detects smoke, or temperature sensor A reads too high a temperature:
  - Programmable logic controller closes flow valves B and C
  - Programmable logic controller opens flow valves A and F
  - Results in back end system purge
  - Programmable logic controller closes flow valve F

Figure 18 – The above schematic shows the process control system for nominal station operation. All vent lines couple to a manifold leading to the stack vent (not shown).
• If hydrogen gas sensor B detects hydrogen gas, combustion sensor B detects smoke, or temperature sensor B reads too high a temperature:
  o Programmable logic controller closes flow valves B, C and E
  o Programmable logic controller opens flow valves D and G
  o Results in front end system purge
  o Programmable logic controller closes flow valve G

Buffer Storage Purge:
• If the buffer storage is to be purged for safety or maintenance reasons:
  o Programmable logic controller closes flow valves B, D, E and I
  o Programmable logic controller opens flow valves C, G and H

Excessive Pressure before Vaporizer:
• If pressure transmitter B reads a pressure above the vaporizer’s rated pressure:
  o Programmable logic controller opens flow valve A until pressure transmitter B reads below rated pressure

Excessive Pressure before Dispenser:
• If pressure transmitter D reads a pressure above the dispenser’s rated pressure:
  o Programmable logic controller opens flow valve D until pressure transmitter D reads below rated pressure

---

Figure 19 – The safety control system is depicted in the above schematic.
Excessive Buffer Storage Pressure:
- If pressure transmitters D or E read a pressure above the buffer storage rated pressure
  - Programmable logic controller opens flow valves H and I until both pressure transmitters D and E read below rated pressure

Power Failure:
- If power is lost to the control system
  - Flow valves A, D, E and H will default open
  - Flow valves B, C, E, F and G will default closed

Relief Valves:
- All relief valves should be set to break at 110% of the rated pressure at the valve location

