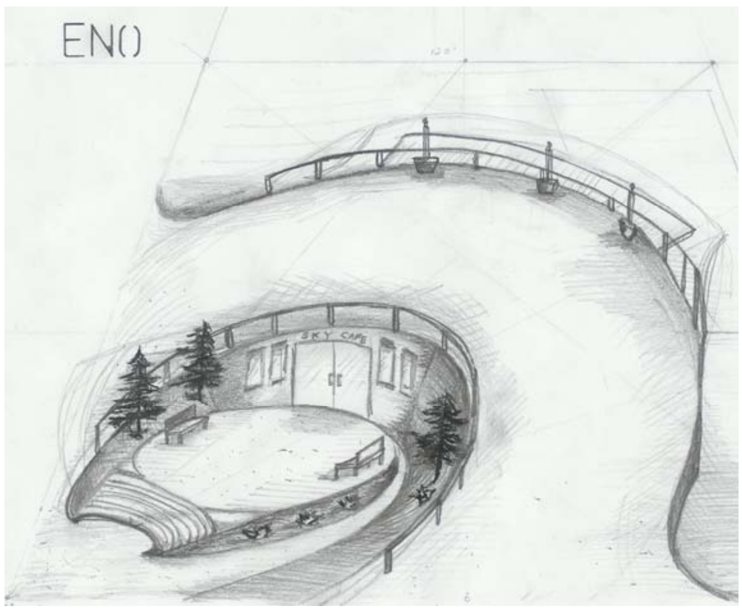
…We're taking hydrogen to a whole new level.

Bid in response to the DOE/NHA proposal[1] to
Design a Public Hydrogen Fueling Station
Location: *Los Angeles, California*.



Submitted by **team eno**:
Christian Adame, *Artistic Director*
Matt Caldwell, *Environmental Analyst*
Jordan Crosby, *Marketing, Chief Editor*
Paul Glanville, *Safety and Environmental Lead*
Maria Gonzalez, *Electrical and Energy Analyst*
Rusty Heffner, *Marketing Director*
Kristin Heinen, *Design/Marketing*
Ryan McCarthy, *Technical Director*
Jonathan Weinert, *Economic Lead, Team Captain*
University of California, Davis

March 3rd, 2004

[1] First Annual University Student Hydrogen Design Contest Hydrogen Fueling Station Presented by the National Hydrogen Association, U.S. Department of Energy & Chevron Texaco.

TABLE OF CONTENTS

Executive Summary

The Eno Corporation, in response to the RFP issued jointly by the DOE and NHA, is pleased to present a unique answer to the challenge of providing safe, clean, and affordable hydrogen fuel to vehicles in an urban environment. Our solution is the Eno Fueling Center (EFC) planned for location in downtown Los Angeles, California.

Station Design

The EFC is a three-level station designed to maximize the safety and asthetics of the fueling experience. Above street level, vehicles refuel on a sloping ramp where dispensers are located. In the refueling area, Eno staff are available to assist motorists with refueling and to educate users about the station. Below street level, the station provides a basement café and excavated outdoor seating area. The café includes a learning center where Eno customers and members of the general public can learn more about the benefits of hydrogen and fuel cell vehicles. Hydrogen production equipment is housed at street level behind the station; parking for café customers is also available on this level. The station's sloping design makes the street-level area less visible to the station's customers as well as pedestrians and motorists who pass the station. In addition, the design physically isolates and protects customers from the hydrogen storage area while they are refueling or visiting the café.

Both the architectural and technical aspects of the EFC are designed to be reproducible. The station uses an on-site steam methane reformer to convert natural gas into hydrogen. The reformed hydrogen is compressed and sent to a three-bank, dual-pressure cascade storage system that connects to the station's dispensers via underground lines. This simple design is suitable for any location where natural gas is available. The EFC is based on the Eno Sizing Model. Based on seven key variables, this model can be customized to accommodate changes in available land area, number of customers, or rentable square footage. The result is a station design that can easily be expanded or scaled down, allowing it to be used in additional locations as the demand for hydrogen refueling increases nationwide.

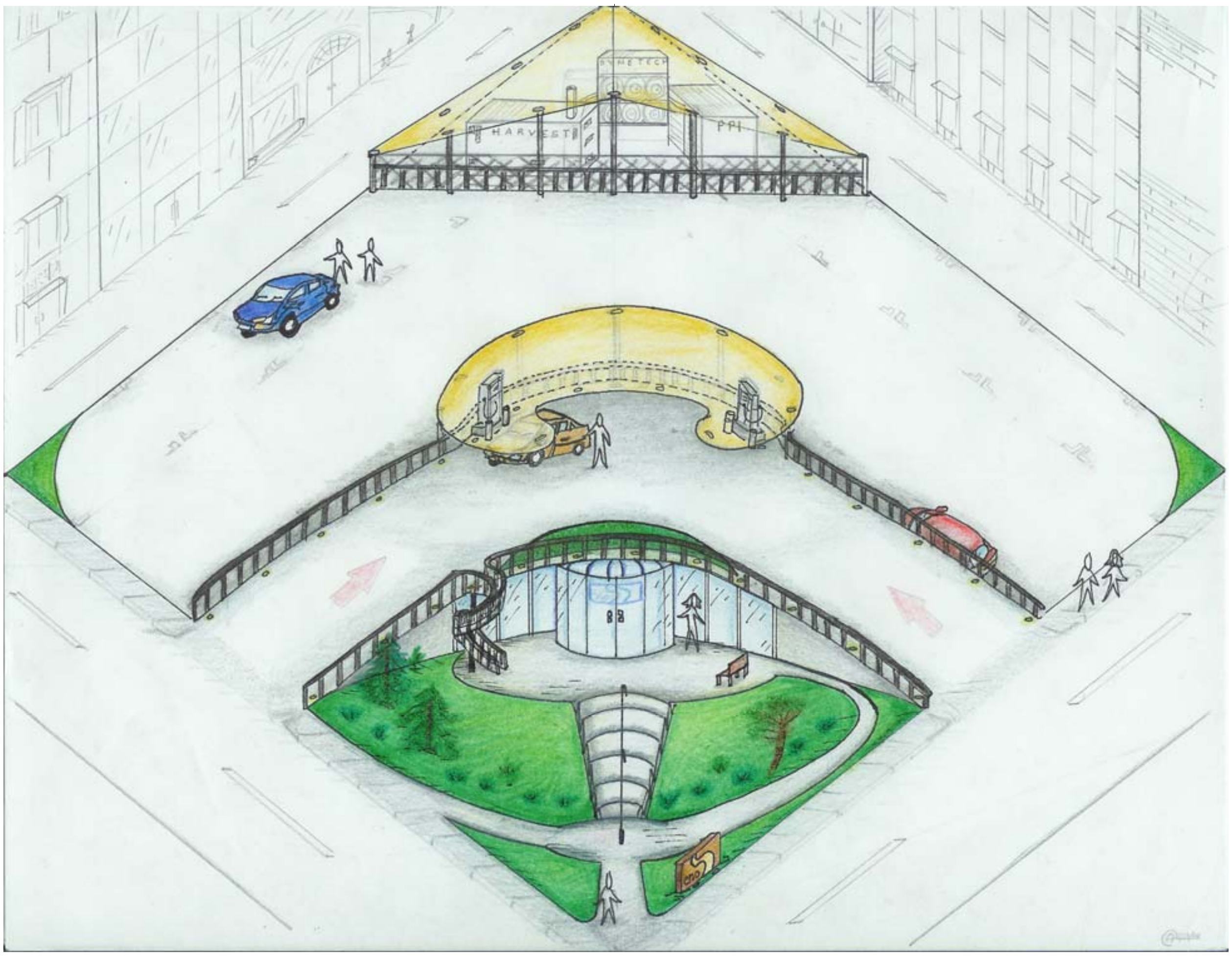
Financial Returns

The EFC's financial returns are derived from multiple income sources. Hydrogen sales generate the majority of the station's revenues: 55,000 kg of hydrogen are sold each year at $14.23/kg. To supplement this income, the station includes retail space that will be leased to a third-party coffeehouse or café provider, such as Starbucks or Caribou Coffee. Revenue from the leased space will offset some of the construction costs, and will provide relief from operating expenses, particularly in early years when the number of fuel cell vehicles is limited. Total costs of station startup are $1.97 million. Including rental income, the station generates a 12% annual return, resulting in a recovery of initial expenses within 10 years.

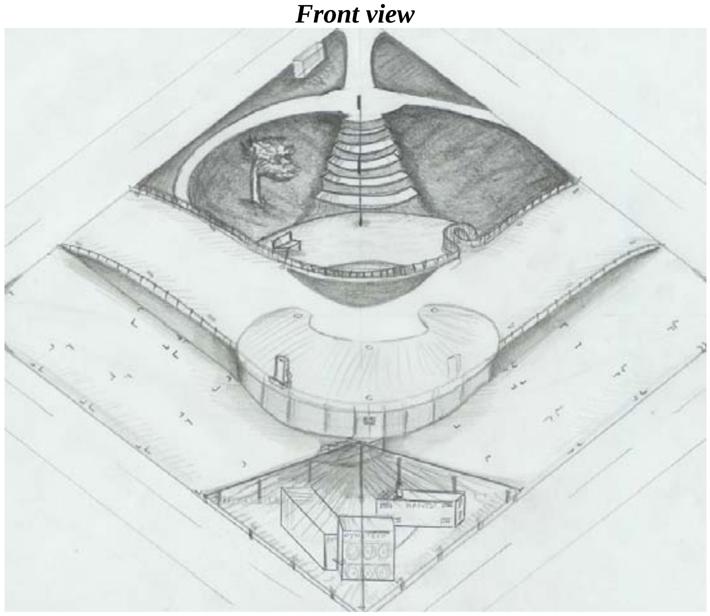
Environmental Benefits

The EFC will generate significant environmental benefits. Vehicles using the station's hydrogen create roughly 54% fewer greenhouse emissions on a well-to-wheels basis. Each year, fuel cell vehicles using the EFC will reduce carbon dioxide emissions by roughly 165,000 kg. In addition, these vehicles will emit no criteria pollutants into the already-strained Los Angeles air basin.

1. TECHNICAL DESIGN



Front view



Rear view

Design Rationale

Hydrogen is produced onsite from steam-methane reformation (SMR) of line-quality natural gas. We chose this pathway because it is currently the least expensive production process and the likely short-term option for widespread, mainstream introduction of hydrogen. Also, onsite SMR eliminates the need to transport hydrogen, which is expensive, energy-intensive, and logistically difficult at a 14,400 sq. ft station. This pathway decision is supported by a recent study completed by the National Research Council, which suggests that a hydrogen transition is "best accomplished initially through distributed (hydrogen) production at the fueling site."[1]

The unique design of the EFC incorporates three levels to maximize site utility and safety. The refueling area is elevated above a sub-grade café to maximize the use of the station plot. It allows more space to be dedicated to the café, landscaping, and parking. Positioning the refueling process at the highest elevation also maximizes safety. As hydrogen always rises, a leak would never pose a threat to people or equipment below.

Along with these benefits of the tri-level design, we have identified some potential problems. First, if a car runs out of fuel it would be difficult to ascend the inclined ramp. Running out of fuel presents a difficult problem for gaseous-fueled vehicles because the fuel is not easily transported or transferred to a vehicle. Consequently, in many cases, vehicles that run out of hydrogen might have to be towed. If the vehicle is hybridized, the battery or ultracapacitors might provide enough range to reach the station. Another issue with the design is the location of the dispensers. They are located along the back railing due to safety concerns associated with running hydrogen piping above the café. One issue with the location is the potential for logistical problems, as vehicles entering from one side may have to turn around if the fueling tank is on the other side. This is addressed by allowing ample room for vehicles to maneuver. The dispenser location also keeps a single dispenser from fueling two cars simultaneously. While this reality adds additional cost,[2] the redundancy also adds reliability.

The ENO Approach

ENO's technical design supplements academic theory with real-world industrial insights. The unique approach, known as "ENO's Dual Evaluation Linking Industry Views with Existing Research Solutions," (ENO DELIVERS) not only draws theory from the literature, but also relies on extensive interaction with industry contacts. At this early stage in the development of hydrogen-based transportation, little is often known outside of industry about the actual state-of-the-art. Thus, we draw from our strong base of industry contacts to accurately assess the design.

The EFC is designed to provide 150 kg of hydrogen per day, with a maximum peak demand of 20 kg/hr.[3] ENO assumed these requirements to be peak demands, calculated to account for seasonal and statistical variations. Thus, we did not include a capacity factor in the design, as one was assumed to have already been included in the demand requirements. Availability factors were included to account for necessary maintenance of the equipment, and are discussed in the component descriptions below.

[1] National Research Council, 2004, p. ES-9.
[2] This configuration costs roughly $20,000 more than a single dispenser with two hoses and simultaneous refueling capability (Quotation Reference #2004-592, Fueling Technologies, Inc., February 20, 2004).
[3] Our load profile actually had a peak hourly demand of 21 kg, the amount of hydrogen required for seven vehicles.

Site Plan

The site plan is shown in Figure 1.1. The hydrogen production, compression, and storage equipment is isolated in the rear corner of the station, from where hydrogen is piped underground across the parking lot and up the back wall of the café to the dispensers. The piping is rated to support vehicle fills to 10,000 psi, to accommodate automaker projections that 10,000 psi tanks will be common on vehicles in the 2007-2010 timeframe.[4]

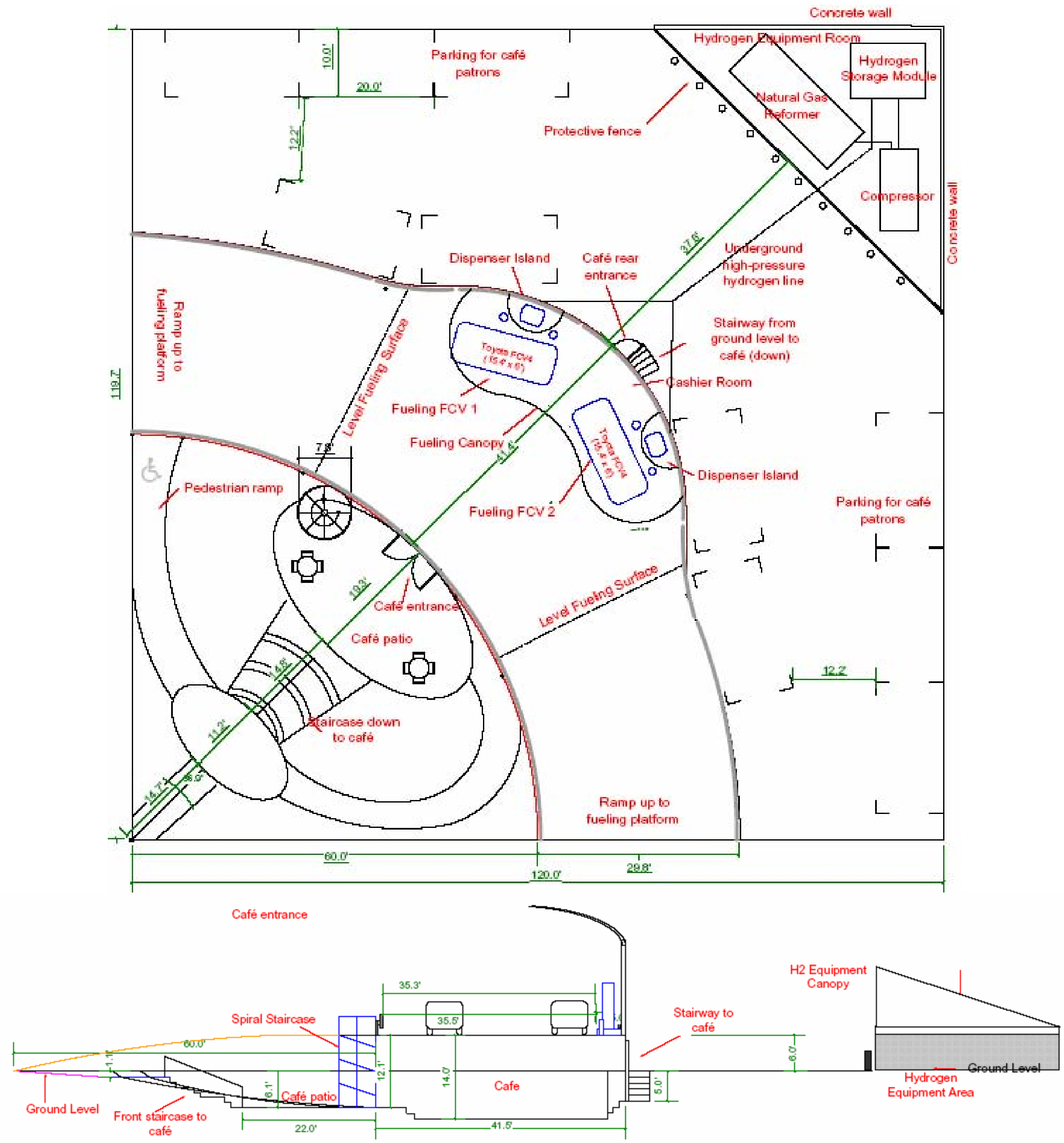


Figure 1.1 Site plan and diagonal cross section

[4] Jesse Schnieder, Daimler Chrysler, personal communication, February 23, 2004.

Process Schematic

Figure 1.2 shows a process schematic for the design pathway. Utility natural gas, electricity, and water enter the generation unit along with ambient air and are converted into hydrogen, water, and carbon dioxide. Hydrogen is then compressed and stored in one of three storage banks, before going to the dispenser. The priority-sequencing panel controls the flow into and out of the storage system.

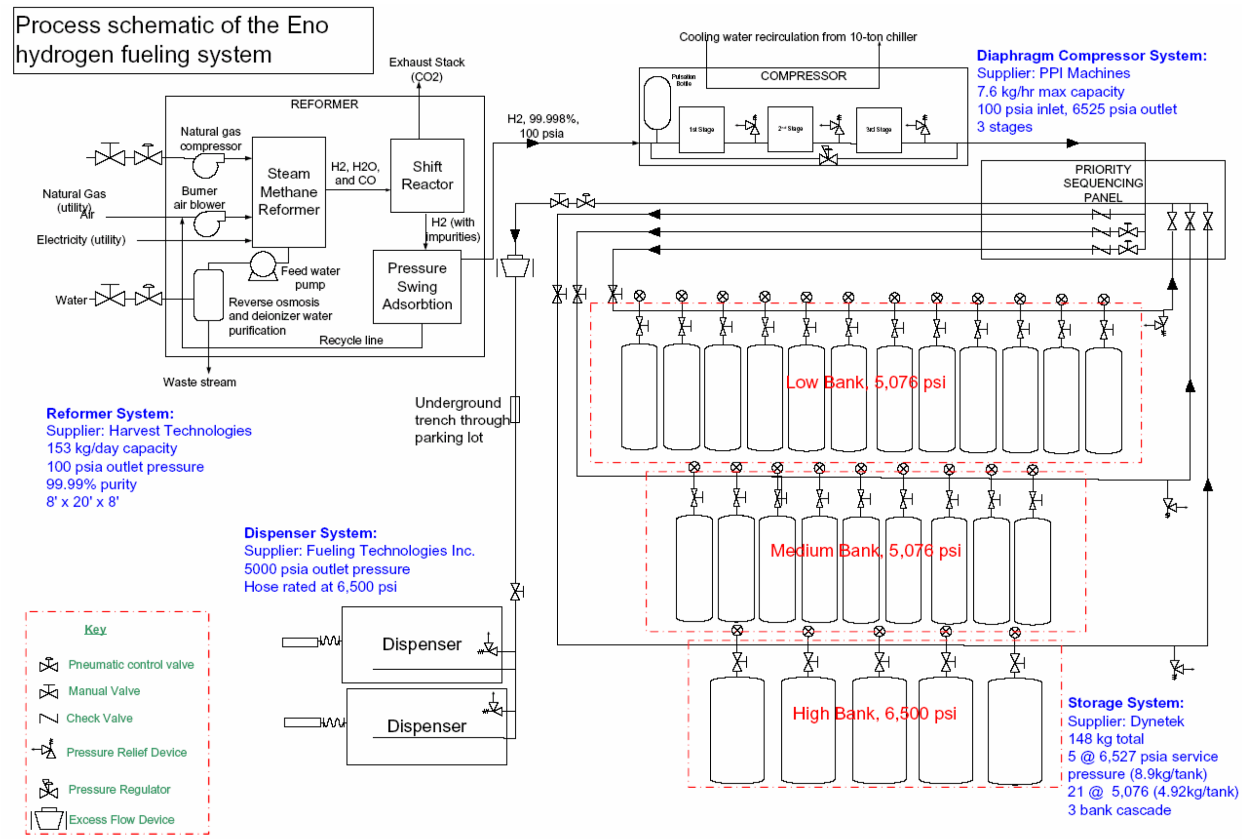


Figure 1.2 Process schematic.

Description of Major Components

Each of the major components of the hydrogen supply system is described below. Component designs followed the ENO DELIVERS strategy. For each component, we contacted multiple suppliers to obtain competitive bids and assure that the design in practice met with that determined from theory. The rationale for choosing particular products is discussed below. Specifications for products both selected and not are compiled in the Appendix.

Hydrogen Production

Harvest Energy Technology will supply an integrated production and purification system, which produces hydrogen from utility-line natural gas via SMR and purifies it up to 99.99% with a pressure swing adsorption (PSA) system.[5] We chose Harvest for their ability to meet our

[5] Reformers from H2Gen and HyRadix were also considered, but both offered products that were undersized for this application. H2Gen's HGM2000 has a capacity of 113 kg/day. HyRadix offers its Adeo™ unit in sizes of

required demand,[6] and their proximity to EFC. They are headquartered in Sun Valley, about 20 miles from EFC, and are easily accessible to provide maintenance and support.

The conversion from natural gas to hydrogen follows the reaction equations below:

Synthesis Gas Production:	$CH_4 + H_2O \rightarrow 3H_2 + CO$
Water-Gas Shift:	$CO + H_2O \rightarrow H_2 + CO_2$

We sized the reformer to provide 150 kg/day at constant load over the course of 24 hours. An availability factor of 0.98 (about seven days worth of downtime per year) was included to account for maintenance and downtime,[7] requiring the reformer to be sized to 153 kg/day, or 6.38 kg/hr. ENO considered over sizing the reformer and compressor to increase output during peak demands, but a study by Directed Technologies found that such a scheme did not result in meaningful cost savings.[8]

Compressor

The station uses a three-stage diaphragm compressor from Pressure Products Industries, Inc. (PPI).[9] A diaphragm compressor was chosen to minimize contamination, since fuel cells require 99.99% pure hydrogen.[10] Diaphragm compressors maintain purity by isolating the hydrogen from all hydraulic, lubricating, and cooling fluids. In addition to providing pure hydrogen, contamination-free operation extends the life of the compressor components, reducing maintenance costs and increasing reliability.

The primary maintenance concern with diaphragm compressors is the life of the diaphragm. Diaphragms tend to have a service life of 2000 – 8000 hours, depending on the purity gas from the reformer, and can be replaced in about an hour by a station attendant.[11]

The compression ratio for each stage in a three-stage compressor is determined from the following equation:

$$R = \sqrt[3]{\frac{P_o Z_i}{P_i Z_o}}$$

50Nm^3/hr and 100Nm^3/hr, about 100 kg/day and 200 kg/day, respectively (Dan Sioui, HyRadix, personal communication, February 2004).

[6] Harvest builds-to-suit, and can size their reformer to any demand (Dave Warren, Harvest Energy Technology, personal communication, February 2004).

[7] This is the availability factor claimed for H2Gen's HGM2000 unit (Sandy Thomas, H2Gen, personal communication, February 2004). Harvest has not verified this availability factor in its units, but claims it a reasonable number assuming future production on the order of tens of units per year (Dave Warren, Harvest Energy Technology, personal communication, February 2004).

[8] Thomas et al, 2001, p.39.

[9] PDC Machines and Hydro-Pac were also consulted for compressors. Both offered price-competitive solutions and guaranteed contamination-free operation (Osama Al-Qasem, PDC Machines, personal communication, February 2004, and Hydro-Pac Proposal # E04-0161, February 25, 2004).

[10] California Fuel Cell Partnership, 2002, p. 16.

[11] Lee Coleman, Pressure Products Industries, Inc., personal communication, February 2004.

where R is the compression ratio, P_o is the pressure at the outlet of the compressor, P_i is the pressure at the inlet of the compressor, Z_i is the compressibility factor at the inlet of the compressor, and Z_o is the compressibility factor at the outlet of the compressor. The compression ratio of each stage of the PPI compressor is about 3.8:1.[12] Hydrogen is cooled after each stage due to the high temperature of compression. The compressor system also includes a pulsation dampener bottle to regulate flow from the reformer, and a base oil heater and base oil cooler to maintain the oil temperature on cold and hot days, respectively.

The flow rate of the compressor should be at least equal to that of the reformer (6.38 kg/hr, or about 48 scfm at 315 K), which it is. The compressor supplied by PPI has a maximum flow rate of 65 scfm[13] (about 7.6 kg/hr).

Storage

EFC uses a cascading storage scheme because it is currently the most common and reliable storage method. Two compression and storage schemes are possible to provide quick fills of gaseous hydrogen: cascading systems and booster systems. In a cascade arrangement, the total storage volume is broken into separate 'banks,' which sequentially fuel the vehicle and always keep one bank at a pressure high enough to provide a complete fill. Booster systems store a larger volume of gas at a lower pressure, and compress it directly into the vehicle. Booster systems are more energy efficient because not all of the gas is pressurized to a high pressure, and tend to be less expensive. But booster compressors are larger and operate transiently, which could reduce reliability.[14] Also, a study by Directed Technologies shows that for small-scale stations, cascading systems using composite tanks are comparable in cost to booster systems.[15]

Dynetek will supply carbon-composite high pressure storage vessels for the storage system.[16] The system is comprised of 5 cylinders with a service pressure of 450 bar (6527 psi) and 21 cylinders with a service pressure of 350 bar (5076 psi). The number of the higher pressure cylinders is minimized to reduce the cost of the storage system.[17] The tanks are arranged in a three-bank cascade in a ratio of 12:9:5, with twelve tanks in the "low pressure" bank, nine in the "medium pressure" bank, and five in the "high pressure bank." A "split bank" configuration allows more efficient use of the storage system than evenly distributing the tanks, since a smaller high pressure bank allows a quicker recovery to maximum pressure.[18]

The cascade storage system was sized according to the load profile depicted in Figure 1.4.[19] The storage required to meet peak demands is determined on a mass basis according to the following equation:

---

[12] Lee Coleman, Pressure Products Industries, Inc., personal communication, February 2004.
[13] Ibid.
[14] Myers et al, 2002, p. 96.
[15] Thomas et al, 2001, p. 53.
[16] High pressure composite tanks are not ASME certified. ASME certification requires a burst factor of safety of 5, but as pressure increases, such a stipulation requires an ultimate bursting pressure of over 30,000 psi, and becomes prohibitive. The Dynetek tanks used here have a burst ratio of 2.2:1, similar to tanks onboard fuel cell vehicles. It is assumed that this will be an acceptable standard for high pressure composite tanks.
[17] Dynetek Quotation # Q10424, February 27, 2004. The cost savings is discussed in the economics section.
[18] Bill Liss, Gas Technology Institute, personal communication, February 2004.
[19] From TIAX. Stefan Unnasch, TIAX, personal communication, February 2004.

$$M_{cascade} = \frac{M_{dispensed} - M_{compressor}}{UF}$$

where $M_{cascade}$ is the mass of cascade storage required to supply demand in a given time period, $M_{dispensed}$ is the mass of hydrogen dispensed over that period, $M_{compressor}$ is the mass of hydrogen added to storage from the compressor in that period, and UF is the utilization factor of the cascade storage system. The utilization factor is the amount of stored hydrogen that is actually available for dispensing to vehicles. It is a function of the number of cascade banks, the maximum pressure of the cascade, and the maximum pressure of the vehicle tank. Praxair modeled the utilization efficiency of a cascade system fueling a vehicle to 5,000 psi.[20] Results from that study are shown in Figure 1.3. The utilization factor for a three-bank cascade system with a maximum pressure of 6250 psi is 44%, which is the value used in our design.

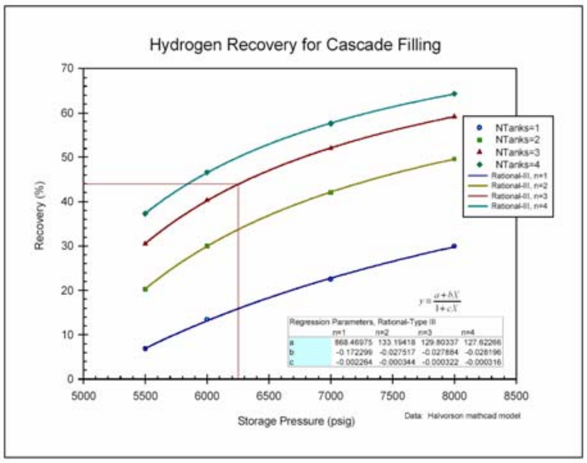


Figure 1.3 Utilization factors for hydrogen cascade storage dispensing to vehicles at 5000 psi.[21]

The total mass of hydrogen storage required is 132 kg. This accounts for the worst-case scenario according to the demand profile, which is filling 47 vehicles over the course of 13 hours.[22] The tanks used in this design provide a total storage capacity of 148 kg.[23]

Figure 1.4 illustrates the relationship between storage availability and the vehicle demand profile. The background region represents the amount of storage available for dispensing, and is equal to the total mass stored multiplied by the utilization factor. The lower (solid blue) portions of each column represent the hourly demand profile of the station. The upper portions of each column represent the amount of storage required to meet the hourly demand, and are equal to the hourly vehicle demand divided by the utilization factor.

The equation used to size the system does not take into account the dynamics between different banks in the storage system. To capture these interactions and verify the design, a software

[20] Halvorson, T. J. et al, 1996. Taken from Thomas et al, 2001, p. 40.
[21] Ibid.
[22] Cascade systems are often designed for two or three hours of peak demand, but here, the 13 hour window requires the most storage. One hour and four hour peaks result in required storages of 33.5 kg and 73.4 kg, respectively.
[23] Dynetek Quotation # Q10424, February 27, 2004. Each 450 bar tank holds 8.9 kg, and the 350 bar tanks, 4.92 kg.

package from InterEnergy™ and the Gas Technology Institute (GTI), CASCADE, was used. [24] CASCADE simulates the refueling process of gaseous fuels from cascade storage systems, and confirmed that the storage system was sufficient.[25]

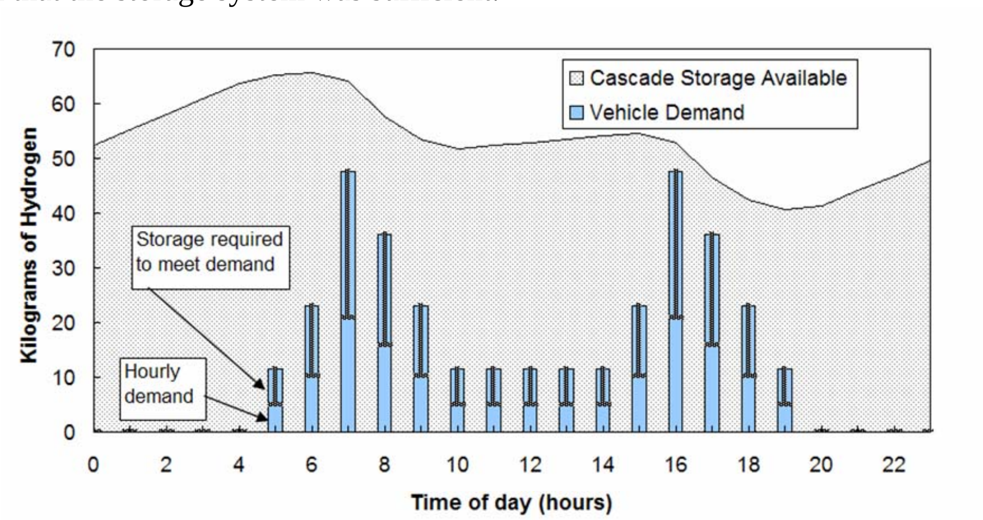


Figure 1.4 Cascade storage availability vs. hourly demand profile.[26]

Dispenser

Two dispensers will be provided by Fueling Technologies Inc. (FTI). Each includes a single delivery hose rated for a maximum delivery pressure of 447 bar (6483 psi) for vehicle fills up to 350 bar (5076 psi).[27] EFC uses two dispensers to allow two vehicles to refuel simultaneously, and to provide reliability in case a dispenser goes down. We use FTI because they have the most experience in the industry.

Fueling Process

The EFC fueling process is similar to that of a conventional gasoline vehicle. First, prepayment and ID validations are required. Once authorized, the customer selects the desired fill pressure and begins the fueling process. The pavement at the fueling area has a static-free coating, so vehicle-to-station grounding is not required. The driver or the attendant will connect the nozzle and begin fueling.[28] The dispenser senses the pressure, temperature and volume of the vehicle tank, and includes a computer for temperature compensated fills.[29] When the vehicle reaches its full density, fueling stops. The customer or attendant replaces the nozzle, and is finished fueling.

The refueling process is expected to take no longer than five minutes. For a vehicle refueling with three kilograms, this implies an average flow rate of 0.6 kg/min. The dispensers have a meter maximum flow rate of 20 kg/min,[30] and can provide sufficient flow. CASCADE confirmed that the storage system could meet a five-minute fill as well.[31] Piping from the

[24] CASCADE, Version 2.1, 2002.
[25] For a detailed discussion on the CASCADE trials, see Appendix A.
[26] Adapted from similar work by TIAX (Stefan Unnasch, TIAX, personal communication, February 2004).
[27] Fueling Technologies Inc. Quotation Reference # 2004-529, February 20, 2004.
[28] It is assumed here that by 2006 any additional communication cables will be integrated with the nozzle.
[29] Fueling Technologies Inc. Quotation Reference # 2004-529, February 20, 2004.
[30] Fueling Technologies Inc. Quotation Reference # 2004-529, February 20, 2004.
[31] See Appendix A for a discussion of the CASCADE software trials.

storage to the dispenser will be sized to handle a flow rate sufficient to fuel two cars simultaneously in less than five minutes.

Component Control

The system is designed for continuous, unattended operation. A supervisory computer data monitoring system provides temperature and pressure data at various points along the system. In the case of any malfunctions, the computer alarm alerts the operator. The entire system can be controlled remotely, including starting and stopping the system.

Turning the system "on" will open the natural gas and water lines and begin the hydrogen production process. The hydrogen generation unit will primarily control the production process itself. Under normal operating conditions, the reformer and compressor will be set at a flow rate of 6.38 kg/hr. The compressor includes a pulsation dampener bottle, which is essentially a buffer storage tank kept at the compressor's designed inlet pressure (100 psi) to ensure a constant flow rate, and keep the compressor from "sucking" on the reformer and pulling the pressure down.[32] It is fed by a "recycle" line from the compressor outlet that allows hydrogen to flow back and maintain the pressure in the pulsation bottle should the compressor flow rate exceed that of the reformer. From the compressor, flow proceeds to the "priority" component of the priority-sequencing panel where it is distributed into three paths, each feeding one cascade bank. The control panel directs flow into the high pressure bank first. If the high pressure bank is full, flow proceeds to the medium pressure bank. When the high and medium pressure banks are both full, flow is directed into the low pressure bank. From each storage bank, hydrogen travels to the "sequencing" portion of the priority-sequencing panel, where flow from the three paths is regulated into one path and sent to the dispenser. During refueling, the low pressure bank initially supplies the vehicle until a pressure differential of 100 psi is obtained.[33] Then the medium pressure bank supplies hydrogen until the minimum pressure differential is obtained. Finally, flow is drawn from the high pressure bank to top off the vehicle. Figure 1.5 demonstrates the control of the ENO cascade.

The dispenser fill computer controls the refueling process. It takes into consideration the Joule-Thompson effect, which is a result of the temperature variations associated with sudden changes in pressure. Ideally the mass of hydrogen transferred to the vehicle could be calculated from the variation in pressure from the storage tank or the vehicle. However, as the pressure drops rapidly in the cascade bank, so does the temperature. Similarly, as the pressure rapidly increases in the vehicle, so does the temperature. The Joule-Thompson effect results in a higher density remaining in the storage bank than in the vehicle tank, even though both are at the same pressure.[34] The fill computer on the dispenser includes an algorithm to account for these temperature effects in the fueling process.

[32] Lee Coleman, Pressure Products Industries, Inc., personal communication, February 2004.
[33] Choosing a minimum pressure differential is somewhat arbitrary, but 100 psi was the value used in CASCADE.
[34] Bossel et al, 2003, p. 26.

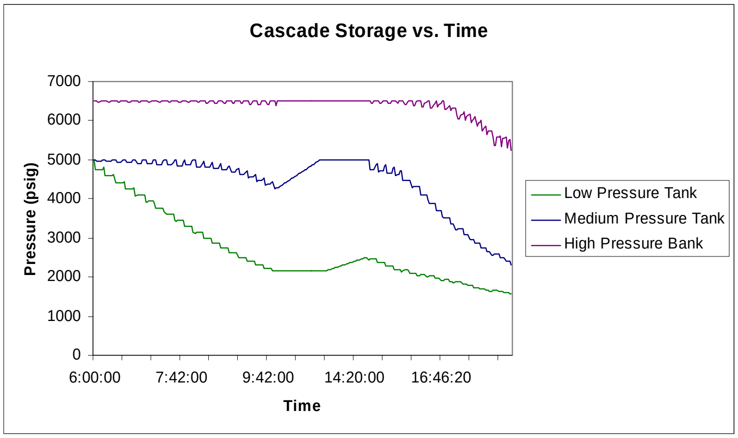


Figure 1.5 Cascade storage vs. time for simulated demand profile[35]

Contingency Planning

Redundancy is not built into the system to account for extended outages of equipment, because to do so would be speculative, and at the small-scale, cost prohibitive. At full storage capacity, about 65 kg of hydrogen is available for transfer to a vehicle, enough for about 22 cars. Anytime the duration of an unexpected equipment outage exceeds the capacity of the storage system, backup equipment would be needed, or service curtailed.

In the event of a contingency at EFC, mobile refuelers would be brought in. They provide storage, compression and dispensing together, and they could serve in any contingency. Mobile refuelers are quite small, however, and several would be needed. If a sufficient number of mobile refuelers were not available, a tube trailer would be brought in. Praxair estimates that its facility in Ontario, CA could provide EFC with a tube trailer in less than 24 hours.[36] Finally, if several hydrogen fueling stations existed in the area, a merchant producer such as Praxair, or an equipment supplier, could take on the role of an insurer. They could charge a monthly fee for the guaranteed provision of backup equipment and/or hydrogen within a certain time period.

Anticipated Energy Use

The anticipated energy use for operation of the station is summarized in Table 1.1, and discussed in detail in the *Environmental Analysis* and Appendix C. Electrical equipment includes the SCADA system, exterior lighting, and system controls.

Equipment	Electricity Use (kW)	Electricity Use (kWh/yr)	Natural Gas Use (MCF/day)	Natural Gas Use (MCF/yr)
Reformer	19.9	174,425	28.6	10,439
Compressor	33.5	293460	--	--
Electrical Equipment	1.7	14,892	--	--
Safety Equipment	1	8760	--	--
Station Operation	5	29,200	negligible	negligible
Total	61.1	541,660	28.6	10,439

Table 1.1 Anticipated energy use of station.

[35] Adapted from CASCADE. See Appendix A for details.
[36] Aaron Rachlin, Praxair, personal communication, February 2004.

2. SAFETY ANALYSIS

Safety is paramount to ENO's design of the fueling center. The EFC uses a redundant strategy of *prevention* and *detection* to ensure that hydrogen, air, and an ignition source are never in the same place at the same time. This redundant design ensures the highest level of safety for the equipment, the surrounding built environment, and the patrons. Prevention is of the utmost importance, as any hydrogen-related accident could hinder the acceptance of hydrogen fuel.

The ENO Integrated Safety System (EISS)

Producing and storing compressed hydrogen on-site makes explosions a realistic and serious concern. To address this, ENO designed a safety system for both prevention and detection by integrating equipment to monitor and maintain the safe production, compression, storage, and transport of hydrogen.[37] From the reformer inlet to the dispenser outlet, hydrogen and natural gas are monitored and controlled to minimize unexpected failures. The EISS schematic, shown below in Figure 2.1, identifies each piece of safety equipment at the station.

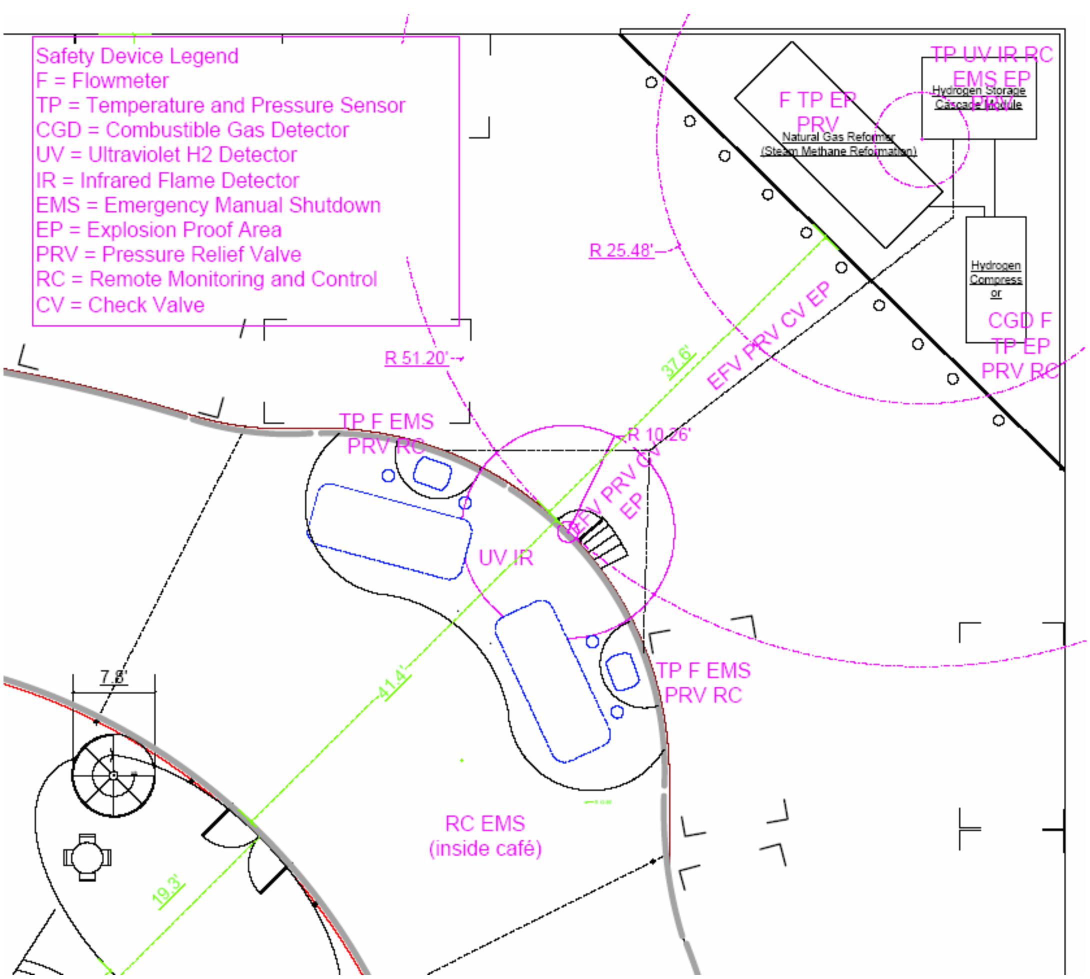


Figure 2.1 ENO Integrated Safety System (EISS).

[37] For example, a leak in the hydrogen dispenser nozzle is prevented by using code-compliant equipment. Should this equipment fail however, the leak will be detected by a combustible gas detector, which will send a signal to the control panel to shut down equipment.

Code Compliance

Our design meets or exceeds current codes and standards in place for hydrogen refueling with the exception of the composite storage tanks. Based on feedback from the chair of the CaFCP Codes and Standards Committee and from Praxair, we are confident this code will be revised by March 2006.[38] Current ASME code requires stationary storage tanks to have a burst pressure to service pressure ratio of at least 5:1, and limit the maximum allowable pressure to 200 bar (2900 psi). The cylinders we use are designed to NGV2 standards, at pressures up to 700 bar (10,152 psi) and with a burst-to-service pressure ratios of at least 2.25:1.[39] Much work is being done to establish pressure vessel codes for high pressure carbon-composite tanks. The process, which began last year, is expected to take 2-3 years.[40] ENO's design assumes that by March 2006 the tanks will be legal in California.

When consulting fire and safety officials about the safety of the ENO design, the only concerns were the proximity of the dispensers to a public entrance, and the code compliance of roof-top fueling. The main hazard in this situation is a leak that could lead to a fire or an explosion. But hydrogen's high buoyancy makes this situation highly improbable. The more likely risk is a rupture of the high-pressure hydrogen line that travels from the ground, up the rear wall to the dispensers. Prevention of this hazard will be covered in the detailed FMEA analysis to follow. Risk of fire to the building is mitigated by using non-flammable roof material (concrete slab with structural steel). Code requires a set back distance of at least 10 feet between the dispensers and the back door, and allows a setback distance of less than 25 feet because fueling occurs above the wall opening.[41]

Construction of the EFC will require the following permits: Certificate of Fitness, Flammable Gas Permit, and Dispensing Permit from the LA Fire Marshal; California PE Stamp; Approved Compliance with California Fire Code; and approval of the local HAZMAT Officer.

Prevention

As discussed above, the strategy of prevention guided the design of the EFC. Hydrogen leaks are prevented by:

- Nozzle valves only open when fueling a vehicle; check valves closed all other times
- UV H_2 detection on sloped canopy and pressure loss detectors to alert auto shutdown
- Automatic leak check at nozzle before each fueling
- Bollards surrounding dispensers and railing along roadway to prevent collisions
- Routing piping up the rear wall through an "indent" or crevice in the wall. This reduces the risk of line rupture should a vehicle hit the wall and enables the line to still be external to the building.

In the case that there is a hydrogen leak, ignition of the leak is prevented by:

- Static spark-resistant coating on fueling surface to prevent static sparks and eliminate the need for a vehicle-station grounding cable.

[38] The industry is confident that the code will be changed by 2006 (Tony Estrada, PG&E, personal communication, February 2004, and Aaron Rachlin, Praxair, personal communication, February 2004).
[39] Dynetek, Quotation # Q-10424, February 26, 2004.
[40] Ibid.
[41] NFPA50A, Table 3-2.2, Item 2.

- Class I Division 2 Electric equipment per NFPA 70
- IR flame detection and temperature sensors initiate auto shutdown
- Hydrogen's buoyancy and sloped canopy disperse and guide leak upwards
- Fueling lighting located below dispenser skid grade 30 ft away[42]
- "No Smoking" and other warning signage

Fault Tree Analysis

To ensure all potential safety concerns are addressed at the EFC, we conducted a fault tree analysis on the station. This is the same analysis used by safety professionals to prove that all possible events leading to a fire and explosion have multiple controls, preventions, and mitigations.[43] The EFC fault tree, shown in Appendix B, identifies events that lead to a fire or explosion and the measures taken for mitigation or prevention. For example, following the rightmost side of the diagram, a fire or explosion requires a fuel leak, which can occur at the compressor. The leak is caused by a connection failure, which is mitigated by unit ventilation and controlled by a low explosion limit (LEL) (4.0% – 74.2% for hydrogen) alarm shutdown and low blower shutdown.

Cause and Effect Analyses

We analyzed the failure modes with the highest probability using a cause and effects analysis. This is the same type of analysis used by engineers at nuclear facilities to ensure premium levels of safety.[44]

1) Vehicle collision with dispensing units, other vehicles, or rail on fueling ramp

Cause – Intentional or unintentional driver error

Effect – Damage to building, possible fire and/or explosion, injury or loss of life

Preventing Vehicle operator error

- Ensure adequate lighting and high visibility, no obstacles or blind spots on ramp
- Install speed bumps to reduce speed on ramp

If Vehicle operator error, preventing damage to equipment

- Protect dispensers with bollards and use highway-grade steel rails along sides of ramp to ensure vehicles cannot go through or over the ramp

If damage to equipment occurs, preventing hydrogen leak

- Dispenser check valves are closed when nozzle not fueling
- Excess flow valve before dispenser closes if flow exceeds set level

If hydrogen leak, preventing fire or explosion

- Sudden pressure drop activates shutdown

If hydrogen leak, preventing ignition

- UV/IR flame detection shuts down equipment
- All surrounding electrical equipment are Class I div 2 per NFPA 70
- Automatic shutdown of equipment by the RMC equipment
- Open air equipment so hydrogen disperses, lowering air/fuel mixture

If ignition occurs, preventing injury or loss of life

---

[42] NFPA 70, 501.9, B-2.
[43] Charlie Hoes, Hoes Engineering, Inc., personal communication, February 2004.
[44] Ibid.

- Fueling ramp design inherently minimizes exposure of pedestrians & café patrons to fueling area
- Sufficient access for fire department vehicles
- Staff trained with flammable gases

2) Vehicle Collision with System (Compressor, Dispenser, Reformer, Storage)
Cause - Driver error, terrorism
Effect – Possible fire and/or explosion, damage to equipment, injury, death

Preventing Collisions

- Speed bumps on ramp, spacing limits speeds, bollards surround equipment

  If collision occurs, preventing leaks

  - Same as (1)
  - Sudden pressure drop activates shutdown
  - Storage tanks mounted in steel lattice structure
  - Reformer enclosed in sturdy steel environmental enclosure
  - Combustible Gas Detector shuts off gas flow if leak detected in C or SMR

    If leak occurs, preventing ignition

    - UV/IR flame detection shuts down equipment
    - All surrounding electrical equipment are Class I div 2 per NFPA 70
    - Automatic shutdown of equipment by the RMC equipment
    - Open air equipment so hydrogen disperses, lowering air/fuel mixture

      If ignition occurs, preventing injury or loss of life

      - Reformer blow-away panels prevent explosion
      - Staff trained with flammable gases
      - Manual shutoff in café, at dispenser, and equipment area
      - Sufficient access for fire department vehicles

3) Piping Leak
Cause – Seal/Joint/Fitting/Material failure, seismic activity, hydrogen embrittlement
Effect – Possible fire and or explosion, loss of contained hydrogen

Preventing Leaks –

- Fail-safe excess flow valves between dispenser and storage close when flow rate exceeds a maximum value
- Minimizing above ground exposure to pipes and protecting pipes that are exposed (like the ones that runs up the rear wall to the dispensers)
- Flow meters and pressure detectors set to initiate shutdown if pressure drop detected
- Check valves close while dispensers are not fueling (most of time)
- Piping, connections, and fittings meet NFPA 50A section 2-3 which prevent rupture and hydrogen embrittlement
- Piping able to withstand medium magnitude earthquake
- Pressure Relief Devices prevent excessive pressure buildup

If leak occurs, preventing ignition

- All surrounding underground conduits and equipment lighting meet NFPA 70

If ignition occurs, emergency procedure

- Same as (2)

Failure Modes and Effects Analysis

The eight major failure modes considered in this analysis represent the most likely scenarios resulting in the most severe potential consequences. Terrorism is considered, but its inherent unpredictability excludes it from the ranking. The table below summarizes the eight failure modes in order of probability (P). A cause and effect analysis for the top three follows. The severity of consequence (S) is ranked according to the risk of personal injury or death. Both are ranked either high, medium, or low (H,M, or L).

Failure Mode[45]	**Cause**	**Effect**	**Prevention & Mitigation**	P	**S**
1) Vehicle collision with building entry, dispensing units, other vehicles on fueling ramp	Driver error	Damage to building, Possible fire and/or explosion if fueling equipment are hit, Risk to consumers inside building	Steel guardrails lining roadway on both sides to contain vehicles, reinforcement in building roof/roadway per code, Speed bumps on fueling ramp, bollards protecting dispensers, high pressure H2 lines going up the wall	H	L
2) Leak in piping	Seal failure, Seismic activity, Hydrogen embrittlement	Possible fire and or explosion, Loss of contained hydrogen	Piping, fittings, and connections used in accordance with NFPA 50A,[46] pressure loss sensors, flow meters, and pressure relief devices used per NFPA 50A,[47]	M	M
3) Vehicle collision with H2 room	Driver error	Possible fire and or explosion, Extensive damage to equipment	Concrete wall, bollards and reinforced fence protecting H2 room.	M	H

[45] TIAX, 2003.
[46] NFPA 50A, Section 2-3.
[47] NFPA 50A, Section 2-2.

4) Ignition of leak at dispenser	Lit cigarettes, static electricity sparks, and other consumer created ignition sources	Fire and or explosion	"No Smoking" signage posted, lighting at a 30 ft distance and below fueling level, nozzle sensors shut off flow at detection of pressure loss	M	H
5) Storage tank bursts	Fire/heat source near storage causes material failure, Storage equipment failure	Explosion, Loss of equipment, Damage to station	Distancing of storage from station buildings per NFPA 50A,[48] fencing around equipment prohibiting consumer access, Tank specs	L	H
6) Hydrogen or natural gas leak in steam methane reformer	Piping failure, Valve failure, Mechanical failure	Gases leak into reformer unit, possible fire and/or explosion	Odorized Gas, Combustible Gas Detector, Temperature & Pressure sensors, Flow detectors, Full shut down	L	M
7) Dispenser damage and leak due to driver leaving with nozzle attached	Driver error	Possible fire and or explosion, Damage to fueling equipment	Breakaway nozzles used for consumer fueling	L	L

8) Terrorism Failure Modes	**Cause**	**Effect**	**Solution/Prevention/Mitigation**
Attacks on H2 room	Security breach, explosive device set off in or near H2 room.	Explosion from ignition of hydrogen or natural gas system.	Pressure Relief Devices on all high-pressure equipment, fencing, roofing, and video surveillance of H2 room, explosion proof equipment and surrounding structures used, non-explosion proof structures distanced per NFPA 50A,
Vehicle driven into dispenser or H2 room	Terrorism	Ignition of hydrogen at dispenser	H2 equipment is protected by bollards.
Vehicle driven off fueling ramp	Terrorism	Injury or death to public	Highway grade steel rails are installed on both sides of the fueling ramp.

Table 2.1 Top eight failure modes ranked according to probability (P) and severity (S).

[48] NFPA 50A, Table 3-2.2.

3. ECONOMIC ANALYSIS

Introduction

Cost is a critical factor in the successful development of fueling infrastructure. Less expensive stations are more easily established and yield faster returns for investors. Therefore, ENO aimed to carefully control station costs when developing its fueling center. To minimize cost, ENO selected the on-site SMR pathway for hydrogen generation, and added a café business to supplement fuel revenues.

The following section describes the costs of the Center, the methods used to calculate these costs, and ENO's selling price for hydrogen. This report includes a sensitivity analysis which examines those design elements with the most influence on hydrogen price. Sources for all costs, and additional data, are documented in the Appendix.

Summary

The main components of hydrogen price are presented in pie chart below on the left. Operating cost, which represents the largest portion of hydrogen price, is broken down further.

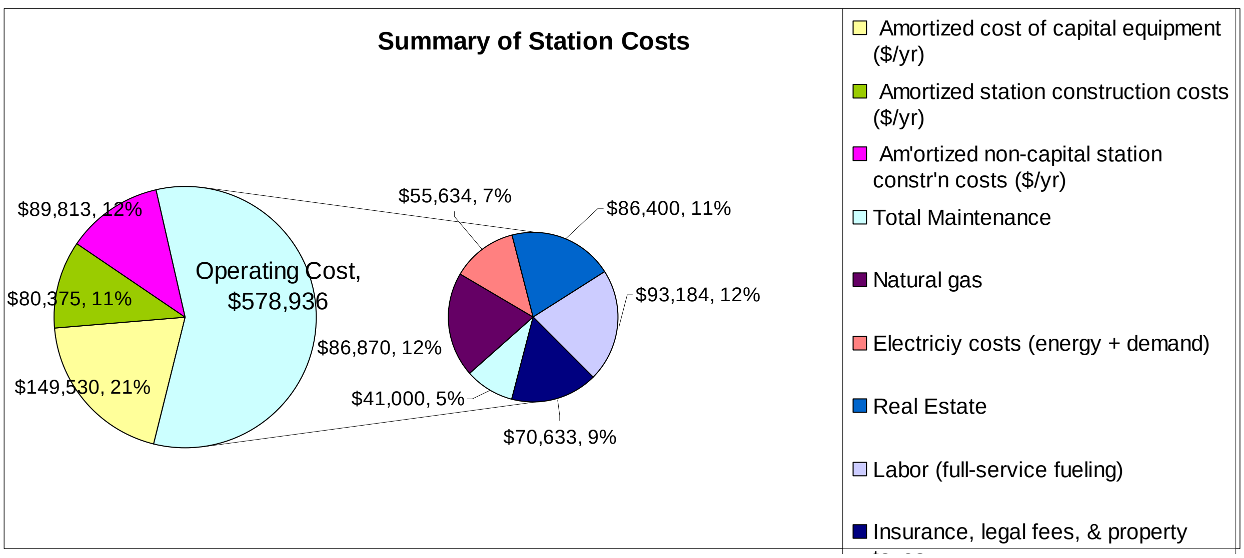


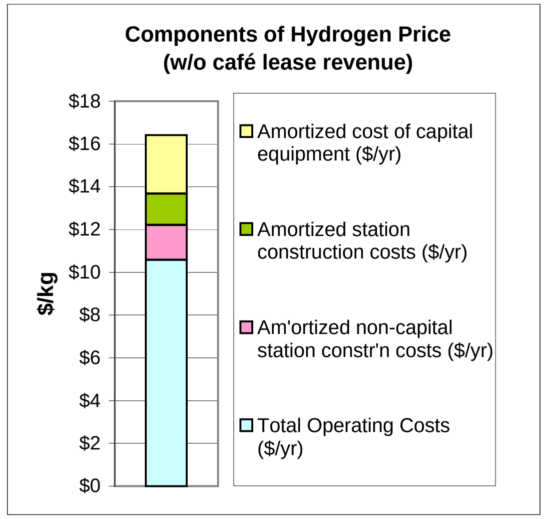
Figure 3.1 Summary of station costs.

Hydrogen Price

ENO will sell hydrogen at **$14.23/kg** to recover the **$1.9 million** initial investment and **$578,936** annual operating costs**.** The cost per mile to a FCV driver at this fuel price is **$0.237/mile**, compared to **$0.058/mile** for a conventional car. Annual revenue from hydrogen sales is expected to be **$779,344** based on the daily sale of 150kg. To augment revenue, ENO will lease the café to a vendor at a lease price of **$119,310/yr**. Based on the anticipated revenue generated by fuel sales and café lease, ENO will achieve a 10% rate of return on the initial investment over the life of the station (10 years). Table 3.1 presents a summary of the station costs. Appendix C presents a more detailed list of the costs, financial calculations, and assumptions for the proposed EFC.

Summary of Eno Fueling Center Costs

Total capital equipment costs	**$ 918,796**
Natural gas reformer (includes purification)	$299,700
Storage System	$310,380
Dispenser	$83,000
Compressor/Pump	$195,000
Electrical Equipment	$38,632
Safety Equipment	$17,500
Miscellaneous Equipment	$37,000



Total station construction costs	**$493,872**
Café excavation	51,382
Front excavation	32,725
Base Building	196,538
Building upgrade to café	80,927
Driveway/Fueling Ramp	52,816
Landscape/Hardscape	25,447
Misc. (Steel guard Rails, H2 walls/fence, canopy)	14,419
Architecture and engineering	23,122

Total non-capital station constr'n costs	**$551,860**
Engineering (incl proj. mgt. & design)	$130,000
Permitting	$30,000
Site Development	$50,000
Safety and Haz-ops Analysis	$30,000
Equipment Delivery	$22,000
Installation	$98,000
Start-up & Comissioning	$31,000

Total Operating Costs ($/yr)	**$578,936**
Total Maintenance	$41,000
Natural gas	$86,870
Electriciy costs (energy + demand)	$55,634
Real Estate	$86,400
Labor (full-service fueling)	$93,184
Insurance, legal fees, & property tax	$70,633

Total Station Costs (amortized)	**$898,654**	**/yr**		*+ operation + insurance*
	$16.41	/kg		
Total capital equipment costs	*$918,796*		=TCE	= *total cap eqpmt costs x ACRF*
Amortized cost of capital equipment ($/yr)	**$149,530**	**/yr**	=ACE	
	$2.73	/kg		
Total station construction costs	*$493,872*		=TSC	
Amortized station construction costs ($/yr)	**$80,375**	**/yr**	=ASC	= *total station constr. costs x ACRF*
	$1.47	/kg		
Total non-capital station constr'n costs	*$551,860*		=TNC	
($/yr)	**$89,813**	**/yr**	=ANC	= *total non-cap. constr. costs x ACRF*
	$1.64	/kg		
Total Operating Costs ($/yr)	**$578,936**	**/yr**	=TO	= operating costs
	$ 10.57	/kg		

Total Station Revenues

Revenue from Fuel Sales	**$779,344**	/yr	=RFS	Annual ROI	12%
	$14.23	/kg			
Revenue from Café Lease ($/yr)	**$119,310**	**/yr**	=CP		
	$2.18	/kg			

Hydrogen Selling Price	**$14.23**	**/kg**	=HP	= Annual Revenues / Q
FCV cost	**$0.237**	**/mile**		, assuming 60 miles/kg

Finanacial Calculations*

Annual Fixed Expenses	$578,936	=E	= TO
Total installed capital costs of the station	$1,964,528	=C	= TCE + TSC + TNC
Capital recovery factor	16.3%	=CRF	= d / (1 - (1+d)^-n)
Annual Revenues	$779,344	=R	= E + (C x ACRF) - CP

Assumptions

Annual hydrogen production (kg/yr)	54,750	= Q
After-tax rate of return	10.0%	=d
recovery period in years	10	=n

The ENO Approach

To determine a realistic hydrogen price, it is essential to understand the true costs of hydrogen equipment today *and* the costs to integrate that equipment at a station. Therefore, to obtain accurate, near-term costs for the hydrogen equipment used at our station, ENO directly contacted vendors and requested price quotes. When companies were unable to provide quotes, we relied on cost data from literature or from exiting stations. Appendix C lists the cost of each item, the specifications or assumption for these items, and the source of this information. The high-price hydrogen equipment items include additional price comparisons using data from other suppliers.

To determine the hydrogen price, we calculate the amortized cost of the initial capital investment, the annual operating cost of the station, and the annual revenues from hydrogen fuel sales and the café vendor lease.[49] The assumptions and calculations are presented in Appendix C.

1. Capital Costs for Hydrogen Equipment

Figure 3.2 summarizes the costs of hydrogen equipment used at the EFC.

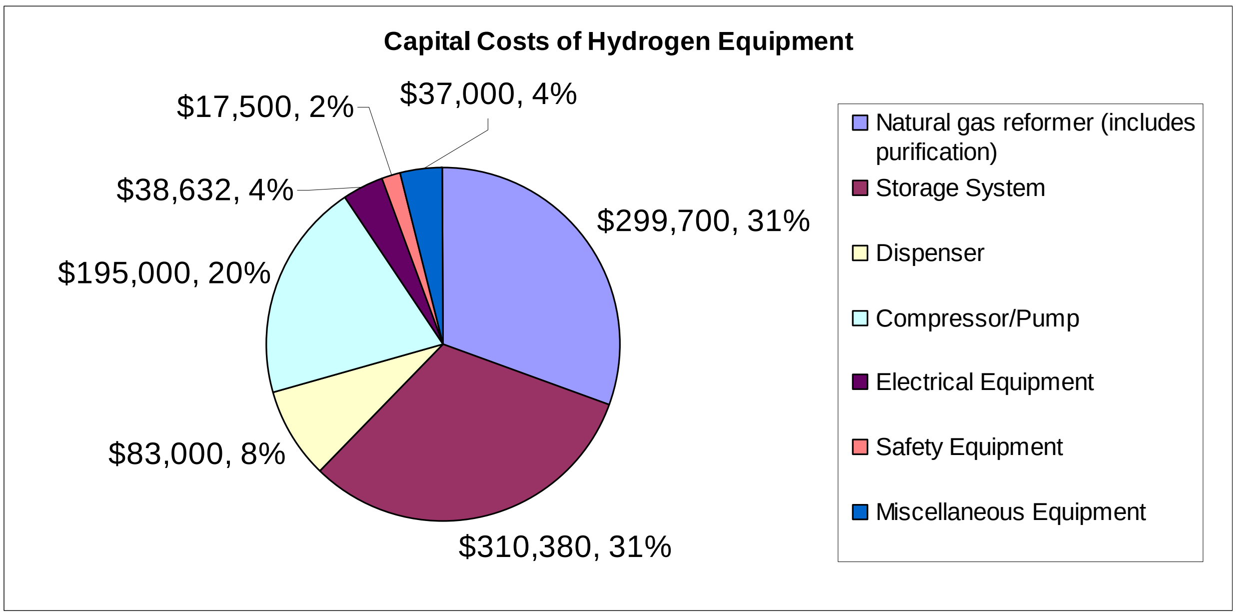


Figure 3.2 Capital costs of hydrogen equipment.

Compressor type and storage tank configuration are two notable equipment choices that impacted hydrogen price. Using PPI's diaphragm compressor instead of the Hydro-Pac reciprocating compressor added approximately $76,000 to our capital cost. We justified this design choice however based on the decreased maintenance cost and increased reliability of diaphragm compressors.[50] A savings of just $5,067/yr in maintenance costs will cover the additional capital cost, without even accounting for the added value of reliability.

[49] Our financial analysis is based off the same methodology used in Sandy Thomas' "Hydrogen Infrastructure Report" to calculate the price of hydrogen. We replaced his assumptions with those given in the contest rules (Thomas, 1997).

[50] John Williams, Quantum Technologies, personal communication, February 2004.

ENO reduced storage costs by $54,000 by choosing a storage system that uses both 350 bar and 450 bar tanks instead of using all 450 bar. Although this option increases the storage footprint since more tanks are required, the effect on real estate cost is negligible. Using more tanks also has the added benefit of increasing cascade efficiency.[51]

2. Operating Expenses

The costs to operate and maintain the EFC account for the largest portion of the hydrogen price. Part of this is attributed to the high cost of natural gas in California, the high value of real estate in Los Angeles, and the full-service fueling capability ENO offers the station. In the near term, insurance and legal fees associated with indemnification and due diligence are also substantial.[52]

Utility Costs

Using an SMR production pathway makes natural gas price critical to the price of ENO's hydrogen. The following figure shows how sensitive the price of hydrogen is to natural gas rates. Hydrogen at an ENO station in Hawaii would cost $18.50/kg.

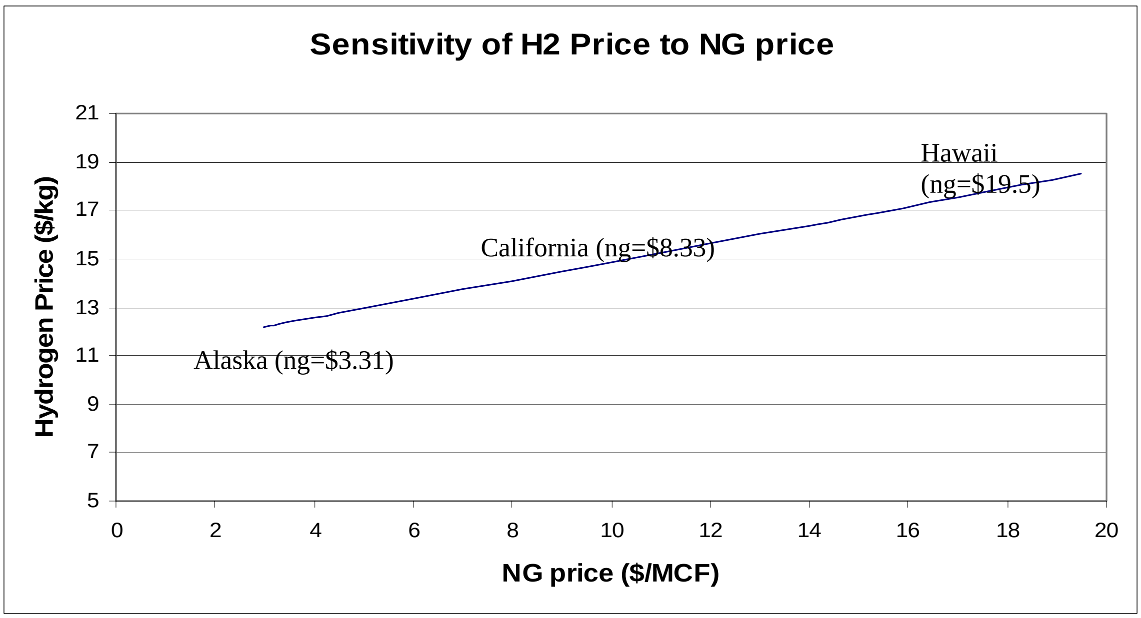


Figure 3.3 Sensitivity of H_2 price to natural gas price.

Since the compressor and reformer operate 24hrs/day, steady-state, we are not able to capitalize on time-of-use rate schedules by varying load during peak hours. The amount of electricity consumed at the EFC does not justify adding reformer/compressor capacity to allow for variable production rates. ENO assumes a constant electricity price which is an average of typical peak and off-peak price.

[51] Stefan Unnasch, TIAX, personal communication, February, 2004.

[52] Bob Boyd, BOC, personal communication, February 2004. He was aware of a case where total insurance costs and legal fess for a station were $500,000.

Maintenance Costs

ENO uses conservative cost estimates for the reformer due to the lack of real-world testing experience with this technology. Small-scale natural gas reformation technology has been used in only three stations to date in the US (Las Vegas, Palm Springs, Penn State), two of these commissioned within the last 16 months. The true maintenance costs over the life of this equipment have not yet been determined.

ENO assumes periodic equipment replacement (e.g. reformer catalysts) is covered by our maintenance costs. Extraordinary annual costs such as catalyst replacement every five years are included.[53]

Labor Costs

Labor makes up the largest portion of operating costs for the EFC and is highly dependent on station operating hours and employee wage. To provide extraordinary customer service, ENO will operate the station 6AM – 10PM daily and employ one station manager at $16/hr to oversee the station and fuel cars. Providing full-service fueling service at the EFC does not add substantial costs since at the minimum, we require one onsite station manager for general station operations, safety, and customer support. At a rate of 50 cars/day, one employee should also be able to fuel each car. We assume the manager will not operate or maintain any equipment but will call off-site ENO support when equipment problems arise.

Full service fueling may actually save substantial costs for legal fees by reducing liability concerns with automakers, not to mention improving both safety and customer satisfaction. In an informal marketing survey we conducted prior to designing the station, several respondents mentioned a desire for full-service fueling.[54] Full service fueling will also encourage customers to spend more time in the café. Fuel cell vehicle manufacturers indicate they expect full service fueling offered at future commercial stations in the near-term.[55] This will mitigate the risk of accidental or intentional operator error at the pump.

3. Capital costs for station construction

Station construction for the EFC will involve building a below-grade café, fueling ramp, parking lot, and front landscaped commons area. To offset a portion of these costs, ENO will lease a majority of the space in our building to a café owner/operator for $119,310. This lease price is based on an assumption that the lease price ($/ft^2/month) for retail building space is 4-5 times higher than the cost of the real estate on which it is built. ENO assumes a real estate cost of $6/ft^2/yr.[56]

[53] Thomas, 1997.
[54] Maura Winkworth and Lisa Iancin, personal communication, December 2003. Approximately 10 people were interviewed and asked several questions, including "What don't you like about existing gas stations?" and "What features would you like to see at future fueling station?"
[55] Jesse Schnieder, Daimler Chrysler, personal communication, February 2004.
[56] This estimate is based off of data from one station operator in LA who pays $4000/month in real estate costs to operate a small corner gas station. $4000×12months/8000 ft^2 = $6/ft^2/yr.

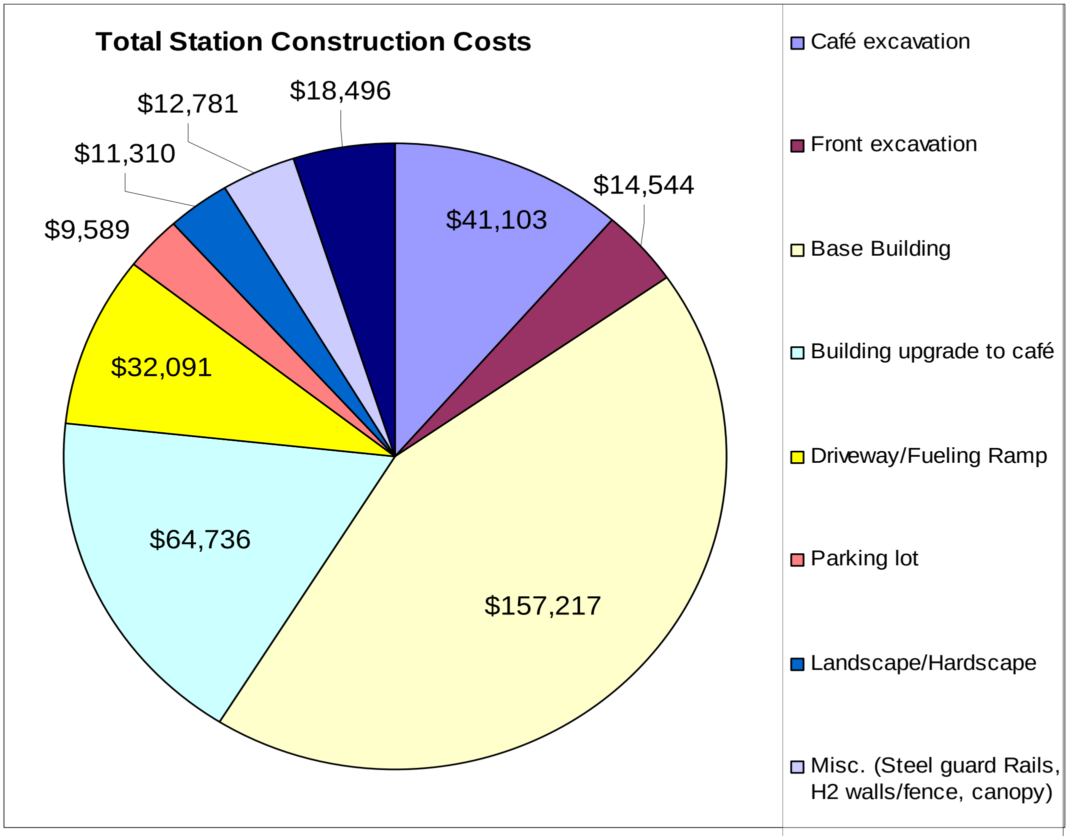


Figure 3.4 Total station construction costs.

ENO has developed an EFC Sizing Model to calculate station construction cost based on seven geometric variables of the station. This model allows ENO to configure stations differently depending on land availability and desired café size. For example, a station in a highly industrial area with limited real estate and low foot-traffic may opt for a smaller EFC (8,100 vs. 14,400 ft^2) with a smaller retail space (990 ft^2 vs. 2312 ft^2). The cost to construct this station would drop by 46% ($271,000 vs. $494,000), and hydrogen price will drop from $14.25 to $13.7. See Appendix C for the EFC Sizing Model and more scenarios.

4. Non-capital costs for station construction

We included the non-capital costs for developing hydrogen stations since they represent nearly 10% of our total station cost. These costs also have the highest variability due to local factors and can thus cause a budget to grow or shrink depending on how well they are anticipated. For example, educating the community, city council, and fire marshal up-front about hydrogen safety can ease the permitting process, thus reducing costs.

4. ENVIRONMENTAL ANALYSIS

Energy Balance

Figure 4.1 shows an energy balance for the hydrogen supply pathway at the EFC. It includes the energy required for the production and compression processes, which are accounted for in the *Technical Analysis* according to product specifications (see Table 1.1).

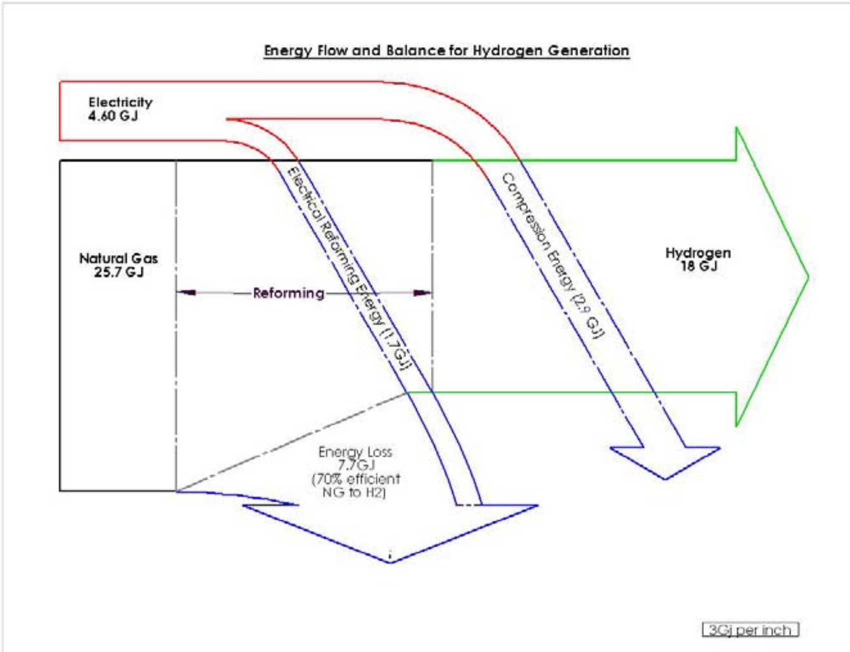


Figure 4.6 Energy balance for all major supply system components

Well-to-Tank (WTT) Emissions

An analysis of the well-to-tank CO_2 emissions requires accounting for the energy used and carbon emitted by every component of the hydrogen supply pathway. The analysis accounts for CO_2 emissions from methane leaks in natural gas pipelines, reformer exhaust emissions, and emissions from the production of grid electricity. Figure 4.2 shows the sources of well-to-tank GHG emissions along the hydrogen pathway, not including electricity emissions.

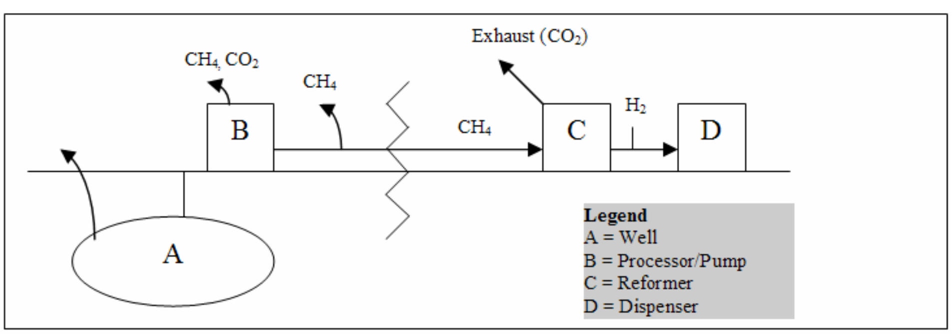


Figure 4.1 GHG emissions for onsite SMR pathway, not including electricity consumption.

We assume a power production emissions rate of 0.32 kg CO_2/kWh.[57] The energy required to pump water is estimated to be 0.00482 kg CO_2/L,[58] but is negligible in this analysis. Table 4.1 presents the well-to-tank CO_2 emissions for gasoline and hydrogen produced via onsite SMR. Hydrogen production at EFC emits roughly eight times as much greenhouse gas emissions on a well-to-tank basis than gasoline. This is a result of the grid power used for hydrogen production and compression.

	Gasoline Station	Onsite SMR
Well-to-station GHGs (g CO_2 equiv./MJ)[59]	13.2	8
SMR emissions (g CO_2/MJ)[60]	None	84.3
Hydrogen equipment power (g CO_2/MJ)	None	22.8
Vehicle energy consumption (MJ/yr)	3.504E+6 MJ/yr	1.2E+6 MJ/yr
Total WTT emissions (kg CO_2/yr)	46,252.8	138,183.5
Total WTT per unit of fuel	**1.7 kg CO_2/gal**	**13.8 kg CO_2/kg of H2**

Table 4.2 Well-to-tank CO_2 emissions, gasoline vs. EFC

Tank-to-Wheels (TTW) Emissions

The amount of energy needed for a fleet of 50 gasoline and hydrogen vehicles was calculated using the lower heating value of the fuel, and assuming each vehicle travels 12,000 miles/year. The total energy demand for 50 gasoline vehicles and 50 fuel cell vehicles is shown in Table 4.2.[61] Table 4.3 gives the tank to wheels CO_2 emissions for gasoline and FCVs. Hydrogen FCVs are assumed to emit zero CO_2 from the tank to the wheels.

Vehicle	Fuel Economy	Total Fuel used	Fuel LHV (MJ/kg)	Energy used (MJ/year)[62]
Gasoline	27.5 mpg	21,818 gal/year	44	3.504E+6
H_2	60 mi/kg	10,000 kg/year	120	1.2E+6

Table 4.2 Total energy used per year for 50 gasoline vehicles and 50 FCVs, assuming 12,000 mi/yr.

[57] SFA Pacific, 2003.
[58] Swistock, 2004.
[59] L-B-Systemtechnik GmbH, 2002.
[60] SMR emissions = 23 gC/MJ (Weiss et al, 2000).
[61] We used similar assumptions as in the MIT report (Weiss et al, 2000).
[62] We used a density of 803 kg/m^3, for gasoline at 300K and 1atm.

Vehicle	Emissions ($kg\ CO_2/MJ$)[63]	Annual Energy Consumption (MJ/year)	Total TTW Emissions ($kg\ CO_2$/year)
Gasoline	.0734	3.504E+6	2.572E+5
Fuel Cell	0	1.2E+6	0

Table 4.3 Tank to wheels emissions calculations, conventional gasoline vehicle vs. hydrogen fuel cell.

Well-to-Wheels Emissions

Emissions from the well-to-tank can be combined with those from the tank-to-wheels to obtain the total well-to-wheels CO_2 emissions. Table 4.4 compares the well-to-wheels emissions of 50 conventional gasoline vehicles with those from 50 hydrogen FCVs.

Vehicle	WTT emissions ($kgCO_2$/year)	TTW emissions ($kgCO_2$/year)	Total WTW emissions ($kgCO_2$/year)
Gasoline	46252.2	2.572E+5	**303,445**
Hydrogen	138183.5	0	**138,183**

Table 4.4 Well-to-wheels emissions for 50 gasoline vehicles vs. 50 FCVs.

Replacing 50 gasoline vehicles with 50 hydrogen FCVs reduces greenhouse gas emissions by 165,262 kg/yr, or by 54%. Despite the fact that hydrogen production at EFC emits more than eight times as many GHGs as the gasoline supply stream, FCVs using EFC hydrogen result in a significant greenhouse gas savings as compared to gasoline vehicles. This is due to the FCVs emission-free operation and high fuel economy.

Table 4.5 below summarizes the assumptions and calculations for the well-to-wheels analysis.

Environmental Impact Forecast

To further examine the future impact of our station on the environment, ENO used the VISION model, version 2.0, which "estimates the potential energy use, oil use and carbon emission impacts through 2050 of advanced light and heavy duty vehicle technologies and alternative fuels."[64] We estimate that our station can support 197 vehicles initially, which in 2006 would constitute 0.00117% of the light duty vehicle market. We assume a FCV market penetration scenario as shown in Figure 4.3. A growth scenario for the station was also envisioned with the installation of greater capacity and more fuel dispensers in future years. Because the station was designed to operate at capacity from the build date, the scenario progresses in a step-wise fashion as shown in the following figure. All hydrogen was assumed to come from natural gas, and the *Annual Energy Outlook 2002* Reference case scenario was used for the utility mix. Given this, and the known number of FCVs per year, the amount of hydrogen produced and the CO_2 reduction from the replacement of standard vehicles is calculated. In 2006, the 197 FCVs

[63] L-B-Systemtechnik GmbH, 2002.
[64] VISION, Version 2.0, 2003. From User Guide worksheet of the model.

Environmental Analysis

Author: Paul Glanville
3/1/2004

Assumptions

Gasoline	803	kg/m^3 at 300K 1at
	27.5	mi/gal
	134	MJ/gal (LHV)
	44	MJ/kg (LHV)
Natural Gas	EU NG mix @ 58 psia	
Hydrogen	2.016	g/mole
	60	mi/kg
	120	MJ/kg (LHV)
Carbon Dioxide	44.01	g/mole
General	150	kg/day
	0.32	kgCO2/kWh
	3.668	kgCO2/kgC
gal to L	3.780	L/gal
m^3 to gal	220	gal/m^3
average miles	**12,000**	**mi/yr**
fleet size	50	cars
Water Delivery Energy	0.057	kWh/gal
	0.015	kWh/L
	4.825E-03	kgCO2/L

Energy usage

Gasoline		
fuel usage	21,818	gal/yr
energy usage	3504000	MJ/yr
Hydrogen		
fuel usage	10000	kg/yr
energy usage	1200000	MJ/yr

Well to Tank

Gasoline			**Hydrogen**		
Well to tank GHG for delivered fuel	13.2	gCO2/MJ	Well to tank GHG for delivered fuel	8	gCO2/MJ
Well to tank GHG for delivered fuel	**1,767**	**gCO2/gal**	Reformer Emissions	84	gCO2/MJ
Total CO2 emitted WTT	46,253	kgCO2/yr	Extra Grid Power Usage and Emissions	467,885	kWh/yr
				22.8	gCO2/MJ
			Total	115.2	gCO2/MJ
			Well to tank GHG for delivered fuel	**13,818**	**gCO2/kg of H2**
			Total CO2 emitted WTT	138,183	kgCO2/yr

Tank to Wheels

Gasoline		
Emissions	0.073	kgCO2/MJ
Total CO2 emitted TTW	257,194	kgCO2/yr
Hydrogen		
Emissions	0.00	kgCO2/MJ
Total CO2 emitted TTW	0	kgCO2/yr

Well to Wheels

Gasoline		
WTT	46,253	kgCO2/yr
TTW	257,194	kgCO2/yr
Total	**303,446**	kgCO2/yr
	30.34464	kgCO2/kgH2
Hydrogen		
WTT	138,183	kgCO2/yr
TTW	0	kgCO2/yr
Total	**138,183**	kgCO2/yr
% Improvement in Vehicle Emissions	54.46	

supported will use 5.3E-6 quads of hydrogen, and save 140 metric tonnes of carbon (MTCe). The future values from the scenario are shown in Figure 4.4 below.

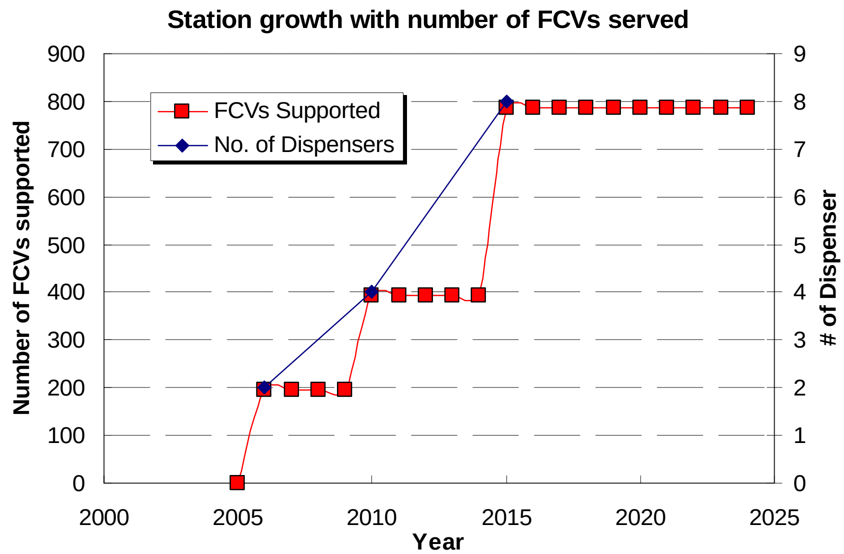


Figure 4.6 Projected station growth scenario.

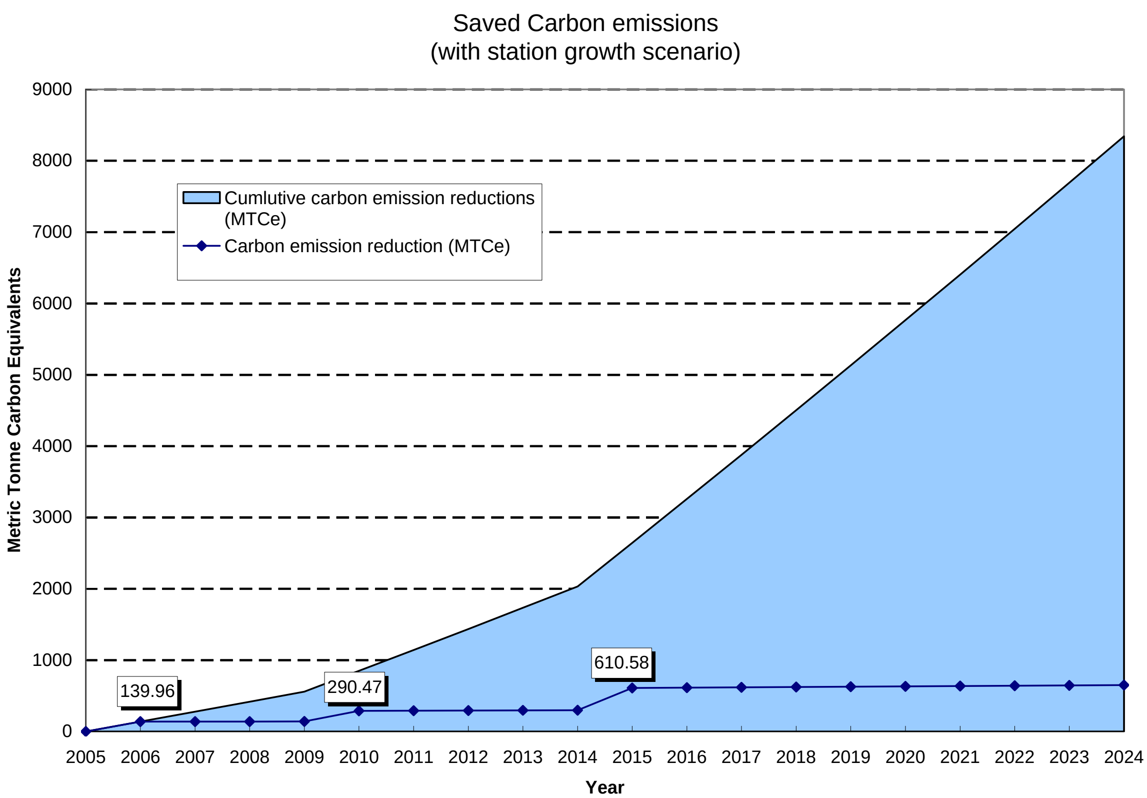


Figure 4.7 Carbon emission savings with station growth scenario.

5. MARKETING

Introduction

Marketing and education is a fundamental component of the EFC's mission to make hydrogen fuel attractive and accessible. ENO's marketing effort aims to attract both drivers of FCVs and the general public. ENO's goal is to bring hydrogen buyers and non-hydrogen buyers to the EFC in order to drive revenue and to heighten awareness of the benefits of hydrogen and FCVs.

The ENO Fueling Center is designed with these goals in mind. Rather than offering a convenience store, the EFC incorporates a small indoor/outdoor café, educational site and communications center. Café patrons can enjoy light food and beverage, and use public internet stations. In addition to serving hydrogen customers, this area attracts members of the general public and provides a familiar environment where they are introduced to the benefits of hydrogen. The center provides visual displays on topics including global warming, criteria air pollutants and associated health issues, FCVs and how they operate, and the generation and use of hydrogen fuel. These displays are integrated into the café, providing non-invasive education for all customers.

The EFC's location in downtown Los Angeles guarantees that the café receives foot traffic from members of the public who work in, live in, or visit the city center. In addition, parking is available for customers that arrive by vehicle but are not refueling.

Objectives

ENO's first marketing objective is to attract users of FCVs to refuel at the station. These consumers generate revenue through hydrogen purchases, and are likely to purchase other items at the café. Assuming commercialization of FCVs has occurred by 2006, this group will include private individuals who have purchased FCVs for personal use, as well as drivers of fleet FCVs. As early adopters of fuel cell technology, these consumers will have a better understanding of fuel cells and hydrogen than the general public. Educational displays will have less impact on these customers, who will be more concerned about the quality and speed of the fueling process.

ENO's second marketing goal is to educate the general public about hydrogen. ENO will show the public that hydrogen fuel is abundant, clean, and safe for use in automotive applications. ENO aims to attract the public to the EFC, where they can participate in monthly tours or view educational displays. Since hydrogen and FCVs essentially work together as a system, some education about FCVs is also appropriate for the public. To teach the public about FCVs, ENO will collaborate with automakers on education and outreach programs.

ENO's general strategy is to encourage both FCV owners and members of the general public to visit the station, since consumers' attitudes toward hydrogen are best changed through direct exposure to the refueling process. Since the most likely visitors are from the region, ENO's marketing effort focuses on the greater Los Angeles area where the station is based.

Marketing Plan

Internet Website with Station Information
ENO will develop and launch a website at www.ENOhydrogen.com. The site will include basic information about the station (location, contact information, hours of operation, etc.) as well as a "Virtual H2 Center" with educational material on hydrogen, hydrogen fueling, and FCVs. The site will also include a schedule of tours and events at the ENO Fueling Center, and will highlight ENO's automotive partners. **Annual Cost: $6,600/yr**

Print Advertisement
ENO has developed an advertising campaign that will attract both hydrogen consumers as well as members of the general public. ENO's "Live Lightly" campaign appeals to a growing desire for greater sustainability in our lifestyle.[65] Children are the center of the advertisement, a reminder that we are environmental caretakers for the next generation. This advertisement will be used in a print advertising campaign that will begin one month prior to the station's opening and last for the first year of the station's operation. Ad placement will occur in regional newspapers, including the *Los Angeles Times*, and special placement will occur on environmental holidays, such as Earth Day (4/22/06). **Annual Cost: $120,000/yr**

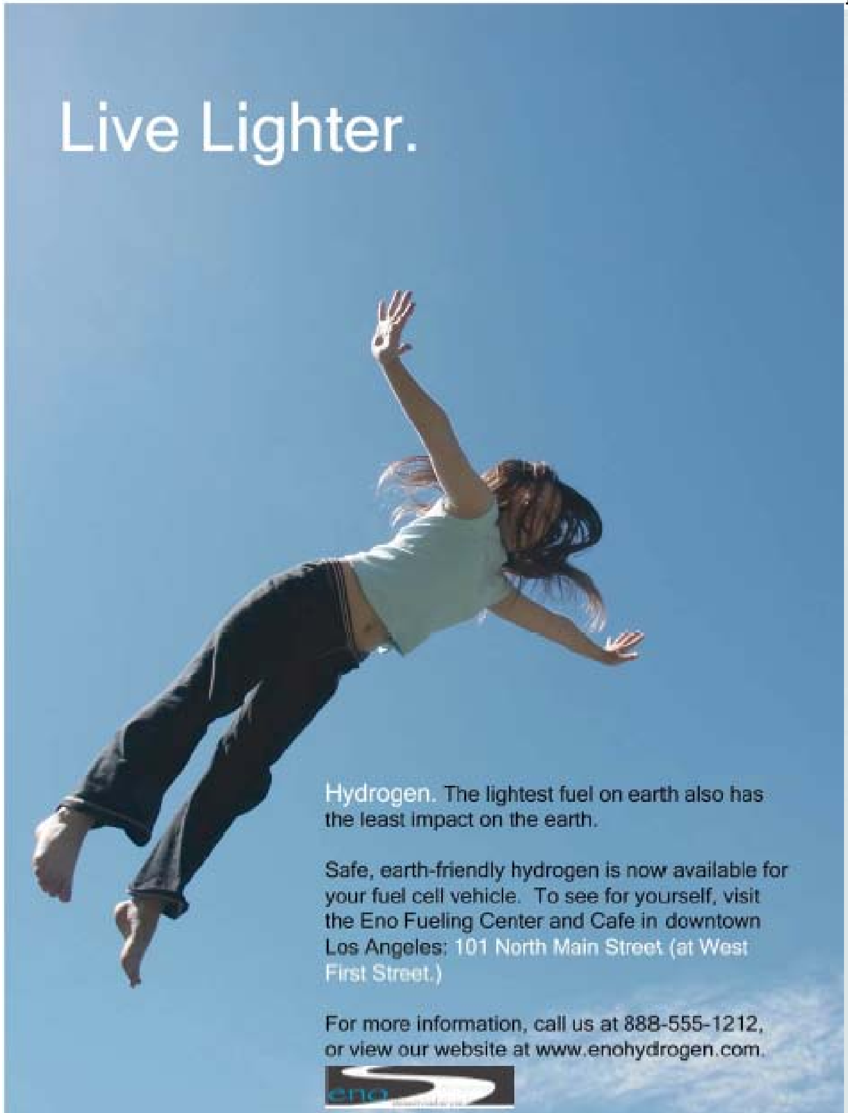
Poster/Flyer
ENO will produce a flyer that will be circulated through auto dealers to buyers of FCVs, through fleet managers to the drivers of fleet vehicles, and to customers of ENO's café. The two-sided flyer will combine a print advertisement and fact sheet. Flyers will provide basic educational information to consumers who are interested in hydrogen and the EFC. **Annual Cost: $1,500/yr**

Onsite Events
Hosted in conjunction with automaker partners, ENO will offer tours of the EFC on the last Saturday of each month. During this time, members of the general public will be invited to tour EFC, guided by engineers who will explain the hydrogen production and fueling process. Automakers will make FCVs available for use by the public, and staff will be present to answer questions. While ENO's main goal is not to sell FCVs, increased adoption of these vehicles will result in higher demand for ENO's hydrogen. Therefore, ENO will partner closely with automakers in education and outreach. Additional advertisements will be placed jointly by ENO and automaker partners. These ads highlight FCVs, but also include information about the EFC. **Annual Cost: $17,760/yr**

Outreach events for Fleet Customers
ENO will sponsor events at companies and agencies that have FCVs in their fleets. These events could include sporting events or fairs and are designed to boost awareness of the ENO brand among users of fleet vehicles. ENO will have a preferred customer program that allows fleets to fill at the EFC and receive reduced rates based on purchase volumes.
Annual Cost: $15,000/yr

[65] According to the Natural Marketing Institute, 62 million adults in the United States compose a demographic group known as "LOHAS", or lifestyles of health and sustainability. These consumers, who spent nearly $226 billion in 2000, have a high social consciousness and prefer environmentally-sound, sustainably-developed goods (2002, "The Lohas Consumer Identified!").

Front side of advertisement:



Back side of advertisement:

PRINT REFERENCES

1. Argonne National Laboratory, (2003) "VISION, Version 2.0."
2. Bossel, Ulf; Eliasson, Baldur; and Gordon Taylor, (2003) "The Future of the Hydrogen Economy: Bright or Bleak?" April 15.
3. California Fuel Cell Partnership, (2002) "Fueling Interface Details Information," August 5.
4. Dynetek, Quotation #Q10424, February 27, 2004.
5. Fueling Technologies, Inc., Quotation Reference # 2004-592, February 20, 2004.
6. Halvorson, T. J.; C.E. Terbot; and M.W. Wisz, (1996) "Hydrogen Production and Fueling System Infrastructure for PEM Fuel Cell-Powered Vehicles," Praxair Inc., Final Report prepared for The Ford Motor Company, Subcontract No. 47-2-R31157, April 12.
7. Hydro-Pac Inc., Proposal # E04-0161, February 25, 2004.
8. InterEnergy and the Gas Technology Institute, (2002) "CASCADE: Environment Friendly Fuels, Version 2.1."
9. L-B-Systemtechnik GmbH, (2002) *GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – A European Study*. September.
10. Myers, Duane B; Ariff, Gregory D.; James, Brian D.; Lettow, John S.; Thomas, C.E. (Sandy); and Reed C. Kuhn, (2002) *Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances.* Directed Technologies, Inc., April, Arlington, Virginia.
11. National Research Council, (2004) "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs," The National Academy Press, Washington D.C.
12. National Fire Protection Association, (1999) *NFPA 50A: Standard for Gaseous Hydrogen Systems at Consumer Sites.*
13. National Fire Protection Association, (2002) *NFPA 70 – National Electrical Code.*
14. Thomas, C.E. (Sandy) et al., (1997) "Hydrogen Infrastructure Report."
15. Thomas, C.E. (Sandy); Reardon, John P.; Lomax, Franklin D Jr.; Pinyan, Jennifer; and Ira F Kuhn, Jr., (2001) "Distributed Hydrogen Fueling Systems Analysis," Proceedings of the 2001 DOE Hydrogen Program Review, NREL/CP-570-30535, Directed Technologies, Arlington, Virginia.
16. TIAX, (2003) *Failure Mode Effects and Analysis for Hydrogen Fueling Station*. CA Energy Commission, Sacramento, CA
17. SFA Pacific, (2003) *Dist Size Onsite Hydrogen via Steam Reformer of Natural Gas With Current Technology – Confidential Third Draft For National Academies.* Model developed for the National Academy of Sciences, June.
18. Swistock, Bryan, and William E. Sharpe, (2004) "Estimating Water Use and Savings in Your Home." Penn State University. http://www.sfr.cas.psu.edu/water/Water%20Audit%20Fact%20Sheet.pdf
19. Weiss, Malcolm A.; Heywood, John B.; Drake, Elisabeth M.; Schafer, Andreas; and Felix F. AuYeung, (2000) *On the Road in 2020 – A Life-Cycle Analysis of New Automobile Technologies.* Energy Laboratory Report # MIT EL 00-003, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, MA, October.
20. (2002) "The Lohas Consumer Identified!" *The LOHAS Journal.* Volume 3, Number 1. Spring.

ENO is very grateful to the following people who shared their valuable time and knowledge with us:

“PERSONAL COMMUNICATION” REFERENCES

1. Aaron Rachlin, Praxair, February 2004
2. Bill Liss, Gas Technology Institute, February 2004
3. Bob Boyd, BOC, February 2004
4. Charles P. Hoes, Hoes Engineering, Inc., February 2004
5. Daniel Sioui, HyRadix, February 2004
6. Dave Warren, Harvest Energy Technology, February 2004
7. Jesse Schnieder, DCX, February 2004
8. John Williams, Quantum, February 2004
9. Lee Coleman, Pressure Products Industries, Inc., February 2004
10. Lisa Iancin, friend, December 2003
11. Maura Winkworth, friend, December 2003
12. Osama Al-Qasem, PDC Compressors, February 2004
13. Sandy Thomas, H2Gen, February 2004
14. Stefan Unnasch, TIAX, February 2004
15. Tony Estrada, PG&E, February 2004

OTHER ACKNOWLEDGEMENTS

1. Joan Ogden- Team Advisor
2. Adam Gromis, California Fuel Cell Partnership
3. Alan Jones, Nissan
4. Bill Crilly, Stuart Energy
5. Bryan Pritchard, J. Fried and Associates
6. Cynthia Verdugo-Peralta, South Coast Air Quality Management District
7. Darren Sokoloski, General Hydrogen Corp.
8. Dave McCarthy, Air Products
9. Don Alessi, Ballard Power Systems
10. Don Fraser, Dynetek
11. Ed Danieli, Praxair Inc.
12. Gabriel Weinert, UCLA Anderson School of Business & Administration
13. Gary Dixon, South Coast Air Quality Management District
14. Jack Johnston, ExxonMobil
15. Jim Guertin, Select Energy
16. Karl Hartman, UC Davis
17. Kyo Hattori, Toyota
18. Lance Atkins, Nissan
19. Laura Hornbuckle, UC Davis Campus Fire Prevention Assistant
20. Mark Sulek, Ford Motor Company
21. Matt Solomon, Ford Motor Company
22. Mike McGowan, BOC Gases

23. Patricia Johnson, UC Davis Captain/Designated Fire Marshal
24. Peilin Yang, UC Davis
25. Ramin Yazdani, Yolo County Planning & Public Works Department
26. Rich Kolodziej, Natural Gas Vehicle Coalition
27. Sheral Arbuckle, Ford Motor Company
28. Spencer Quong, Quong and Associates
29. Steven Kim, UC Davis Architects and Engineers, January 2004
30. Thomas Connelly, Hydro-Pac, Inc.
31. Todd Suckow, California Fuel Cell Partnership
32. Tracy Stewart, Fueling Technologies
33. Trevor DeMayo, Chevron Texaco
34. Zubin Canteenwalla, Fueling Technologies

APPENDIX A

CASCADE was used to capture the dynamic interactions between cascade storage banks and verify that tank pressures would remain high enough throughout the day to provide full fills. The equation given in the *Component Descriptions* that was used to size the cascade storage system is based only on the mass of hydrogen stored, and does not consider this dynamic behavior. Given user inputs regarding the vehicle, storage system, and fueling characteristics, CASCADE graphically outputs the relation between banks during the refueling process. Typical inputs used in our trials are shown in the figure below. The total storage volume of the vehicle tank is calculated as follows:

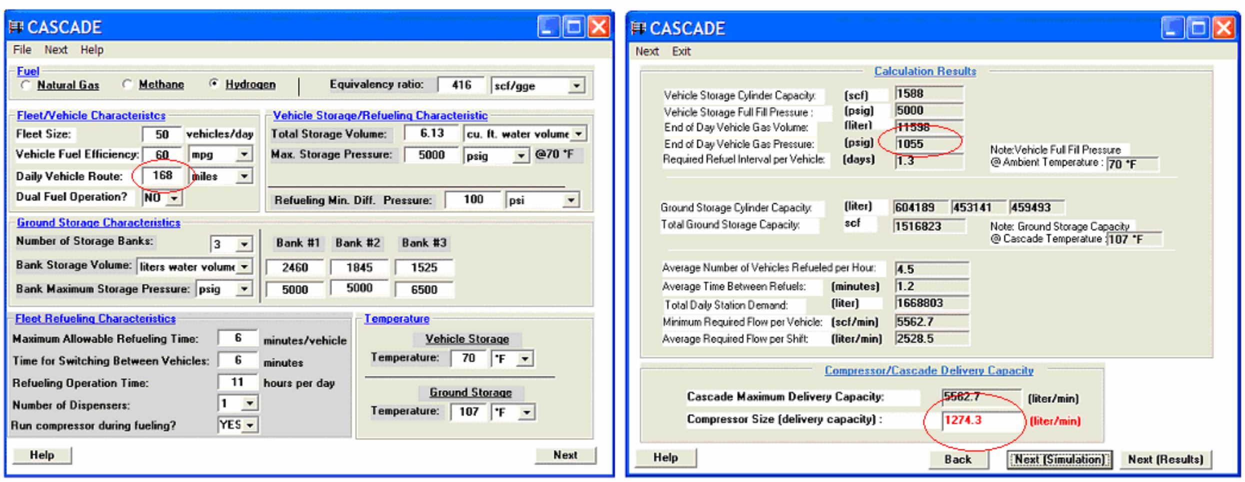
$$Pv = ZRTm$$

$$(34474\text{kPa})v = (1.22)(4.124\frac{\text{kPa}\cdot\text{m}^3}{\text{kg}\cdot\text{K}})(293\text{K})(4\text{kg}) \Rightarrow v = 0.174\,\text{m}^3 = \underline{\underline{6.13\,\text{ft}^3}}$$

Once the volume of the tank has been determined, the "empty" pressure can be calculated similarly, where $(1+6.73\times10^{-6}P)$ solves for Z as a function of the pressure:

$$Pv = ZRTm$$

$$P(0.174\,\text{m}^3) = (1+6.73\times10^{-6}P)(4.124\frac{\text{kPa}\cdot\text{m}^3}{\text{kg}\cdot\text{K}})(293\text{K})(1\text{kg}) \Rightarrow P = 7285\text{kPa} = \underline{\underline{1057\,\text{psi}}}$$

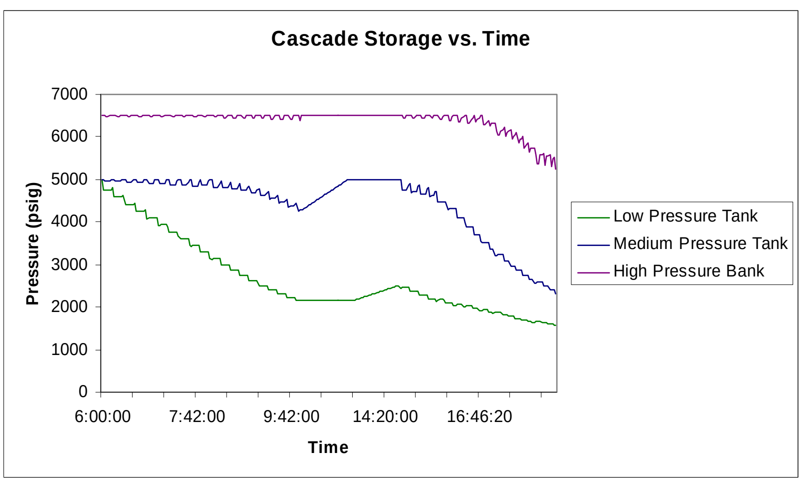


CASCADE calculates the empty pressure of refueling vehicles according to the "Daily Vehicle Route." After calculating the empty pressure of vehicles, we can adjust this parameter to get the proper empty vehicle pressure in CASCADE. Here, a daily vehicle route of 168 miles resulted in an "End of Day Vehicle Gas Pressure" of 1055 psi, which matches our calculated empty pressure value.

We want to simulate the worst case demand scenario in CASCADE to verify our design. This demand comes during the afternoon peak, when storage is already low. A shortcoming of the program is that the simulation can not follow a load profile. We tried to simulate a load profile according to the schedule below. We assumed a full storage system at 6:00 AM, the beginning of the first hour that demand exceeds production. The demand over the next four hours (hours where demand exceeded production) was averaged and simulated in a CASCADE trial. The pressure existing in the tanks after that trial was then input as the bank pressure for the next trial, and so on.[1] From 10:00 to 15:00, demand is less than production, so hydrogen is added to the storage tanks.[2] After those hours of low demand comes the afternoon peak. Each of the four hours where demand exceeds production in the afternoon are simulated.

Time	Demand	Low Pressure	Medium Pressure	High Pressure
6:00	20 vehicles in 4 hours	21,565 scf 5076 psi	16,174 scf 5076 psi	16,206 scf 6500 psi
10:00	5 hours at +1.28 kg/hr	10,613 scf 2200psi	14,630 scf 4482 psi	16,206 scf 6500 psi
15:00	4 vehicles/hr	+2.9 kg 11,926 scf 2500 psi	+3.5 kg 16,174 scf 5076 psi	+0 kg 16,206 scf 6500 psi
16:00	7 vehicles/hr	10605 scf 2193 psi	15286 scf 4723 psi	16227 scf 6500 psi
17:00	6 vehicles/hr	9275 scf 1888 psi	11,545 scf 3367 psi	15,879 scf 6317 psi
18:00	4 vehicles/hr	8251 scf 1659 psi	9362 scf 2640 psi	14,714 scf 5722 psi
19:00		7794 scf 1558 psi	8365 scf 2322 psi	14,154 scf 5446 psi

The results for the entire schedule were adapted from individual CASCADE outputs, and are shown in the figure below. The graph shows that the high pressure storage bank does indeed remain at a high enough pressure throughout the day to top off vehicles. That the assumptions used in reaching this conclusion were conservative adds confidence to the design.



[1] Inputting the lower pressure in subsequent runs introduces a conservative error that underestimates the capacity of our station because the compressor is not able to fill the bank above the new pressure.
[2] Demand is 5.1 kg/hr over that time period, and production is 6.38 kg/hr. So, 1.28 kg is added each hour.

APPENDIX A:
EFC Electrical System

Note: This electrical plan includes the option to place PV panels on top of the fueling canopy

PANELS #	PHOTOVOLTAIC SYSTEM DESCRIPTION	PEAK POWER (W)	I AT PEAK POWER (A)	V AT PEAK POWER (V)	Ish (A)	Voc (V)	TOTAL POWER (W)	TOTAL Ish (A)	TOTAL Voc (V)
1	PHOTOWAT 1000 MODEL1000 FOR 24 V OPERATION	105	3.05	34.6	3.15	43.2			
Row=11 Panels	INDIVIDUAL PANELS IN SERIES						1155	3.15	475.2
Array=8 Rows	ROWS IN PARALLEL						9240	25.2	475.2

SERVICE: 277/480V 3PH
DESIGNATION: PANEL #4 HYDROGEN STATION
LOCATION: MAINTENANCE ROOM

BK #	LOAD LABEL	BREAKER SIZE AMPS/POLES	LOAD kVA	BK #	LOAD LABEL	BREAKER SIZE AMPS/POLES	LOAD kVA
1	REFORMER	60/3	12.5	2	COMP MOTOR1	60/3	36
3	LIGHTS1&2	20/1	0.400	4	COMP MOTOR2	80/3	45
5							
7							
9							
11							

TOTAL= 94 kVA
Iph = 94 kVA/ (480 V*sqrt(3)) = 112 A

GENERAL NOTES:

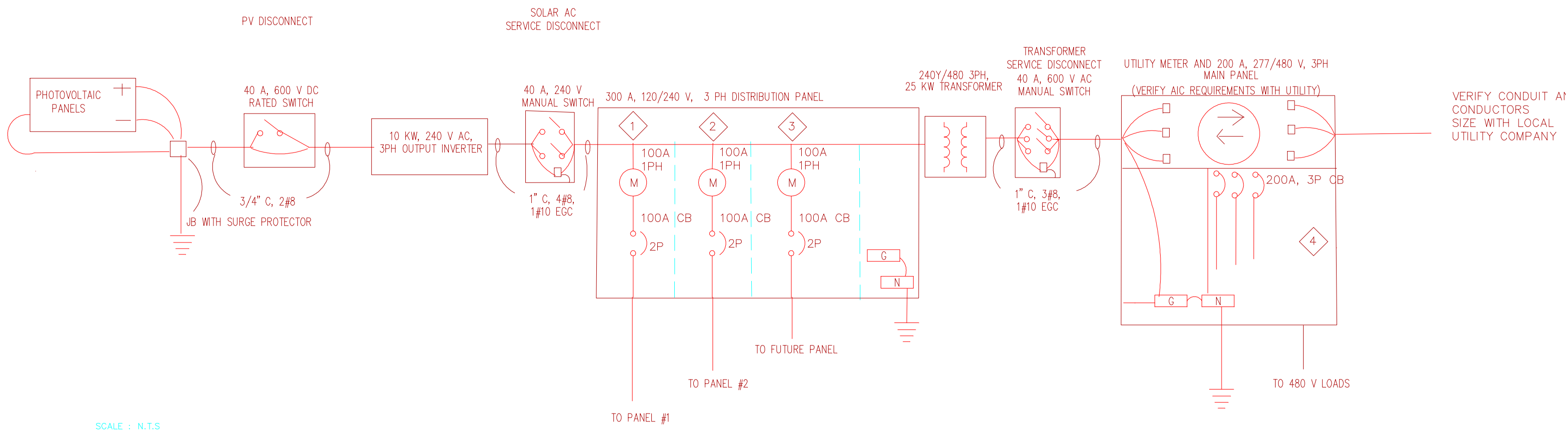
1. CONDUCTORS SHALL BE COPPER THHN.
2. INTERCONNECTING WIRE BETWEEN PHOTOVOLTAIC PANELS AND UP TO THE NEAR JUNCTION BOX SHALL BE OF THE USE-2 #10 TYPE.
3. CONDUIT SHALL BE OF EMT TYPE.
4. ANY EXPOSED EQUIPMENT SHALL BE RATED FOR WET CLASS 1 LOCATIONS.

SCHEMATIC NOTES:

1. DEDICATED TO STATION.
2. DEDICATED TO COFFEE HOUSE.
3. FUTURE CELLULAR PROVIDER.
4. DEDICATED TO 480 V LOADS IN THE HYDROGEN GENERATION STATION. SEE DESCRIPTION OF PANEL #4.

ABBREVIATIONS:

1. EGC = EQUIPMENT GROUNDING CONDUCTOR.
2. GFCI = GROUND FAULT CIRCUIT INTERRUPTOR.
3. JB = JUNCTION BOX



SCALE : N.T.S

ONE LINE DIAGRAM FOR A GRID-CONNECTED PHOTOVOLTAIC SYSTEM ATTACHED TO A HYDROGEN GENERATION/DISTRIBUTION STATION

ENO

COOPERATIVE COMPANY
SPECIALIST IN HYDROGEN FUELING STATIONS

DESIGN ENGINEERING TEAM

University of California, Davis
Element Number One (ENO)

For questions in the drawing, contact:
MARIA C. GONZALEZ

SITE INFORMATION

HYDROGEN FUELING STATION
any place

First Annual University Student Contest
National Hydrogen Association
U.S. Depart. of Energy
Chevron Texaco

TOTAL NUMBER OF PLANS IN PROYECT

2

SHEET ENGINEERING DESIGN TYPE

HYDROGEN GENERATION/ FUELING FACILITY AND COFFEE HOUSE

SHEET TITLE

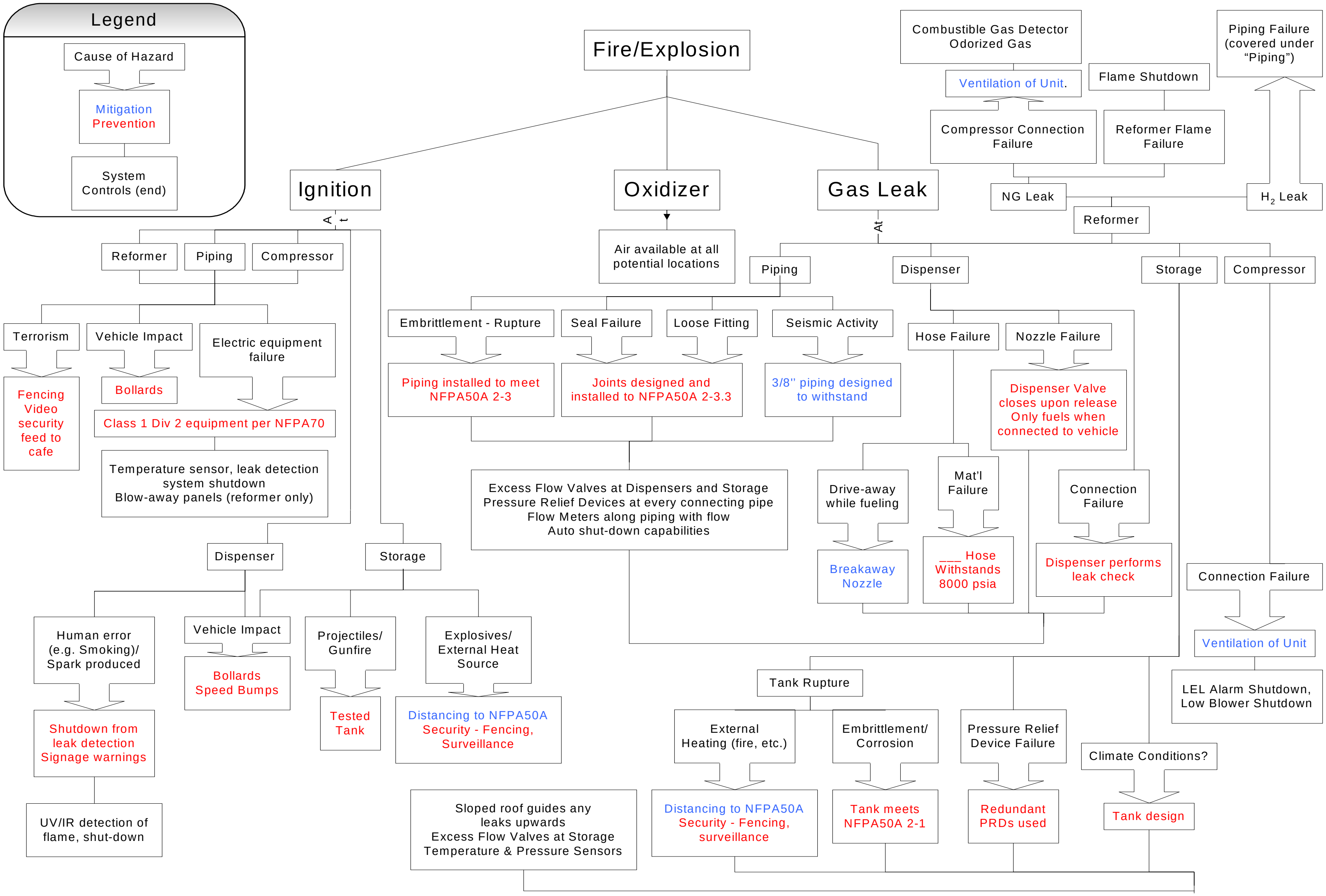
ONE-LINE DIAGRAM

SHEET NUMBER: E-1
REV.: 0

APPENDIX A

Process schematic of the Eno hydrogen fueling system
Cooling water recirculation from 10-ton chiller
Exhaust Stack (CO_2)
REFORMER
Natural gas compressor
Natural Gas (utility)
Burner air blower
Air
Electricity (utility)
Steam Methane Reformer
H2, H2O, and CO
Shift Reactor
H2 (with impurities)
Feed water pump
Water
Reverse osmosis and deionizer water purification
Pressure Swing Adsorbtion
Recycle line
Waste stream
H2, 99.998%, 100 psia
COMPRESSOR
Pulsation Bottle
1st Stage
2nd Stage
3rd Stage
Diaphragm Compressor System:
Supplier: PPI Machines
7.6 kg/hr max capacity
100 psia inlet, 6525 psia outlet
3 stages
PRIORITY SEQUENCING PANEL
CONFIDENTIAL, DO NOT CITE
Low Bank, 5,076 psi
Medium Bank, 5,076 psi
COPYRIGHT© March 3, 2004
High Bank, 6,500 psi
Underground trench through parking lot
Reformer System:
Supplier: Harvest Technologies
153 kg/day capacity
100 psia outlet pressure
99.99% purity
8' x 20' x 8'
Dispenser System:
Supplier: Fueling Technologies Inc.
5000 psia outlet pressure
Hose rated at 6,500 psi
Dispenser
Dispenser
Storage System:
Supplier: Dynetek
148 kg total
5 @ 6,527 psia service pressure (8.9kg/tank)
21 @ 5,076 (4.92kg/tank)
3 bank cascade
Key
Pneumatic control valve
Manual Valve
Check Valve
Pressure Relief Device
Pressure Regulator
Excess Flow Device

APPENDIX B:
Fault Tree Analysis for Hazards at the Eno Fueling Center



APPENDIX C:

Eno Fueling Center Costs, Specficiations, and Assumptions

1. Total capital equipment costs	*$918,796*
2. Total station construction costs	*$493,872*
3. Total non-capital station construction costs	*$551,860*
4. Operating Costs	**$578,936** /yr

Hydrogen Selling Price	**$14.23 /kg**
FCV cost	**$0.237 /mile**
Gasoline Vehicle Cost	**$0.058 /mile**

Key Assumptions			Source	Notes
				orange font items are estimates based on engineering judgement
Station type	On-site reformation			
product usage pattern	50	cars/day		
FCV mileage	60	miles/kg		
Average vehicle refuel	3	kg		
Average production capacity	150	kg/day		
annual hydrogen production	54,750	kg'/yr		
design peak flow rate	20	kg/hr		
natural gas cost (commercial)	$ 8.33	/MCF	EIA, Commercial rate, CA	
electricity cost (commercial)	$ 0.083	/kWh	EIA, Commercial rate, CA	weighted average of peak and off-peak rate
electricity cost (on-peak)) ($/kWh)		get from Tony		
Power demand charge	$15	/kW/mor	LADWP	
water cost	$0.00550	/L	LADWP	
Total station real estate size	14400	ft^2		= 120' x 120'
interest rate	10%			
Taxes, insurance, and legal fees	5%	of total cost		
lease rate	$52	/ft^2	Gabe Weinert, UCLA Bus	=4.5 * land rent rate
land rent rate (Downtown Los Angeles)	$6	/ft^2/yr	Gabe Weinert, UCLA Business school	
Station manager wage (incl overhead, workers comp)	$ 16.00	/hr		Oversees station and calls maintenance if equipment problems occur
Hours of operation	16	hrs		
days/wk	7	days/wk		

1. Capital Equipment Costs	**Our Station**	**Suppliers or Reports…**		
	Harvest	H2Gen	Simbeck and Chang	HyRadix
Natural gas reformer (includes purification)	**$299,700**	$ 280,000	$ 299,700	
avg production capacity	150 kg/day	113 kg/day	$ 1,998 /kg/day	50 or 100 Nm^
or	18 GJ/day		based on 1000 kg/day	
type (SMR, ATR, Pox)	SMR	SMR		ATR
avg power requirement	19.9 kW	15 kW		
electricity consumption	174,425 kWh			
voltage	460 VAC	460 VAC, 3 phase		
water consumption	675 L/day	2.4 L/min		
Natural Gas consumption	25.7 GJ/day			
or	*28.6* MCF/day			
operating pressure	120 psig			
inlet state	5 psig	5 psia (line)		7 bar
outlet state	132 psia	132 psia (line)		
weight				
footprint	8' W x 20' L x 8' H	6'6" w x 7'10" L x 6'11" H		2.3m x 6.0m x 2.4
lifetime	10 yrs			10 yrs
purity	99.99%	99.95-99.999%		up to 99.999%
efficiency (%)	0.7	69% LHV		
Equipment included in cost estimate	PSA	PSA		
vent gas		with all applicable EPA standards		
notes	Harvest builds their units to suit the specs of the customer. Catalysts need to be replaced after 3-5	The HGM safety system meets or exceeds the requirements of all applicable national and international codes, facilitating permitting and siting.		
	Harvest	Questair	Thomas, DTI 2002	
Purification	included in Reformer costs		$26,738	
purity requirement (% pure H2) or standard	99.95-99.999%	99.999%	100%	
Technology (PSA, other)	PSA	PSA	PSA	
Capacity (kg/hr)	150 kg/day	250 Nm^3/hr	115 kg/day	
cycle time			2.16 min	
CO concentration	5 ppm		10 ppm	
S concentration			0 ppm	
H20 concentration			0 ppm	
efficiency (%) (H2 recovery)			75%	
model		H-3200		
	PPI	PDC Machines	HydroPac	Simbeck and Ch
Compressor/Pump	**$ 195,000**	125,000	$119,000	$ 3,000 /kW
stages or boost time (min)	3 stages	2 stages	3	
capacity (kg/hr)	7.6 kg/hr	7.6 kg/hr	6.5 kg/hr	
peak flow (kg/hr)	9.9 kg/hr			
peak power	67.0 kW	67.3	44.76 kW	
load factor	50%	50	50%	
avg power (kW)	33.5 kW	33.65 kW		
electricity consumption	293,460 kWh/yr			

APPENDIX C:
Eno Fueling Center Costs, Specficiations, and Assumptions

type (recip, screw, diaphragm)	diaphragm	diaphragm		
speed	350 rpm	400 rpm		
inlet state (gaseous, liquid)	100 psia	100 psi	100-120 psi	
outlet state	6250 psi	6250 psi	7000 psi	
compression ratio	3.8:1			
production volume (units/year)				
oil contamination	zero ppm	zero	zero	
footprint	(+3' clearance)	84 1/4" x 96" x 72"	inches	
weight	11000 lbs	9000 lbs max		
Equipment included in cost estimate			two compressors	
model	BA/PDC4-3500	GD-5-1000-6500		
	Dynetek	**Quantum**	**FIBA**	**Simbeck and Ch**
Storage System	**$247,964**	$55,000	$55,000	**$310,380** or
location/configuration (ground level, above, below)	ground	ground	ground	$ 2,100 /kg
storage state (liquid, gaseous, chemical)	gaseous	gaseous	gaseous	
tank material (composite, steel, cryo, other)	composite	TriShield Composite	steel	
pressure (service)	6,500 psia	5000 psi	5000 psi	
operation type (boost, cascade)	cascade	50 kg	50 kg	
Capacity	147.8 kg			
weight				
Volume	m^3			
Cascades (#)	3			
tanks (#)	26			
production volume (units/year)			3.684031499	
Equipment included in cost estimate				
service life		15 years		
notes				
Equipment included in cost estimate				
	Fueling Technologies	**Simbeck and Chang**	**General Hydrogen**	
Dispenser	**$83,000**	$ 15,000 /dispenser		
# of single hose dispensers	2	*(for 150 kg/day production)*		
outlet pressure	5000 psig			
max capacity (kg/min)	20 kg/min			
model	H131229			
Electrical Equipment	**$38,632**	**LAX station, Stuart**		
Power cable, control & communications wiring	$10,000			
Transformer	included in electricity rate			
controls	$15,000	$15,000		
SCADA	$1,000			
DISPLAY	$1,000			
Electrical modification	$5,000	$20,000		
Lighting	$6,632	$4,500		
avg power (kW)	1.7 kW			
electricity consumption	14,892 kWh/yr			
Safety Equipment	**$17,500**	**LAX station, Stuart**	**CaFCP, Todd Suckow**	
Hydrogen sensors (2)	$2,000		$1,000 /sensor	
Hydrogen sensor controls	$3,500		$3,500 /control box	
Bollards	$5,000	$5,000		
Fencing/Security	included in station constr.	$20,000		
IR sensors (2)	$4,000			
Video surveillance	$3,000			
avg power (kW)	1 kW			
electricity consumption	8,760 kWh/yr			
Miscellaneous Equipment	**$37,000**	**Praxair-BP (LAX station)**		
Anciliary piping, valves, fittings (10,000 psi rated)	included in PPI quote	$27,500		
Buffer tank	$2,000			
Skids (for mounting equipment)	$10,000			
Concrete pads	$20,000	$20,000		
Environmental enclosures for equipment	$5,000	$5,000		

O&M Costs		**Praxair-BP (LAX station)**	**ISE Research (Co**	**BOC**	**H2Gen**
Total Maintenance	**$41,000** /yr	$13,000	96000	$40,000	
reformer maintenance	$17,000 /yr			$15,000	$17,000
Storage maintenance	$500 /yr				
compressor maintenance	$10,000 /yr	$2,000 /yr		$15,000	
dispenser maintenance	$2,500 /yr	$2,500 /yr			
tube trailer backup (when H2 equipment fails)	$6,000 /yr	$6,000 /yr			
periodic hydrogen quality inspection	$5,000 /yr				

Total Utility	**$143,860** /yr
Natural gas	$86,870 /yr
Water	$1,355 /yr
Electriciy costs (energy + demand)	$55,634 /yr
Electricity costs (kWh)	*$43,377 /yr*
Electricity demand costs (kW)	*$12,257 /yr*
with	

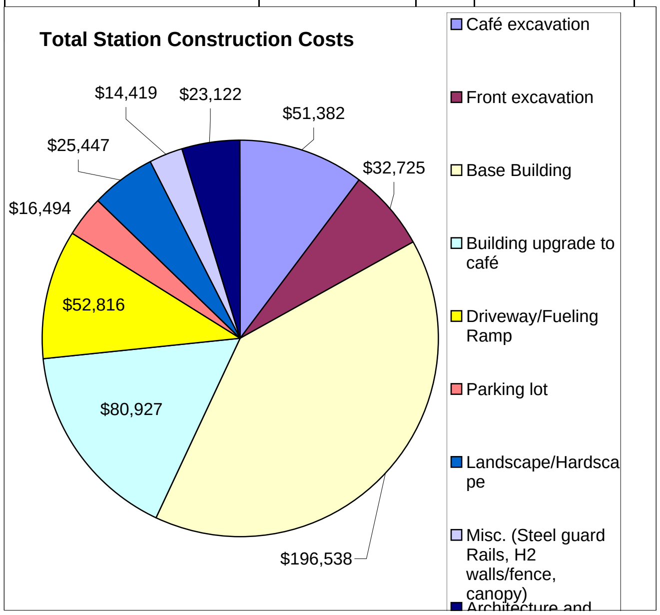
APPENDIX C:
Eno Fueling Center Costs, Specficiations, and Assumptions

total electricity consumption	520,737	kWh/yr			
total power demand	66				
Real Estate	**$86,400**	**/yr**	$7,200 /month		
Labor (full-service fueling)	**$93,184**	**/yr**			
					BOC
Insurance, legal fees, & property taxes	**$70,633**	**/yr**	= TILR x total capital invested		$500,000
Station Construction Costs	**$493,872**		**Bryan Pritchard, Construction Associate, J Fried and Associates,**		Mr. Glanville, Architect
Café excavation	$51,382		$51,382		
Front excavation	$32,725		$32,725		
Base Building	$196,538		$196,538		
Building upgrade to café	$80,927		$80,927		
Driveway/Fueling Ramp	$52,816		$52,816		
Parking lot	$16,494		$16,494		
Landscape/Hardscape	$25,447		$25,447		
Misc. (Steel guard Rails, H2 walls/fence, canopy)	$14,419				14419
Architecture and engineering	$23,122		$23,122		
Assuming					
General facility power demand (lighting, signage, etc	5	kW			
Cafe power demand (avg)	5	kW			
café electricity usage	29,200	kWh/yr			
café natural gas consumption (negligible for LA)	negligible				
Non-Capital Station Construction Costs			**Praxair-BP (LAX station)**	**BOC**	**ISE Research (Coachella Valley station)**
Engineering (incl proj. mgt. & design)	**$130,000**				
Project management	$80,000		$82,111		
Design & estimation of system performance	$50,000		$67,600		$43,540 includes permitting
Permitting	**$30,000**		$10,000	$30,000	
Site Development	**$50,000**		$49,900		$71,626 as of 12/03
Civil Site Preparation (includes excavation, footings)					
Excavation					
Civil trenching					
Form, Pour and Cure equipment pads					
Conduit Trenching/ Install Electric Service					
Install below grade piping					
Safety and Haz-ops Analysis	**$30,000**		$30,000		
Equipment Delivery	**$22,000**				
shipping costs	$9,000		$12,000		
product receival and inspection	$5,000				
Crane rental	$6,000				
Acquire third party certification and local AHJ approval	$2,000				
Installation	**$98,000**		$107,200		86855 as of 12/03
Set/mount equipment	$12,000				
Backfill trench	$12,000				
Install above-grade piping/tubing	$12,000				
Install power cable, control & communications wiring	$12,000				
contractor labor	$50,000		$50,000		
Start-up & Comissioning	**$31,000**		$47,600		17847 as of 12/03
fueling	$10,000				
Test wiring and communication	$5,000				
Obtain approval from AHJs	$5,000				
Collect H2 sample and send to lab	$5,000				
Complete station documentation	$2,000				
Training costs for station operation	$4,000		$4,000		
Marketing	**$160,860**				
Internet Website	$6,600				
Print Advertisements	$120,000				
Poster/Flyer	$1,500				
Onsite Events	$17,760				
Fleet Outreach	15000				

APPENDIX C:
Eno Station Sizing Model

Eno Station Sizing Model

Total Construction Costs	$493,872			
Café excavation	$51,382		CCE	= EX x CEV
Front excavation	$32,725		CFE	= EX x FEV
Base Building	$196,538		CBB	= BB x AC
Building upgrade to café	$80,927		CBU	= SC x AC
Driveway/Fueling Ramp	$52,816		CDF	= DF x (AC +AD)
Parking lot	$16,494		CPL	= PL x AP
Landscape/Hardscape	$25,447		CLH	= LH x AF
Misc. (Steel guard Rails, H2 walls/fence, canopy)	$14,419			= (GRL x CGR) + (CWF x (FL+2xWL)) + CC x (AH + 1/4 x AC)
Architecture and engineering	$23,122		CAE	= AE x AC

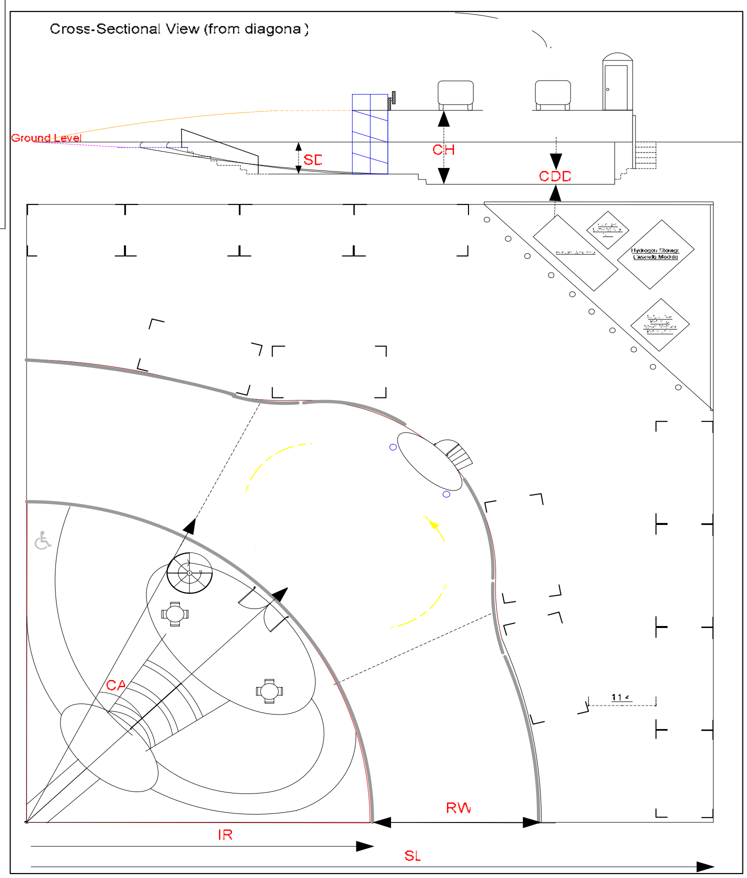


Key Station Variables *(these can be adjusted for different site & station size)*

Inner Radius	60	ft	IR
Site length	120	ft	SL
Site depth	6	ft	SD
Café height	14	ft	CH
Café depth differential	2	ft	CDD
Theta (angle between cafe side wall and midline, using station	18.4	o	CA
H2 equipment wall length	42	ft	WL
Ramp width	30	ft	RW

Site Parameters (calculated)

Outer Radius	90	ft	OR	= IR + RW
Area of café	2,312	ft^2	AC	=[Pi * (2*CA/360) * (OR^2 - IR^2)] + [IR/3 x (PI() x 2 x OR x (CA x 1.5/360)
Area of driveway	2,089	ft^2	AD	= Pi x [90-(2 x CA)/360] x (OR^2 - IR^2)
Area of parking area in rear	7,171	ft^2	AP	={ SL^2 - [Pi x (90/360) x OR^2]} - [IR/3 x (PI() x 2 x OR x (CA x 1.5/360)
Area of front commons	2,827	ft^2	AF	= Pi x (90/360) x IR^2
Total area	**14,400**	ft^2	AT	= SL^2
Area of H2 equipment room	882	ft^2	AH	= 1/2 x WL^2
Parking entrance road width	30	ft	PE	= SL - (IR + RW)
Length of fueling ramp incline	34.8	ft	FRL	= 2 x Pi x [(45-CA)/360] x [IR+ (RW/2)]
Fueling ramp max height	6.0	ft	FH	= CH - CDD - SD
Fueling ramp grade	**17.2%**		GFR	= FH x 100 / FRL
Length of pedestrian ramp	235.6	ft	PRL	= 2 x Pi x (IR x 5/6) x 3/4
Pedestrian ramp grade	**2.5%**		GPR	= SD x 100 / FPRL
Length of guard rails	236	ft	GRL	= 2 x Pi x (IR + OR)/4
Length of H2 equipment area fence	59	ft	FL	= (2 x WL^2)^(1/2)

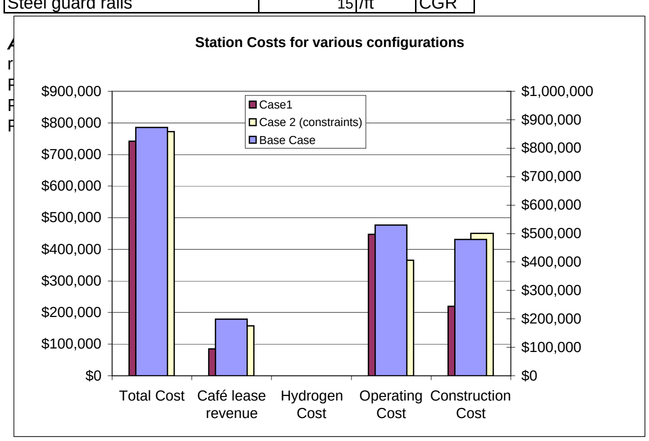


Excavation Calculations

Café excavation area	2,312	ft^2		= AC
café excavation depth	8	ft	CED	= SD + CDD
Café excavation volume	**18,498**	ft^3	CEV	= CED x CEA
Front excavation area (approxim	1963	ft^2	FEA	= Pi * [(IR*5/6)/2]^2
front excavation depth	6	ft		= SD
Front excavation volume	**11,781**	ft^3	FEV	= FEA x SD

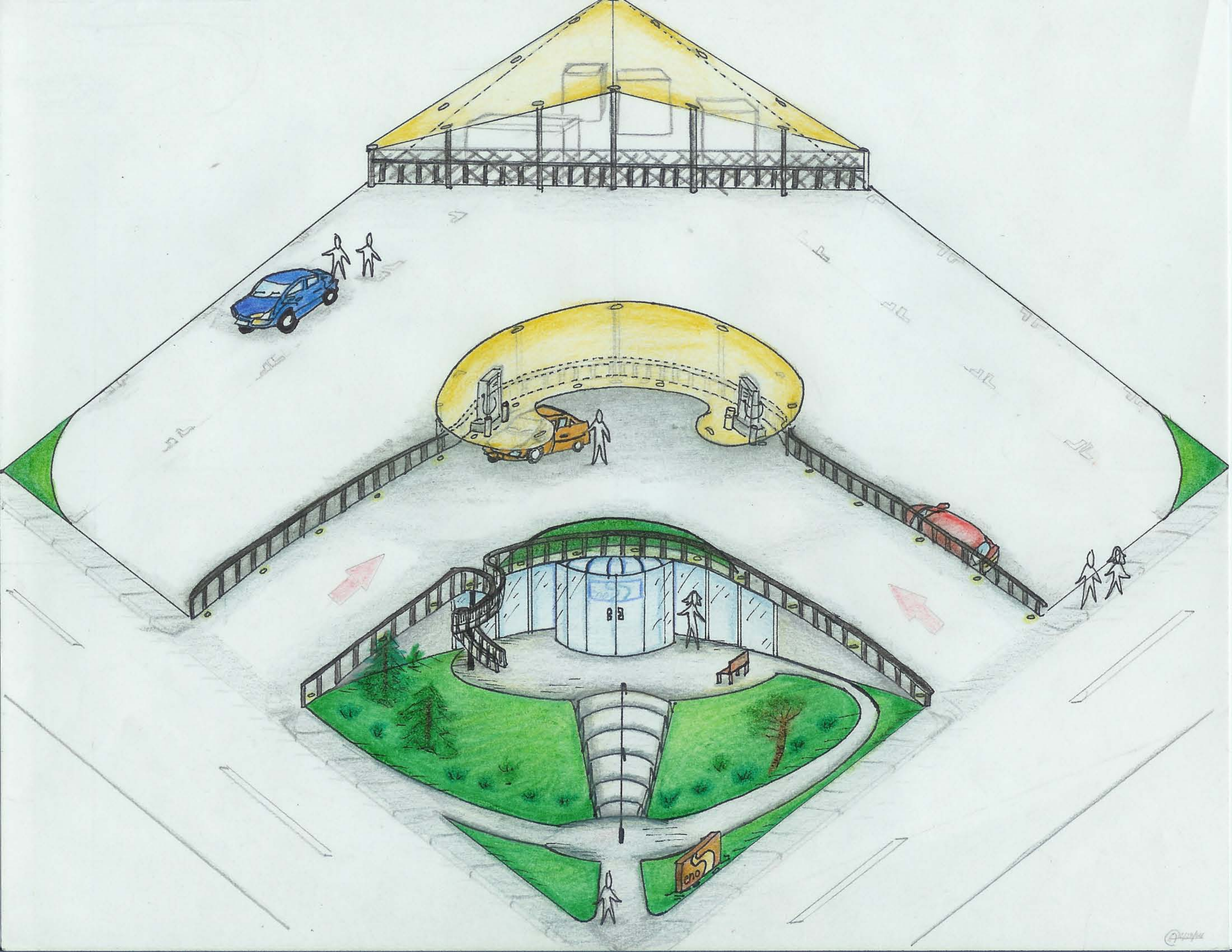
Construction Assumptions

Base Building (reinforced)	$85	/ft^2	BB
Base building upgrade (to café)	$35	/ft^2	SC
Driveway/Fueling Ramp	$12	/ft^2	DF
Landscape/Hardscape allowance	$9	/ft^2	LH
Parking lot	$2.30	/ft^2	PL
Architecture and engineering	10	/ft^2	AE
Excavating	$2.78	/ft^3	EX
Walls/fences	25	/ft	CWF
canopy costs	5	/ft^2	CC
Steel guard rails	15	/ft	CGR



Results from Site Layout Model

	Base Case	Case1	Case 2 (constraints)
Total Cost	$872,690	$742,209	$772,571
Café lease revenue	$198,850	$85,016	$158,129
Hydrogen Cost	$12.3	$12.0	$11.2
Operating Cost	$529,499	$447,202	$365,147
Construction Cost	$479,452	$219,510	$450,568
Inner Radius	60	40	40 ft
Site length	120	90	88 ft


eno