Burst Discs:
- All burst discs should be set to rupture at 120% of the rated pressure at the disk location
## Appendix D – Well-to-Wheel Analysis, GREET Input Variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Value</th>
<th>Units</th>
<th>Ref.</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Petroleum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂ by weight</td>
<td>0.4</td>
<td>%</td>
<td>[1]</td>
<td></td>
</tr>
<tr>
<td>Sulphur Level</td>
<td>150</td>
<td>ppm</td>
<td>[2],[3]</td>
<td></td>
</tr>
<tr>
<td>Oxygenate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation Generation Mix</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>0.1</td>
<td>%</td>
<td>[2],[3]</td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>5.7</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>2.4</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.0</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>91.8</td>
<td>%</td>
<td></td>
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</tr>
<tr>
<td>Stationary Generation Mix</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>0.0</td>
<td>%</td>
<td>[1]</td>
<td></td>
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<tr>
<td>Natural Gas</td>
<td>32.9</td>
<td>%</td>
<td></td>
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<tr>
<td>Coal</td>
<td>21.3</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>14.7</td>
<td>%</td>
<td></td>
<td></td>
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<tr>
<td>Others</td>
<td>31.1</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Advanced Natural Gas Combined Cycle Turbine Efficiency¹</strong></td>
<td>20.0</td>
<td>%</td>
<td></td>
<td>Near-term values</td>
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<td><strong>Advanced Coal Cycle Turbine Efficiency¹</strong></td>
<td>5.0</td>
<td>%</td>
<td></td>
<td></td>
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<td><strong>Liquid Hydrogen Pathway Options:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>H₂ Production Location</td>
<td>Central Plant</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed Stock</td>
<td>North American Natural Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ Sequestration in Central Plant</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Natural Gas Based Plant Design</td>
<td>Without Stream Export</td>
<td></td>
<td></td>
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<tr>
<td><strong>Parametric 1</strong></td>
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<td></td>
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</tr>
<tr>
<td><strong>Petroleum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crude Oil Recovery Efficiency</td>
<td>97.7</td>
<td>%</td>
<td>[1]</td>
<td></td>
</tr>
<tr>
<td>Conventional Gasoline refining Efficiency</td>
<td>85.5</td>
<td>%</td>
<td></td>
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<tr>
<td><strong>Electricity</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual Oil Utility Boiler Efficiency (current)</td>
<td>35.0</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual Oil Utility Boiler Efficiency (future)</td>
<td>35.0</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas Utility Boiler Efficiency (current)</td>
<td>34.0</td>
<td>%</td>
<td></td>
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</tr>
<tr>
<td>Natural Gas Utility Boiler Efficiency (future)</td>
<td>35.0</td>
<td>%</td>
<td></td>
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<tr>
<td>Natural Gas Simple Turbine Efficiency (current)</td>
<td>34.0</td>
<td>%</td>
<td>[1]</td>
<td></td>
</tr>
<tr>
<td>Natural Gas Simple Turbine Efficiency (future)</td>
<td>35.0</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas Combine Cycle Efficiency (current)</td>
<td>35.0</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas Combine Cycle Efficiency (future)</td>
<td>55.0</td>
<td>%</td>
<td></td>
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<tr>
<td>Advanced Coal Technology for Power Generation</td>
<td>41.5</td>
<td>%</td>
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<tr>
<td>Electrical Transmission and Distribution Losses</td>
<td>5.0</td>
<td>%</td>
<td></td>
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<tr>
<td><strong>Hydrogen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Central Plant Efficiency (no stream export)</td>
<td>71.5</td>
<td>%</td>
<td>[5]</td>
<td></td>
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<tr>
<td>Liquefaction Efficiency (Central Plant)</td>
<td>71.0</td>
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<td>Parametric 2</td>
<td>Value</td>
<td>Units</td>
<td>Ref.</td>
<td>Notes</td>
</tr>
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<td>-------------------------------------------------</td>
<td>-------</td>
<td>-------</td>
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<td><strong>Transport Modes (Gasoline Baseline)</strong></td>
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<tr>
<td>Tanker</td>
<td>10.0</td>
<td>%</td>
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<td>[1],[5]</td>
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<tr>
<td>Avg. tanker distance</td>
<td>1,700</td>
<td>miles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barge</td>
<td>4.0</td>
<td>%</td>
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<td></td>
</tr>
<tr>
<td>Avg. Barge distance</td>
<td>520</td>
<td>miles</td>
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<tr>
<td>Pipeline</td>
<td>73.0</td>
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<tr>
<td>Avg. Pipeline distance</td>
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<td>miles</td>
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<tr>
<td>Rail</td>
<td>7.0</td>
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<td></td>
</tr>
<tr>
<td>Avg. Rail distance</td>
<td>800</td>
<td>miles</td>
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<tr>
<td><strong>Ocean Tanker size</strong></td>
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<tr>
<td>Conventional Gasoline</td>
<td>1,143,000</td>
<td>tons</td>
<td>[1]</td>
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<td>Crude oil</td>
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<td><strong>External Input Values</strong></td>
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<tr>
<td>Travel to Refineries</td>
<td>16,700</td>
<td>km</td>
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<tr>
<td>Travel for LH$_2$ from Sacramento to Vancouver$^2$</td>
<td>892.16</td>
<td>miles</td>
<td>[1]</td>
<td>$^2$ 100% of LH$_2$ transported by trucks</td>
</tr>
<tr>
<td>Travel in Vancouver case (ERCO plant)$^2$</td>
<td>15</td>
<td>km</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BC Hydro Generation Mix</strong></td>
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<tr>
<td>Residual Oil</td>
<td>0.10</td>
<td>%</td>
<td>[2],[3]</td>
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<td>Natural Gas</td>
<td>5.66</td>
<td>%</td>
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<tr>
<td>Coal</td>
<td>2.44</td>
<td>%</td>
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<td></td>
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<tr>
<td>Nuclear Power</td>
<td>0.00</td>
<td>%</td>
<td></td>
<td></td>
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Appendix E – Discounted Cash Flow Analysis

$(K, USD)

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<th>Low Cost Scenario</th>
<th>Operating Expenses</th>
<th>Capital Investment</th>
<th>Income Before Taxes</th>
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<th>Low Cost Scenario</th>
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<th>Cash Flows</th>
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Operating Expenses:
- LH₂ Tank Rental
- Repairs & Maintenance
- Electricity
- Wages, Salaries, Benefits
- Insurance
- Space Rental
- Marketing & Advertising
- Miscellaneous Expenses
- Controller
- Valves
- Construction & Installation
- Vaporizer Canadian Registration
- Total Investment in Depreciating Equity
- Total Capital Investment

Capital Investment:
- Cryogenic LH₂ Pump
- Vaporizer
- Buffer Tanks (2)
- Dispenser
- Vacuum Jacketed Piping & Connectors
- Leak Detection Sensors
- Heat & Smoke Detectors
REFERENCES

Technical Design:


Safety Analysis:


Economic Analysis:


Environmental Analysis (including Appendix D):

Marketing and Education:

Process Control: