Design Proposal
for a
Mobile Hydrogen Fueling Station

HYDROGEN STUDENT DESIGN CONTEST 2014

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EXECUTIVE SUMMARY

The objective of Ideal Gas Station design is to establish a safe, adaptable, and affordable hydrogen fueling station that allows for rapid development of hydrogen fuel infrastructure while minimizing the risk to the investor. These pre-fabricated fueling stations will be available for delivery to candidate sites in order to facilitate market demand for hydrogen fuel. The success of these stations will build confidence in the hydrogen vehicle market for both consumers and investors, encouraging the development of more permanent infrastructure while also promoting the production and retrofit of more hydrogen fueled vehicles.

The station is housed in a 40 ft shipping container and is designed to receive deliveries of hydrogen fuel approximately every three days, eliminating the need for on-site hydrogen generation. An electrolyzer was considered for this system, but ultimately rejected due to cost and system complications. Delivery allows for specialization within the hydrogen fuel market, enabling investors to focus on hydrogen production, hydrogen transportation, and hydrogen vending independently.

A two-stage compression system and buffer tank with an overall 20 bar minimum inlet pressure is utilized to move the gas from the on-site tube trailer to the high pressure cascade storage system. The compression system will move the 200 bar delivered hydrogen into the cascade storage system of up to 900 bar. A cascade storage system will hold the pressurized hydrogen gas in 9 tanks: three each at 900 bar, 650 bar, and 400 bar pressures. A cascade storage system was selected because it minimizes the required compression pressures, compression time, and overall system costs by avoiding the costs of purchasing all high pressure storage tanks.

Cooling of the compressed hydrogen will occur in two stages: the first stage occurs in an isolated cooling box houses the storage tanks and can reach -10°C, and the second occurs as instantaneous cooling in-line with a heat exchanger on the dispensing side of the storage system. The second stage cools the gas down to -40°C so as to ensure that the temperature of vehicle’s hydrogen tank during fast fill does not exceed 85°C. In order to maintain the 700 bar dispensing pressure, an additional booster compressor is utilized in case the pressure of the storage system drops below the minimum required to meet the 1kg/min dispensing time.

The capital cost of the Ideal Gas Station is estimated to be $980,000. Assuming a 100 kg/day demand, the annual operating cost and revenue is estimated to be $286,000, and $340,500, respectively. The revenue is based on renting digital advertisement space as well as a selling the hydrogen fuel at $9/kg. Under these assumptions, the Ideal Gas Station is estimate to have a discounted payback period of 5.9 years, and a net present value at the end of a 10 year planning horizon of $1.5M. An economy of scale analysis indicates that for the capital cost for the 5th, 100th, and 500th station produced will cost an estimated $745,000, $542,000, and $457,000 respectively.

An environmental analysis of the Ideal Gas Station indicates that the station is will produce about 65 dBA at 1 m to the surrounding area. Further, by choosing to have the hydrogen delivered, the total emissions associated with the station is estimated to be 322 tons CO₂ per year, 225 tons NOx per year and 64 tons of Sox per year.
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1 INTRODUCTION

In order to facilitate the rapid development of the hydrogen fueling infrastructure, low-cost, portable, and stand-alone fueling stations are needed across the country. To solve this problem, Humboldt Hydrogen Solutions presents the Ideal Gas Station, a standardized model that can be mass-produced and quickly implemented.

The objective of this design is to develop a safe, adaptable, and affordable hydrogen fueling station that allows for rapid development of hydrogen fuel infrastructure while minimizing the risk to the investor. These pre-fabricated fueling stations will be available for delivery to candidate sites in order to facilitate market demand for hydrogen fuel. The success of these stations will build confidence in the hydrogen vehicle market for both consumers and investors, encouraging the development of more permanent infrastructure while also promoting the production and retrofit of more hydrogen fueled vehicles.

The station is designed to receive deliveries of hydrogen fuel, eliminating the need for on-site hydrogen generation. An electrolyzer was considered for this system, but ultimately rejected due to cost and system complications. Delivery allows for specialization within the hydrogen fuel market, enabling investors to focus on hydrogen production, hydrogen transportation, and hydrogen vending independently.

The Ideal Gas Station will store the bulk of its hydrogen in an onsite compressed hydrogen tube trailer. The housing is a forty foot shipping container chosen for its high mobility. To address the need for a five minute fueling time, the Ideal Gas Station utilizes a cascade storage system with a booster compressor. The cascade storage system quickly and efficiently delivers the gas to the dispenser. In the absence of enough high pressure hydrogen to complete a fill, the booster compressor will be employed to quickly bring the hydrogen up to 700 bar in line with the dispenser.

2 SYSTEM DESIGN

2.1 Overview

The proposed design is a safe, low cost, modular, drop-in hydrogen fueling station that could be installed in one location to increase confidence in the hydrogen fuel market, or in hundreds of locations to quickly generate a grid of hydrogen refueling stations.

The station is designed to receive a hydrogen gas delivery approximately every three days. A delivery truck will drop off a compressed hydrogen gas tube trailer. A two stage compression system, compressing moves the gas from the on-site tube trailer to the high pressure cascade storage system.

The gas will be drawn from the high pressure tanks by the programmable logic controller for a to meet the required fueling time, delivering a final pressure of 700 bar to the consumer’s on-board tanks (Figure 1). The gas will be cooled to -40 °C upon dispensing by a two-stage cascade cooling system. A programmable logic controller (PLC) system will open and close valves throughout the system to optimally manage storage, compression, and delivery temperatures as well as relay necessary information to the remote monitoring station.

The station will be housed in a converted forty foot shipping container. A shipping container was chosen for this design because it fully encloses the station, thereby permitting the station to be
easily transported. The interior station components will be bolted to the container to allow for transportability without incurring damage due to shipping. The dispensing unit will be attached such that the outside of the unit is flush with the edge of the trailer, eliminating a potentially awkward protrusion. The existing ground must be torn up, then electricity inputs and an earthquake-safe foundation installed. The fueling station will be transported on a truck, then moved from the truck to the prepared site with a crane. Security cameras and lights will then be mounted on the station. Finally the station will be surrounded by bollards and a fence. After the initial system compression is finished, the station will then be operational.

The hydrogen will be delivered in a 200 bar tube trailer. When the tube trailer pressure sensor detects a sufficiently low trailer pressure, the telecommunications equipment will contact the hydrogen delivery service.

The delivery service will send a driver with another tube trailer to deposit the full tube trailer, and then retrieve the empty tube trailer. The tube delivery driver will disconnect the empty tube trailer from the station using a shutoff valve, safely connect the full tube trailer manifold to the appropriate station inlet, than release that shutoff valve. The truck will then take the empty trailer back to the production facility.

![Figure 1: Process flow diagram of the key components of the Ideal Gas Station.](Image)

### 2.2 Storage and Compression

Before the gas is dispensed, it is compressed from the trailer to a cascade storage system at -10°C, then cooled to -40°C from the high pressure tank to the car tank (Schneider 2013).

#### 2.2.1 On-Site Tube Trailer

The bulk of the hydrogen will be stored in the delivered tube trailer at 200 bar. The tube trailer has the capacity to store 300 kg of hydrogen in six 50-kg tanks and is forty feet long (Highlands & Islands Enterprise Renewable Energy 2006). Using the Van Der Waals equation, the volume of these tanks have been calculated to be 21,020 L.

The tube trailer will be delivered by truck. The driver will place the full trailer next to the empty trailer, then connect the manifold system connection to the tube trailer tanks. Then the truck driver will haul the empty tank away.
When an internal pressure sensor senses that the tube trailer’s pressure has dropped below a threshold of 150 bar, a signal will be sent to the telecommunications unit indicating the threshold value has been reached. At this point, there will be enough gas to accommodate a 48-hour fuel delivery shut-down assuming a daily hydrogen demand of 100 kg. The telecommunication module will then notify the hydrogen production facility, requesting a tank swap two days after the threshold pressure has been reached.

### 2.2.2 Two-Stage Compression System

The motivation behind the two-stage compression system is that the recommended high pressure compressor has a minimum inlet pressure of 103 bar. If the system only used a high pressure compressor to move gas from the tube trailer to the cascade storage system, once the pressure of the tube trailer dropped below 103 bar the remaining hydrogen gas in the tube trailer tanks would remain inaccessible. As a result, only 134 kg of the 300 kg tube trailer would be dispensable, which would leave 55% of the fuel inaccessible.

Mitigation of the high inlet pressure for the higher pressure compressor was achieved by using a compressor with a low inlet pressure of 20 bar, followed by a buffer tank and the high pressure compressor, thereby achieving the high pressure required for dispensing (Figure 2). Initially, all the fuel will be extracted from the tube trailer using the high pressure compressor. Once the pressure of the tube trailer drops below threshold pressure, the low pressure compressor will take over and compress the fuel into a buffer tank. The advantage of this approach is that it permits increasing the maximum accessible fuel from the tube trailer.

One hundred fifty bar was chosen as the threshold pressure because that is the lowest pressure the compression system will be able to extract 200 additional kilograms of hydrogen from the tank trailer. The volume of the tube trailer has been calculated as 21020 L using the Van Der Waals non-ideal gas relationship. The mass of hydrogen in the tank at the low compressor minimum inlet pressure of 20 bar was calculated as 34 kg. This mass represents the hydrogen that will not be accessed by the compression system, and will be transported to back to the hydrogen production facility in the “empty” compressed tank trailer. Thus, under this scenario the maximum amount of fuel that can be extracted from the tube trailer is 266 kg, or 89% of the fuel. Adding 200 kg to the amount of inaccessible fuel mass (34 kg) represents the mass of hydrogen in the trailer at the desired threshold value. This was calculated to correspond to 150 bar using Van Der Waals relationship. These calculations assume a temperature of 20°C inside the trailer.

![Two-stage compression process](image)

**Figure 2:** Two-stage compression process required to extract a maximum of 89% of the hydrogen from the tube trailer.

#### 2.2.2.1 Low Pressure Compressor

When drawing hydrogen from the tube trailer, the hydrogen will be compressed by a low pressure compressor when the pressure in the tube trailer drops below 150 bar. This compressor
is manufactured by RIX Industries, has the capability to intake hydrogen at pressures as low as 20 bar, and to compress it to 150 bar, which is well above the minimum inlet pressure for the high pressure compressor. The hydrogen compressed by the low pressure compressor will be fed to an intermediate buffer storage tank, which is connected to the high pressure compressor to bring the hydrogen to the final pressures in the cascade storage system. Utilizing a low pressure compressor will minimize the amount of hydrogen in the tube trailers that cannot be used.

Doug Richmond, sales engineer at RIX industries, quoted a compressor with a 20-bar minimum inlet pressure capable of outputting 120 bar at a flow rate of 26 kilograms per hour. The recommended model is the 4VX-2BG. He also estimated the size of the unit as 1.3 x 2.0 x 1.3 m, and weighing at about 1360 kg (Personal Communication, March 19 2014).

### 2.2.2.2 High Pressure Compressor
To compress the hydrogen to the final fueling pressure of 700 bar, the fueling station will use a single stage diaphragm compressor. The recommended model is the PDC-4-12000 manufactured by PDC Machines, Inc. This model is designed with an inlet pressure ranging from 103 to 517 bar and an outlet pressure of up to 900 bar (PDC Machines, 2004). At an inlet pressure of 200 bar from the tube trailer or the buffer tank, the compressor will be able to handle a flow rate of hydrogen at about 31 scfm (PDC Machines 2014). At this designated load, the energy usage of the compressor is 19.5 kW (PDC Machines 2014).

### 2.2.3 Cascade Storage System
The cascade system has 9 tanks: three each at 900 bar, 650 bar, and 400 bar pressures. These values were selected based on the values in Rothuizen’s Modelica optimization (Rothuizen 2014). The storage tanks will be maintained at a constant temperature of -10°C by the cooling system. The tanks will be located inside a sub-compartment within the container. The compartment will be completely sealed and air-tight. In the event of a leak, hydrogen gas will evacuate through a passive vent in the roof. The compartment will be insulated with 10 cm (4 in) polyurethane providing an R-value of 26.770.

Upon initiation, hydrogen will first be drawn from the low pressure storage until the pressure gradient between the tanks reaches a level where one kilogram per minute is no longer maintained. This was chosen as the cutoff flow rate to maintain sufficient flow rate to fill a five kilogram tank in 5 minutes. Next, dispensing will switch to medium and then high pressure storage using the same strategy until the vehicle tank reaches 700 bar.

The internal storage tanks will be interconnected with a manifold configuration that permits simultaneous compression into and dispensing out of different tanks. These tanks will be monitored and maintained by the PLC and digital pressure gauges utilizing a dynamic compression algorithm. When dispensing switches from a lower pressure to higher pressure tank, compression into the lower pressure tank will initiate.

### 2.2.4 Booster Compressor
A Hydro-Pac single stage diaphragm compressor will act as a backup compressor after cooling the hydrogen to -40°C for two scenarios. The first scenario is that the booster compressor will be available to quickly intensify the pressure of the hydrogen from the storage tanks up to 700 bar in the case of depleted cascade storage units. The booster compressor will be utilized in this capacity if the highest level storage tank is depleted and there is someone waiting to refill. In addition, while cooling, the pressure will drop from the high storage pressure. The booster

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Humboldt Hydrogen Solutions

Ideal Gas Station
compressor can make sure that maximum delivered pressure does not drop below an appropriate
level after cooling it to -40°C.

2.3 Dispensing Unit
In order to dispense the hydrogen fuel, a single Powertech 10,000 psig (700 bar) hydrogen
dispensing unit will be included at the end of the station and made accessible to the consumer.
The dispensing units are converted at Powertech Labs from blank dispensers used for gasoline
fueling, and therefore have many of the same exterior size and interface specifications as
standard gasoline dispensers. In addition, the dispensing unit incorporates safety breakaways, has
a SAE TIR 2799 compliant nozzle, dispenses at a maximum rate of 60 g/s, is SAE TIR J2601
compliant, and can communicate with the station about the tank conditions of appropriately
equipped vehicles (Powertech 2014; Angela Das, personal communication, March 10, 2014).
Hydrogen can be dispensed in less than four minutes at -40°C depending on fuel tank size
(Schneider 2013). An additional unit can be added to provide a second, simultaneous dispensing
source. Point of sale (POS) equipment is included in the Powertech unit, thereby making this unit
more modular than dispensing units that require separate POS equipment.

Humboldt Hydrogen Solutions decided to recommend a Powertech dispenser after considering
alternative dispensers. While Bennett Pumps and Air Products released a high pressure dispenser
to some clients in 2013, the president of Bennett Pumps was reluctant to provide a cost estimate
of a pump. Bob Chase, the senior manager of Bennett Pumps in Ohio, called the president of
Bennett after being pressed for a price. The president relayed back the message that Bennett has
had various difficulties in producing these dispensers, and are still experiencing internal
electronics issues (Personal Communication, March 19 2014).

2.4 Cascade Cooling System
The cooling system for this design provides cooling for system storage, dispensing, compressors,
and the telecommunications module. To meet the dispensing requirements of the system, the
hydrogen fuel must be cooled to a temperature of -40°C (Schneider 2013). This is accomplished
using a cascade cooling system where cooling is performed in medium temperature and low
temperature stages in succession. By connecting two refrigeration systems in series using
differing refrigerants, the low temperature can be affected (Elliot, 2014).

2.4.1 Cooling System Design
The cooling system for the fueling station is a cascade system with two separate temperature
stages, each in a closed loop. The medium temperature stage rejects heat from the hydrogen
storage tanks that are located inside an insulated sub-compartment within the container. The
medium temperature stage also rejects heat from the hydrogen compressors and system
electronics. The low temperature stage, connected in series with the evaporator of the medium
temperature stage, rejects heat from the hydrogen gas as it is dispensed.

2.4.1.1 Medium temperature stage
The medium temperature stage of the cascade cooling system functions using refrigerant R-134a
and Copeland compressor model ZB38KCE-TFE. This stage maintains the cascade storage
system at -10°C. The evaporator for the medium stage is located inside the compartment and is
also the condenser for the low temperature stage via heat exchange.
2.4.1.2 Low temperature stage
The low temperature stage of the cascade cooling system functions using refrigerant R-744 (carbon dioxide) and Copeland compressor model ZOD104KCE-TFE. Using the evaporator from the medium stage provides an appropriate temperature for condensing the carbon dioxide refrigerant. The low temperature stage reaches a temperature of -58°C. This stage rejects heat from the flowing hydrogen fuel before dispensing using a heat exchanger. The heat exchanger used for this process is a counter-flow double pipe, where one pipe is positioned concentrically inside another. This type of heat exchanger is appropriate for systems with high pressures (Saunders, 1988).

2.4.2 System Features
This system has several advantages. In the event of a low stage refrigeration failure, the station can still dispense fuel with an increased fueling time. Given the failure of the low stage, hydrogen could still be dispensed at -10°C. This system uses readily available refrigerants, without the use of proprietary blended refrigerants which are often used in low temperature systems. To maintain the blend ratio, a blended refrigerant would necessitate recharging the entire system in the case of a small leak or failure (ESS 2014). Additionally, R-744 has zero ozone depletion potential and minimal global warming potential (Linde 2014).

According to a sales representative at PDC Machines Inc., the system compressors that we will be using have a temperature operating range of -20°C to 50°C (Personal Communication, 2014). The telecommunications module has an operating range of -20°C to 70°C (Digi, 2014). These system components will be cooled via the medium temperature stage of the cascade cooling system.

To ensure safety, the cooling system will be monitored for refrigerant leaks. System pressures will be relayed to the monitoring station to ensure resolution of a proper service condition. Should the cooling system fail completely, a station shutdown will be enacted.

2.5 Communications
The following section outline the internal communications and control systems as well as the telecommunications modules

2.5.1 Internal Communications and Control
Real-time monitoring and control of the internal components of the hydrogen station will be managed by a Crouzet Millenium 3 (XD26) 240VAC, 60Hz programmable logic controller (PLC). Since the safety of the entire system depends upon the PLC’s automation capabilities, a reliable PLC is paramount to ensuring proper functionality during dangerous scenarios. Communications between the compressors, pressure gages, dispensing equipment, safety equipment, and the cooling system will be managed by the ladder logic of the PLC. The PLC was chosen because of its proven performance. The PLC is certified by the Conformance European, Underwriters Laboratories, Canadians Standards Association, and Germanischer Lloyd, and conforms to applicable International Electrotechnical Commission/European standards (Crouzet, 2014).

The PLC will be used to communicate between pressure gauges, compressors, the COOLING unit and other sensors to ensure safe and efficient operation of the system. The PLC will utilize real-time pressure readings to maintain optimal storage pressures of the storage tanks during delivery, storage, and dispensing of the hydrogen gas. The PLC will also be used to determine the voltage or wattage at various points in the system to confirm proper operation. For example,
if there is a service outage, the controller will engage the backup battery system. Another example is if there is a circuit fault that may result in a fire hazard the controller would engage a series of security protocols such as emergency warning lights and/or sirens, engage fire suppression systems, and relay the fault signal to a third-party.

2.5.2 Telecommunications
Communication between the fueling station and a remote third-party will be accomplished by a cellular-enabled wireless router. The router chosen to accomplish this task is a Digi ConnectPort X4. The router is capable of transmitting over the GSM, CDMA, or WiMAX cellular networks at up to 4G rates (Digi, 2014), which amounts to theoretical transmission at rates of about 1 gigabit/s or 128 megabytes/s (Hwang et al., 2007). The Digi Connect will be used to relay real-time station measurements, usage data, and permit communication between the fueling station and a third-party remote operator. The ConnectPort X4 was chosen because of its high throughput ability, which would be required during audiovisual communications while simultaneously transmitting measurement and usage data.

2.6 Safety Equipment
Safety equipment will be installed in the station in case of disaster. The fire suppression system will include a smoke detector, sprinkler system, and thermocouple heat detectors connected to the telecommunication equipment, ready to call for help in an emergency. There will be a breaker to cut off electrical communication. In the event of the breaker being switched, all valves in the system will close, and the compressor will shut off. LED lights will illuminate the station after sunset, and there will be a seven-camera surveillance system. In the event of an emergency, warning lights and an acoustic alert system will be activated. In the event of a hydrogen leak in the storage compartment, hydrogen gas will escape from a passive vent in the roof.

The surveillance system has one camera mounted to each upper corner of the station, a camera mounted on top of the container between the two dispensers, as well as a camera in each dispenser. These cameras will be linked to the telecommunications units, and the video will be recorded on an external server.

The SBS H2 hydrogen detector complies with IEEE standard 484-2002 National Fire Protection Agency (NFPA) Article 64 and Uniform Building Code (UBC) Section 6400. This unit initiates a warning light and ventilation fan at 1% detection followed by audible alarm and security system notification at 2%. The two highly accurate sensors will adequately monitor the enclosure. Lastly, the system is equipped with dual AC or DC supply leads and battery back-up.

![Figure 3: The hydrogen leak detector required to prevent fires (SBS Battery 2014).](image-url)
The Cease Fire CFF 800 is a waterless fire suppression unit tested and approved for class A, B and C fires. Three of these stand-alone heat activated units shall be mounted to the ceiling along the length of the enclosure. The functionality is not dependent upon a power supply, however the unit can be equipped with a discharge notification signal.

![Cease Fire CFF 800](image)

Figure 4: Carbon dioxide based fire suppression equipment (CeaseFire 2014).

In the case of a power outage, the Ideal Gas Station comes equipped with a back-up battery system. This system will provide enough energy to maintain control/monitoring of the station with the PLC for 24 hours and to immediately signal an on-call worker of the issue via the telecommunications equipment.

3 ECONOMIC ANALYSIS

An economic was performed to determine the discounted payback period and the economy of scale of the Ideal Gas Station. First, the capital, maintenance, and operating costs were analyzed for one station. The minimum price of hydrogen to achieve a 10 year payback period assuming a 5% discount rate. The change in initial cost of the Ideal Gas Station with respect to units produced was then explored.

3.1 Capital Costs

The capital costs of each component of the system were estimated using the best available data. The components of the Ideal Gas Station that had this highest impact on the capital cost included the compressors, the storage tanks, and the dispensing unit (Table 1). Refer to Appendix E for a detailed bill of materials. Assuming that the installation cost is 15% of the capital and a 10% contingency on the capital, the total capital cost was estimated to be $980,000.

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cascade Storage System</td>
<td>$130,000</td>
<td>Weinert et al (2007)</td>
</tr>
<tr>
<td>High Pressure Compressor</td>
<td>$100,000</td>
<td>PDC sales representative</td>
</tr>
<tr>
<td>Booster Compressor</td>
<td>$82,700</td>
<td>Waterloo (2010)</td>
</tr>
<tr>
<td>Low Pressure Compressor</td>
<td>$100,000</td>
<td>Doug Richmond, Sales Engineer, RIX Industries</td>
</tr>
<tr>
<td>Dispenser</td>
<td>$300,000</td>
<td>Angela Das, Project Engineer, Powertech (2014)</td>
</tr>
</tbody>
</table>
3.2 Operating Costs and Revenue
The cost of operating the Ideal Gas Station includes the cost of hydrogen, electricity, tube trailer rental, and routine maintenance (Table 2). The cost of compressed hydrogen gas at 200 bar was assumed to be $7/kg delivered. The UC Berkeley Richmond Fueling Station has a system with similar electric demand as the Ideal Gas Station. Additionally, the Richmond station utilizes tube trailer delivery to obtain the hydrogen. The gas is compressed to either 350 bar or 700 bar, then dispensed at -18°C. The monthly electric use of the station is generally between 2500 and 3000 kilowatt hours. (Lipman et al. 2013). Therefore, a conservative estimate 4000 kWh per month of electricity was assumed for the Ideal Gas Station. Tim Litman, the co-director of the Transportation Sustainability Research center and supervisor of the Richmond station, estimates the cost of renting tube trailers to be $2400 (Personal Communication, March 19 2014). The annual fixed operating costs for maintenance checks and general upkeep of the station is $1,275 assuming 100 kilograms of hydrogen are dispensed daily (Melaina and Penev 2012). Thus, the total operating cost of the Ideal Gas Station comes from the purchase of hydrogen gas.

<table>
<thead>
<tr>
<th>Operating Cost</th>
<th>Unit Cost</th>
<th>Unit Size</th>
<th>Quantity</th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Gas</td>
<td>$7</td>
<td>$/kg</td>
<td>100 kg/day</td>
<td>$255,500</td>
</tr>
<tr>
<td>Electricity</td>
<td>$0.1058</td>
<td>$/kWh</td>
<td>4000 kWh/mo</td>
<td>$423</td>
</tr>
<tr>
<td>Tube Trailer Rental</td>
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<td>$/month</td>
<td>12 mo</td>
<td>$28,800</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$1,275</td>
<td>$/yr</td>
<td>LS</td>
<td>$1,275</td>
</tr>
</tbody>
</table>

**Total Annual Operating Cost**: $286,000

The revenue earned for the station was contingent upon any potential revenue earned from renting advertisement space on the station as well as the fuel price set for the consumer. Advertisement space for the Ideal Gas Station was offered as billboard space on the front of the station as well as digital advertisement space in the user interface. The combined advertisement space was assumed to earn approximately $1,000 per month. An analysis of the optimal fuel price and the discounted payback period is discussed in the next section.

3.3 Price of Hydrogen and Economy of Scale
The payback period for the Ideal Gas Station is heavily dependent on the price at which hydrogen is sold to the consumer. Figure 5 shows the effect of the price of hydrogen on the payback period. A price of $9/kg of hydrogen was decided upon because it would not be price prohibitive to consumers would cause a 5.9 year payback period on the investment, which is well below the maximum desired 10 year payback period.
An economy of scale analysis was performed by evaluating the capital costs of producing and implementing multiple Ideal Gas Stations. The economy of scale analysis was performed using the methods outlined in Melaina and Penev (2013) for early station capital investment requirements.

To perform the economy of scale analysis, an assumption was made that 75% of the capacity of the station will be used. The base station capacity of 250 kg/day is based off of the capacity of State-of-the-Art (SOTA) hydrogen stations, which was determined from NREL’s station types presented in the Hydrogen Station Cost Calculation (HCSS) function (Appendix F) SOTA stations have a hydrogen production of up to 250 kg/day and have the most recent models of components, although they typically do not include novel or demonstration parts not yet tested in the field. The cumulative capacity at cost status of the base station was determined to be 17,000 kg/day, based on NREL’s estimated total installed station capacity of California in 2015 (Melaina and Penev 2013). Based on this function and the given assumptions, Table 3 shows the calculated the capital costs of producing multiple stations.

Table 3: Capital cost based on an economy of scale.

<table>
<thead>
<tr>
<th>Station Produced</th>
<th>Capital Cost of the Station ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>$978,000</td>
</tr>
<tr>
<td>5th</td>
<td>$745,000</td>
</tr>
<tr>
<td>100th</td>
<td>$542,000</td>
</tr>
<tr>
<td>500th</td>
<td>$457,000</td>
</tr>
</tbody>
</table>

Figure 5: The impact of the consumer price of compressed hydrogen on the discounted payback period.
Figure 6 shows the capital cost to the investor of each Ideal Gas Station if 1, 5, 100, or 500 units are produced. The economy of scale is based on NREL’s hydrogen station cost equation.

![Figure 6: Capital cost of the Ideal Gas Station as production increases.](image)

Figure 6 shows the net present value per station of the Ideal Gas Station if 1, 5, 100, or 500 units are produced, which analysis assumes the Ideal Gas Station is dispensing hydrogen at a price of $9/kg.

![Figure 7: Net present value per station for the Ideal Gas Station for the 1st, 5th, 100th, and 500th station produced.](image)
4 SAFETY ANALYSIS

The identification of potential safety risks and necessary corresponding mitigation measures is critical for delivering a safe, reliable product which will serve to build public confidence and act as a pathfinder for the hydrogen fueling industry.

A Failure Modes and Effects Analysis was conducted in order to determine all foreseeable deviations from expected operation of the fueling station and to establish the safety risk posed by each one. Codes and standards pertaining to the fueling station components including storage, compression, and delivery of hydrogen were compiled and applied to the station design in order to mitigate risks associated with each component where applicable.

4.1 Failure Modes and Effects Analysis

The fueling station is divided into its individual components or subsystems in this analysis. The types of failure, likely causes, and potential effects of each failure path are then presented for each section of the station (Table 4). The relative severity of failure effects is denoted by letter “S” and rated on a scale from 1 to 10, where 1 is a minimal effect and 10 includes those effects which can cause injury or death. The likelihood of a potential failure occurring is denoted by letter “O” and is rated on a scale from 1 to 10, where 1 is a remote possibility and 10 is certain to occur. The severity and occurrence scores are multiplied together for each potential event, and the resulting product of the scores constitutes the criticality number “CRIT,” representing the overall magnitude of the threat posed by a potential failure path. Detection, controls, and procedures for any of the potential failures are not included in this initial analysis matrix.

The most significant risks for failure identified in the analysis are in the event of a serious vehicle collision with the dispenser and a scenario in which a vehicle drives away from the dispenser while the fueling hose is still attached to the vehicle. These two events have the highest criticality score (50), and both involve human error on the part of unknown persons who may not be familiar with the procedures and dangers associated with the hydrogen fueling process. The second tier of significant risks involves overpressure or overheating in the compressors, storage tanks, or pipes as a result of external fires, valve failures, leaks, blockages, or failures in the control system. Additional second tier risks include tank ruptures due to flooding, reversed flow due to a malfunctioning vehicle check valve, uncontrolled inflow or outflow of gas due to mechanical or control system failures, and rupture of a pipe due to severe cold weather.

The most significant effects resulting from the aforementioned critical failure modes are fires and explosions. There is little to no risk of suffocation posed to an individual, as the station’s hydrogen storage, compression, and conditioning equipment is almost exclusively self-contained. In the event of a hydrogen leak or emergency venting procedure, the hydrogen gas can be expected to vacate the station and ascend rapidly by virtue of its high buoyancy.

Table 4: Preliminary failure modes and effects analysis for Ideal Gas Station (Waterloo, 2010)

<table>
<thead>
<tr>
<th>Function</th>
<th>Potential Failure Mode</th>
<th>Failure Effects</th>
<th>S</th>
<th>Cause of Failure</th>
<th>O</th>
<th>CRIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Compression</td>
<td>Overpressure</td>
<td>Explosion, leak, fire</td>
<td>10</td>
<td>Failure of downstream valve, leakage on input side</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>High Temperature</td>
<td>Overpressure</td>
<td>Explosion, leak, fire</td>
<td>10</td>
<td>Failure of lubrication,</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

12
<table>
<thead>
<tr>
<th>Function</th>
<th>Potential Failure Mode</th>
<th>Failure Effects</th>
<th>S</th>
<th>Cause of Failure</th>
<th>O</th>
<th>CRIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Storage</td>
<td>Overpressure</td>
<td>Explosion, fire</td>
<td>10</td>
<td>Excessive fill rate, failure of refrigeration system, ignition, fire, obstructed vent, ambient temp change</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Underpressure</td>
<td>Implosion, fire</td>
<td>10</td>
<td>Obstructed vent, excessive draw rate, ambient temp change</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>High Temperature</td>
<td>Rupture, leak, fire</td>
<td>10</td>
<td>Failure of refrigeration system, fire</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>High External Liquid Level</td>
<td>Implosion, fire</td>
<td>10</td>
<td>Flooding</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Overfill</td>
<td>Failure of storage vessel, leak, fire</td>
<td>10</td>
<td>Fill control failure, uncontrolled inflow</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Low Level</td>
<td>Implosion, fire</td>
<td>10</td>
<td>Fill control failure, uncontrolled outflow</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>Booster Compression</td>
<td>Overpressure</td>
<td>Explosion, leak, fire</td>
<td>10</td>
<td>Failure of downstream valve, leakage on input side</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>High Temperature</td>
<td>Explosion, leak, fire</td>
<td>10</td>
<td>Failure of lubrication, failure of refrigeration system</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Low Flow</td>
<td>Leak, fire</td>
<td>10</td>
<td>Reduced inflow, obstruction, power failure</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Reverse Flow</td>
<td>Leak, fire</td>
<td>10</td>
<td>High output pressure</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Overspeed</td>
<td>Leak, fire</td>
<td>10</td>
<td>Failure of speed control system</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Loss of Containment</td>
<td>Fire</td>
<td>10</td>
<td>Operating at a fraction of capacity</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>Coolant leak</td>
<td>Rupture, leak</td>
<td>10</td>
<td>Mechanical failure</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Insufficient cooling</td>
<td>Rupture, leak</td>
<td>10</td>
<td>Control system failure, coolant leak, power failure, excessive ambient temperature</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Excessive cooling</td>
<td>Rupture, leak</td>
<td>10</td>
<td>Control system failure</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Dispensing</td>
<td>Hose leak</td>
<td>Fire, explosion</td>
<td>10</td>
<td>Mechanical failure</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Car drives away with hose</td>
<td>Fire, explosion</td>
<td>10</td>
<td>Human error</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Hose discharge or leak</td>
<td>Fire, explosion</td>
<td>10</td>
<td>Human error</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Backflow of gas from vehicle</td>
<td>Fire, explosion</td>
<td>10</td>
<td>Vehicle check valve failure</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Vehicle collision</td>
<td>Fire, explosion</td>
<td>10</td>
<td>Human error</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>Function</td>
<td>Potential Failure Mode</td>
<td>Failure Effects</td>
<td>S</td>
<td>Cause of Failure</td>
<td>O</td>
<td>CRIT</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------</td>
<td>----------------</td>
<td>---</td>
<td>-----------------</td>
<td>---</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>Dispenser supply pipe rupture</td>
<td>Fire, explosion</td>
<td>10</td>
<td>Corrosion, cold ambient temp</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Vehicle tank overheat</td>
<td>Fire, explosion</td>
<td>10</td>
<td>Failure of sensor, failure of control system</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Piping and valves</td>
<td>Overpressure</td>
<td>Rupture, fire</td>
<td>10</td>
<td>Line blockage</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>High temperature</td>
<td>Rupture, fire</td>
<td>10</td>
<td>External fire</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>High flow</td>
<td>Rupture, fire</td>
<td>10</td>
<td>Upstream mechanical failure, human error</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Loss of containment</td>
<td>Fire</td>
<td>10</td>
<td>Overpressure in pressure or temperature sensor, thermal stress</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>All components</td>
<td>Large external force</td>
<td>Explosion, fire</td>
<td>10</td>
<td>Vandalism, sabotage, deliberate act</td>
<td>3</td>
</tr>
</tbody>
</table>

### 4.2 Mitigation of Identified Risks

Codes pertaining to the design and operation of hydrogen fueling stations are established by multiple agencies. An exhaustive search was conducted to identify all relevant codes, as well as consultation with agency experts.

The agencies or bodies of legislation with established codes include:

- ASME - The American Society of Mechanical Engineers
- CFC - California Fire Code
- CGA - Compressed Gas Association
- IFC - International Fire Code
- IFGC - International Fuel Gas Code
- NEC - National Electrical Code
- NFPA - National Fire Protection Agency
- SAE - SAE International (Society of Automotive Engineers)

Table 5: Summary of relevant codes and regulations.

<table>
<thead>
<tr>
<th>Component/Subsystem</th>
<th>Relevant Code</th>
<th>Brief Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bollard Placement</td>
<td>NFPA 2 - 4.14.1.2</td>
<td>Defines required placement of protective bollards</td>
</tr>
<tr>
<td>Compressed Gas and Electrical Systems</td>
<td>NFPA 497</td>
<td>Classification of flammable liquids/gases and installation of electrical systems</td>
</tr>
<tr>
<td>Container Access</td>
<td>CFC 5303.16.13</td>
<td>Specifies entryway size and confined space procedures</td>
</tr>
<tr>
<td>Dispensing System</td>
<td>SAE J2600</td>
<td>Specifies design, safety features, and operation of hydrogen refueling devices</td>
</tr>
<tr>
<td>Fire Suppression</td>
<td>CFC 903</td>
<td>Specifies installation and operation of fire suppression system</td>
</tr>
<tr>
<td>General</td>
<td>CFC 404</td>
<td>Specifies creation of a Fire Safety Plan</td>
</tr>
<tr>
<td></td>
<td>NEC 500</td>
<td>Identifies hazardous conditions in the operation of the fueling station and proper procedure/precautions to minimize risk</td>
</tr>
<tr>
<td>Component/Subsystem</td>
<td>Relevant Code</td>
<td>Brief Description</td>
</tr>
<tr>
<td>----------------------</td>
<td>----------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Hazard Communication</td>
<td>CFC 407</td>
<td>Specifies proper identification and labeling of hazardous material</td>
</tr>
<tr>
<td>Monitoring Equipment</td>
<td>CFC 5303.16.10</td>
<td>Specifies installation of hydrogen leak sensors</td>
</tr>
<tr>
<td>Operations</td>
<td>NEC 501</td>
<td>Specifies configuration of wiring, seals, spark prevention, and ventilation to minimize risks where flammable gases are present</td>
</tr>
<tr>
<td>Personnel</td>
<td>CFC 406</td>
<td>Specifies required training for employees and operators</td>
</tr>
<tr>
<td>Piping System</td>
<td>ASME B31.12</td>
<td>Defines standards for hydrogen pipes</td>
</tr>
<tr>
<td></td>
<td>CFC 5003.2.3</td>
<td>Defines required placement of shutoff valves on the pipe system</td>
</tr>
<tr>
<td></td>
<td>CFC 5003.2.5</td>
<td>Defines required installation of check valves</td>
</tr>
<tr>
<td></td>
<td>CGA G-5.4</td>
<td>Defines standards for pipe systems at consumer locations</td>
</tr>
<tr>
<td></td>
<td>CGA G-5.5</td>
<td>Specifies design of hydrogen venting system</td>
</tr>
<tr>
<td></td>
<td>CGA S-1.3</td>
<td>Defines standards for pressure relief valves</td>
</tr>
<tr>
<td></td>
<td>IFGC 703.3</td>
<td>Defines required placement of pressure relief valves</td>
</tr>
<tr>
<td></td>
<td>IFGC 704.1.2.3</td>
<td>Defines required materials for hydrogen tubing</td>
</tr>
<tr>
<td></td>
<td>IFGC 704.1.2.4</td>
<td>Defines required joints and fittings for hydrogen tubing</td>
</tr>
<tr>
<td>Seismic Anchoring</td>
<td>CFC 5003.2.8</td>
<td>Stipulates compliance with building code</td>
</tr>
<tr>
<td>Shutoff Valves</td>
<td>CFC 5803.1.3.1-2</td>
<td>Defines required placement of shutoff valves at source and point of use</td>
</tr>
<tr>
<td>Signage</td>
<td>IFC 2309.3.1.2.2</td>
<td>Specifies placement of “no smoking” placards</td>
</tr>
<tr>
<td>Station Siting</td>
<td>IFC 2309.3.1</td>
<td>Broadly specifies site preparation and construction of hydrogen fueling stations</td>
</tr>
<tr>
<td>Ventilation</td>
<td>CFC 5303.16.9</td>
<td>Provides requirements for exhaust ventilation in enclosed spaces</td>
</tr>
</tbody>
</table>

A programmable logic control (PLC) system is incorporated into the design which coordinates the operation of compressors, valves, cooling system, and dispensing. The PLC is further informed of the operating conditions of the station via pressure and temperature sensors as well as hydrogen detection external to the compression and distribution system.

The PLC will affect a complete system shutdown and evacuation of hydrogen from the system if any significant fault or deviation from standard operation is detected, as defined in Table 4. This may include pressure drops or overpressure, overheating, unresponsiveness from any component, and hydrogen leaks. The PLC will also be able to respond to external shutdown commands, power failure, or detection of internal or external fires.

The major components of the refueling station are to be compliant with relevant codes as summarized in Table 5. The CFC stipulates the placement of multiple safety valves throughout the hydrogen system. These include check valves, shutoff valves, and pressure relief valves. The NFPA specifies the placement of protective bollards which are to be installed surrounding the fueling station to reduce or mitigate the risk of vehicle collision. Electrical components are regulated by multiple sections of the NEC. Hydrogen storage tanks are to be compliant with ASME standards, and the dispensing system is to be compliant with both SAE and NFPA standards.
5 SITING

Refueling station availability is crucial to the success of hydrogen powered vehicles (HPV). At present there are stations existing or under development in the Los Angeles basin and Northern California, including the Bay Area, Sacramento, and the upper North Coast. This arrangement relegates the ownership of a HPV to a novelty item for commuting purposes only, since it is currently not possible to drive between Northern and Southern California due to refueling station logistics. In order to bring the idea of owning a HPV to the next level in the eyes of the public, it is essential that a station bridging this gap is brought on-line. Such a station would make it possible to use HPVs to travel the length of California.

The site location chosen for The Hydrogen Fueling Station is the Harris Ranch Shell located at 24505 West Dorris Avenue near Coalinga along Interstate Highway 5. This location has a number of attractive characteristics. First and foremost, a station at this location would close the gap between Northern and Southern refueling sites from nearly 640 miles to approximately 300 km in either direction.

Though there are many other potentially appropriate sites within a 50 mile radius that would link the Northern and Southern networks, centrality is not the only appeal of the selected site. Based in a survey of existing hydrogen fueling stations, Shell Oil has already shown its receptiveness to alternative fuel technologies by hosting other stations in the state for both hydrogen and electric technology. In fact, an analysis of the site indicated that there is a Tesla electric vehicle charging station nearby. The Harris Ranch, Doyle, station owner has expressed an interest in a drop-in hydrogen station to evaluate feasibility of a permanent installation (Personal Communication, Feb. 28, 2014). Though the majority of this area is zoned as agriculture only, the Fresno County Planning Commission re-zoned this parcel as commercial in 2006. The site has been permitted for automobile and truck service stations and would warrant minor, if any, further permitting (Fresno, 2006). Harris Ranch is presently in the Research and Development (R&D) stage of manure to methane facility. This facility will potentially have a reforming component for the production of hydrogen that could supply the station’s needs. The best case scenario is that once Harris Ranch installs the methane reformation system, they will upgrade their bovine shipping fleet to run on hydrogen. This will ensure that the Ideal Gas Station will have a booming hydrogen demand, as well as an on-site production facility.
Figure 8: Location of the Ideal Gas Station with respect to the major cities to the north and south (OpenStreet 2014).
6 OPERATION AND MAINTENANCE

Semi-annual routine maintenance visits will be scheduled to ensure that every component of the fueling station is properly working, and routine replacement of parts will be done during these visits. The automated system will signal the telecommunications module in the case of an unexpected maintenance issue.

Each task displayed in Table 1 is to be checked during the routine bi-annual maintenance visit. This routine is based on the Schatz Research Laboratory’s maintenance schedule for the Humboldt State University Hydrogen Fueling Station. The annual cost of routine maintenance can be found in the Economic Analysis.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDC Machines &amp; HydroPac Compressors</td>
<td>Lube oil pressure and levels</td>
</tr>
<tr>
<td></td>
<td>Coolant check</td>
</tr>
<tr>
<td></td>
<td>Abnormal noise and vibration check</td>
</tr>
<tr>
<td></td>
<td>Automated system functionality</td>
</tr>
<tr>
<td></td>
<td>Leak detection status</td>
</tr>
</tbody>
</table>
Equipment | Task
---|---
Oil filter change | Diaphragms and diaphragm O-ring seals
Process check valves | Oil inlet and relief valve
Normal process inlet filter | Inspect crankcase assembly
Inspect compressor lower head | Inspect injection pump
Fuses | Dispenser
Filter: drain bowl and inspect element | Inspect piping for damage and leaks
Inspect breakaways | Nozzle: full leak check, clean, inspect jaws
Verify calibration of pressure transducer | Check grounding of clamp and plumbing
Miscellaneous Equipment | Test station emergency shutdown switches
Test fire suppression system | Test thermocouple heat detectors
Test emergency breaker | Test alert system
Inspect PLC unit | Test over/under voltage relay
Check router and wireless connections

7 ENVIRONMENTAL ANALYSIS

The Environmental Analysis outlines major impacts associated with the Ideal Gas Station which include the resource analysis, emissions analysis, and a noise analysis.

7.1 Resource Analysis
With nine pressure tanks in the cascade storage system, approximately 55% of the energy used is projected to be used by the compressor system, while 45% is used by cooling facilities (Roth 2014). The cost of cooling should significantly decrease in colder areas. An area with an ambient temperature of -40°C, such as North Canada, would have little or no cooling needs. Therefore that location would have an electricity bill approximately 45% less than the projected cost.

The station occupies a 27x15 meter space including the fenced area. This area could be reduced by approximately 15x6 meter through installing the gate along the compressed hydrogen tube trailer delivery parking spots.

7.2 Emission Analysis
The CO2 emissions from the Ideal Gas Station are based on the electricity usage of the station and the production of the hydrogen received by the station. There are two different scenarios to
consider when analyzing the emissions from the Ideal Gas Station; if the hydrogen delivered has been produced through electrolysis or via steam reforming of methane.

As stated in the Siting section, locating the Ideal Gas Station at the Harris Ranch provides a strong opportunity for the delivered hydrogen to be produced via steam reforming of methane in the same location as the station. This form of producing hydrogen emits lower amounts of CO₂ than electrolysis, allowing the Ideal Gas Station to take another step towards creating a greener transportation economy.

### 7.2.1 Hydrogen Production via Electrolysis

The hydrogen that the initial Ideal Gas Station receives may be produced via electrolysis, although this is an unlikely scenario. Table 7 displays the annual CO₂ emissions resulting from this scenario. The average energy efficiency of an electrolyzer is 54 kWh/kg of H₂ (NREL, 2009). The Ideal Gas Station will be receiving 36,500 kg of H₂ in one year, assuming 100 kg of gas are used every day.

<table>
<thead>
<tr>
<th>Electricity Source</th>
<th>lb CO₂/kWh</th>
<th>Annual kWh</th>
<th>Annual Tons CO₂</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station Electricity Usage</td>
<td>1.5196</td>
<td>33,000</td>
<td>25.07</td>
<td>(U.S. EPA 2010)</td>
</tr>
<tr>
<td>Electrolysis Production</td>
<td>1.5196</td>
<td>1,971,000</td>
<td>1,497.57</td>
<td>(NREL 2009)</td>
</tr>
<tr>
<td><strong>Total Annual Tons CO₂</strong></td>
<td></td>
<td></td>
<td>1,522.64</td>
<td></td>
</tr>
</tbody>
</table>

### 7.2.2 Hydrogen Production via Steam Reforming of Methane

It is possible the hydrogen received by initial Ideal Gas Station will be produced from steam reforming of methane; Table 2 displays the CO₂ emissions resulting from this scenario. In steam reforming of methane without CO₂ capture, 16.296 lb CO₂ is produced per kg H₂ (Abánades, 2012).

<table>
<thead>
<tr>
<th>Electricity Source</th>
<th>lb CO₂/kWh</th>
<th>Annual kWh</th>
<th>Annual Tons CO₂</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station Electricity Usage</td>
<td>1.5196 lb/kWh</td>
<td>33,000 kWh</td>
<td>25.07</td>
<td>(U.S. EPA, 2010)</td>
</tr>
<tr>
<td>Steam Reformation of Methane</td>
<td>16.296 lb/kg H₂</td>
<td>36,500 kg H₂</td>
<td>297.40</td>
<td>(Abánades, 2012)</td>
</tr>
<tr>
<td><strong>Total Annual Tons CO₂</strong></td>
<td></td>
<td></td>
<td>322.48</td>
<td></td>
</tr>
</tbody>
</table>

### 7.2.3 NOₓ & SOₓ Emissions

Due to the station’s electricity usage, NOₓ  and SOₓ  emissions will also be produced. Table 9 displays the total amount of each pollutant resulting from the station’s electricity use.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>lb of pollutant/kWh</th>
<th>Annual kWh usage of station</th>
<th>Annual pollutant emissions (lb)</th>
</tr>
</thead>
</table>

20
7.3 Noise Analysis

The following noise analysis first addresses the existing surrounding ambient noise levels, and then addresses how the noise produced by the Ideal Gas Station impacts the surroundings.

7.3.1 Harris Ranch Noise Setting

According to the City of Coalinga Master Environmental Impact Report (Morro Group, Inc. 2009) the stationary noise source must meet two noise objectives:

1. To prevent the introduction of new noise-producing uses in a noise sensitive area, and
2. To prevent encroachment of noise-sensitive land uses upon existing noise-generating facilities.

Based on the Harris Ranch Airport Land Use Policy, the Harris Ranch is an acceptable location for the fueling station. According the Policy, any noise produced by the station will be compatible with the surrounding Public, Residential, Commercial, Industrial, Agricultural and Recreational land uses (Fresno County 1995).

The Ideal Gas Station will be placed in the Harris Ranch, which is a relatively noisy area and the noise produced by the station was found to cause a less than significant impact to the surrounding area. The surrounding area consists of the freeway I-5 approximately 280 m to the west, the highway CA-198 located 100 m to the north of the site, an agricultural field beyond the highway 150 m to the north, a Shell petroleum refueling station 80 m to the east, the Harris Ranch Inn 160 m to the east, and the Harris Ranch Airport 150 m to the south. Amongst these points of interest, the main external noise producers are the freeway, the airport and the nearby petroleum refueling station.

The Community Noise Equivalent Levels of Harris Ranch airport are estimated to range between 55 dBA and 65 dBA in the south-west vicinity of the fueling station (Fresno County 1995). These noise levels are the measured as the average noise level over a 24-hour period by an airport (WAC Inc., 2009).

The station will be placed in a high traffic zone which is exposed frequent refueling of heavy trucks and light duty auto at all hours of the day. According to OSHA (2014a), the average noise level of heavy trucks at 15 m (50 feet) is approximately 90 dBA, which would be observed as approximately 75 dBA at the station.

The Ideal Gas Station will refuel 25 cars a day, and an average of 27 airplanes a day go through the Harris Ranch Airport (AirNav 308, 2010). The station noise impact should not significantly affect noise levels at this location, because there is already similar noise frequently generated by the Harris Ranch Airport.

7.3.2 Station Noise

The primary noise emitter of the fueling station is the high pressure compressor, which is estimated to produce a maximum of 85 dBA at one-meter distance (PDC Machines, Inc. 2014). The noise levels of the other components were estimated based on similar equipment due the limited available data. The top noise emitters for the fueling station are tabulated in Table 10.
These components were determined to present the highest risk of acoustical impact. The combined noise level of these station components was calculated using the logarithmic decibel scale and was estimated to be 85 dBA. An analysis of the noise produced by the remaining, quieter components show no significant increase in the combined noise level.

**Table 10: Top noise emitters of the Ideal Gas Station and the combined noise level.**

<table>
<thead>
<tr>
<th>Noise Emitter</th>
<th>Maximum Noise Produced (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Compressor (PDC Machines, Inc, 2014)</td>
<td>85</td>
</tr>
<tr>
<td>Medium Pressure Compressor(^1)</td>
<td>72</td>
</tr>
<tr>
<td>Low Pressure Compressor(^1)</td>
<td>65</td>
</tr>
<tr>
<td>(2) Cooling System Compressors(^1)</td>
<td>(2) 65</td>
</tr>
<tr>
<td>Cooling Fan</td>
<td>41</td>
</tr>
<tr>
<td><strong>Combined Noise Level</strong></td>
<td><strong>85</strong></td>
</tr>
</tbody>
</table>

The combined noise level of the station is permissible by the Occupational Safety and Health Administration (OSHA, 2014b) standards statement of permissible exposure limits (Table 11). Assuming that the drivers will spend a maximum of 30 minutes refueling at the Ideal Gas Station, under OSHA regulations the maximum permissible sound levels that anyone should be exposed to is 110 dBA (OSHA 2014b). However, 85 dBA is still loud enough to cause noise a disturbance to sensitive hearing and especially when considering that the mechanical components produce this noise within an enclosed metal container. Therefore, the incorporation of noise absorption material, along with acoustical enclosures, into the system will be used to dampen the noise levels. This is considered an economic and efficient way to reduce the significance of noise levels by between 20 and 40 dBA (OSHA Technical Manual, 2011). These noise absorption and acoustical enclosure modifications require minimal maintenance and work best with high frequency noise.

**Table 11: Short duration permissible noise exposure (OSHA, 2014).**

<table>
<thead>
<tr>
<th>Duration per day, (hours)</th>
<th>Sound level, slow response (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>105</td>
</tr>
<tr>
<td>1/2</td>
<td>110</td>
</tr>
<tr>
<td>1/4 or less</td>
<td>115</td>
</tr>
</tbody>
</table>

Using acoustical dampening to reduce vibrations of the metal shipping container, the combined noise level all the components in the station was found to be 65 dBA. In addition, the surrounding impact of all the noise inputs the area contains will not be amplified by the Ideal Gas Station, especially taking into account the dampers, or noise absorption materials, that will be placed inside the Ideal Gas Station which will decrease noise levels to 65 dBA (see table 4).

Furthermore, for the safety of any user of the Ideal Gas Station, an alarm system will be activated when the hydrogen sniffer detects a hydrogen leakage. This emergency alarm system will be at a set decibel sound pressure level of 15 dBA above the average sound levels from our

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\(^1\) Estimates based on schematics of comparable components.
Ideal Gas Station (CFC 2013). Since our combined total will be 65 dBA, our alarm will equal roughly 80 dBA in order to comply under the California fire alarm regulations and provide proper safety to anyone using the Ideal Gas Station. This alarm will last a minimum of 60 seconds with 90 to 120 pulse sounds per minute (CCR, 2013b).

8 INTERFACE DESIGN

The user interface of the Ideal Gas Station will be the connection point between the driver and the fueling station. The interface consists of a touch-screen display, a video camera, and an onboard computer. The interface will serve as a digital gas station attendant: it will instruct the driver on how to initiate the point of sale transaction, how to fuel, and what to do in an emergency. Additionally, the display will also be used for resupply, routine maintenance, and station diagnostics.

8.1 Refueling and Driver Interactions

When the station is idle, the screen will remain in a powered-down standby mode so as to conserve power, preserve the life of the display, and to limit light pollution to the surrounding environment. A simple notification will be written adjacent to the screen notifying the driver to touch the screen to begin fuelling. When the driver first interacts with the screen the following set of options are displayed

![Interface Design Image]

Figure 10: Introduction screen for the interface.

If Begin Fueling is selected, the driver will be prompted to initiate his or her payment transaction via the point of sale terminal connected to the dispensing unit. Once processing of the payment method is complete, the fueling nozzle will be unlocked from the dispensing unit and the screen will display simple pictorial instructions showing the driver how to perform the steps required to fuel their vehicle. If at any time the driver needs assistance the Request Assistance option will always be available at the bottom of the interface.

During fueling when no interaction with the interface is required, the interface will be used to display non-interference advertisements. The benefit of the non-interference advertisements is
that they promote the awareness of local renewable energy businesses and services. These
advertisements will be limited within the scope of renewable resources and promoting
sustainability. An additional benefit of the on-screen advertisements is that they will generate
revenue for the station owner, thereby shortening the station’s payback period.

The second option, Find a Station, presents the driver with a Locate Nearby button, a search
query field, and a map. The driver may use the Locate Nearby button to identify any stations
within a 500 km radius. If, however, the driver seeks to route a trip to the next few stations, the
driver may choose to search for stations using the search option. Finally, for all results the screen
will pinpoint the location of the stations in a map as well as in list format including an address of
each station.

The Request Assistance option will consist of a two secondary options: an option for written
instructions on how to refuel and an option to communicate with a remote operator. The written
instructions will outline in detail the steps to refuel his or her hydrogen vehicle. If the driver has
issues of any nature, the driver may choose to speak with a remote operator. If selected, the
interface will prompt the user to confirm that he or she want to initiate a video call to the remote
operator. Once connected, the operator will be able to assist the driver with issues such as
processing a payment, initiating fueling or disengaging fueling should a fault occur or requesting
assistance from local safety personnel such as local authorities.

The Report an Emergency option is available in case any person notices an unsafe situation at the
Ideal Gas Station. Unsafe situations might include broken hoses, external damage due to vehicle
collisions, vandalism to key components, or even fires. Due to the severity of emergency
situations, the emergency option will not initiate any direct communication with the remote
operator. Rather, if there is an emergency situation that is reported, an audible alarm will instruct
customers to immediately clear the area to a safe distance. To protect from false alarms, upon
initiation of the Emergency protocols, all sensors in the system will verify the faults at the same
time as the remote operator visually inspecting the area with the remote accessed security
camera. If any faults are detected or the operator identifies an immediate emergency, the alarms
will sound. As a fail-safe, a battery backup system will ensure that, if there is a power outage, the
system will still engage the emergency protocols. On the same token, if there is a power outage,
the interface will display a low power message indicating that service is unavailable.

8.2 Maintenance and Diagnostics
The user interface also doubles as a diagnostics terminal for the maintenance personnel. The
person performing maintenance can access either user interface (if two dispensers are installed)
to perform system diagnostics on the station and generate reports that would be sent to the
remote operator. The maintenance personnel access the Maintenance Mode terminal of the user
interface by securely logging in the using touch-screen keypad that shows up on screen.

Under the Maintenance Mode, the maintenance personnel can query the state of the station and
pull up any data as required during inspections. The state of the station may be represented by
the sensors such as the pressure sensors and hydrogen leak detectors sniffers, which may be	abulated or called up in graphs. Additional data that is available for on-site monitoring includes
vehicle fueling behavior. The Maintenance Mode also permits the maintenance personnel to pull
and submit inspection logs as well as report repairs. The advantage of the Maintenance Mode is
that it permits maintenance personnel to access the station data that may not be available if there
were a cellular service outage or telecommunications failure. Furthermore, the Maintenance
Mode permits reconfiguring of the logic controller in the event of a station modification or upgrade.

9 CONCLUSIONS & RECOMMENDATIONS

The key findings/recommendations of this report, in the order of most to least important…

- The capital costs of $980,000 make the Ideal Gas Station economically competitive, with a 5.9 year discounted payback period.
- The net present value of a single Ideal Gas Station is estimate to be $1.5M.
- The station is highly mobile in that all the system components fit in a standard 40 ft shipping container, which it is very easily transportable.
- The Ideal Gas Station uses readily available components, which significantly reduces the capital costs through mass production.
- The station is fully automated so that minimal human intervention is required to ensure long-term operation of the station.
- The station is ideal for connecting hydrogen fuel infrastructure over large distances. It’s low capital costs, high mobility, and high reproducibility make the Ideal Gas Station ideal for linking the Hydrogen Highway together, and making long distance hydrogen fueled travel feasible.
## 10 REFERENCES


AirNav 308. (2014). “Harris Ranch Airport, Coalinga, California, USA”. 


Doyle, Kirk. 2014. General Manager Harris Ranch Fast Track Fueling Station. Personal Correspondence.


Lipman, Timothy, Maggie Witt, and Matthew Elke. 2013. Lessons learned from the installation and operation of Northern California’s first 70-MPa hydrogen fueling station. University of California e Berkeley, Transportation Sustainability Research Center. Berkeley, California


Shipping Container Pros. (2014).”Shipping Container Prices”,

<http://www1.eere.energy.gov/hydrogenandfuelcells/education/pdfs/thomas_fcev_vs_battery_evs.pdf>


Figure A-1: Ideal Gas Station schematic showing the interconnections of the hydrogen gas piping and cooling system
APPENDIX B  FLOOR PLAN

Figure 11: Floor plan of the Ideal Gas Station.
See full page advertisement attachment.
The Fuel of the Future

Humboldt Hydrogen Solutions presents:

The Ideal Gas Station
Coming to a location near you

A mobile platform for the coming hydrogen infrastructure market
Hydrogen is the fuel of the future

Get on board or get left behind...
APPENDIX D  USER GUIDE

See full page user guide attachment.
1. Select “Begin Fueling” on the pump console.

2. Enter payment information.

3. Insert pump nozzle into vehicle fuel receptacle.

4. Secure nozzle by twisting lock into the locked position.

5. Select “Start Fueling” on the pump console.

6. When desired fuel is dispensed select “Stop Fueling”. The pump will automatically stop fueling when tank is full.

7. After fueling unlock and remove nozzle, and return to pump.

8. Close vehicle refueling receptacle.

9. Your vehicle is now refueled and ready to drive.
APPENDIX E  DETAILED ECONOMICS DATA

This section

Table 12: Detailed bill of materials, annual operation and maintenance costs, and annual revenue.

<table>
<thead>
<tr>
<th>Capital Costs</th>
<th>Qty</th>
<th>Unit Cost ($)</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cascade Storage System</td>
<td>1</td>
<td>$ 130,000</td>
<td>$ 130,000</td>
</tr>
<tr>
<td>High Pressure Compressor</td>
<td>1</td>
<td>$ 100,000</td>
<td>$ 100,000</td>
</tr>
<tr>
<td>Boosting Compressor</td>
<td>1</td>
<td>$ 82,700</td>
<td>$ 82,700</td>
</tr>
<tr>
<td>Low Pressure Compressor</td>
<td>1</td>
<td>$ 100,000</td>
<td>$ 100,000</td>
</tr>
<tr>
<td>Shipping Container</td>
<td>1</td>
<td>$ 7,000</td>
<td>$ 7,000</td>
</tr>
<tr>
<td>Cooling System</td>
<td>LS</td>
<td>--</td>
<td>$ 34,000</td>
</tr>
<tr>
<td>Dispenser</td>
<td>1</td>
<td>$ 300,000</td>
<td>$ 300,000</td>
</tr>
<tr>
<td>Touch Screen Interface/Computer</td>
<td>LS</td>
<td>$ 1,000</td>
<td>$ 1,000</td>
</tr>
<tr>
<td>Piping Equipment</td>
<td>LS</td>
<td>--</td>
<td>$ 7,650</td>
</tr>
<tr>
<td>Valves</td>
<td>LS</td>
<td>--</td>
<td>$ 1,000</td>
</tr>
<tr>
<td>Fire Suppressors</td>
<td>3</td>
<td>$ 1,295</td>
<td>$ 3,885</td>
</tr>
<tr>
<td>Hydrogen Leak Detectors</td>
<td>3</td>
<td>$ 1,500</td>
<td>$ 4,500</td>
</tr>
<tr>
<td>Security Cameras</td>
<td>2</td>
<td>$ 69</td>
<td>$ 138</td>
</tr>
<tr>
<td>Telecommunications</td>
<td>LS</td>
<td>--</td>
<td>$ 1,048</td>
</tr>
<tr>
<td>Pressure Sensors</td>
<td>5</td>
<td>$ 325</td>
<td>$ 1,625</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>$ 774,546</strong></td>
<td></td>
</tr>
<tr>
<td>Installation Cost</td>
<td>LS</td>
<td>15%</td>
<td>$ 116,182</td>
</tr>
<tr>
<td>Contingency</td>
<td>LS</td>
<td>10%</td>
<td>$ 89,073</td>
</tr>
<tr>
<td><strong>Total Capital Cost</strong></td>
<td></td>
<td><strong>$ 979,801</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual O&amp;M</th>
<th>Qty</th>
<th>Unit Cost</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel ($/kg/day)</td>
<td>100</td>
<td>$ 7</td>
<td>$ 255,500</td>
</tr>
<tr>
<td>Electricity ($/kWh)</td>
<td>4000</td>
<td>$ 0.1058</td>
<td>$ 423</td>
</tr>
<tr>
<td>Tube Trailer Rental ($/month)</td>
<td>12</td>
<td>$ 2,400</td>
<td>$ 28,800</td>
</tr>
<tr>
<td>Maintenance Cost ($/yr)</td>
<td></td>
<td>$ 1,275</td>
<td>$ 1,275</td>
</tr>
<tr>
<td><strong>Total Annual O&amp;M</strong></td>
<td></td>
<td><strong>$ 285,998</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Revenue</th>
<th>Qty</th>
<th>Unit Price</th>
<th>Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Price ($/kg)</td>
<td>100</td>
<td>$ 9.00</td>
<td>$ 328,500</td>
</tr>
<tr>
<td>Monthly Ad. Space (Sign and Digital)</td>
<td>12</td>
<td>$ 1,000</td>
<td>$ 12,000</td>
</tr>
<tr>
<td><strong>Total Annual Revenue</strong></td>
<td></td>
<td><strong>$ 340,500</strong></td>
<td></td>
</tr>
</tbody>
</table>
The following equation, and the assumed model parameters, was used to estimate the scaling of the capital cost as more Ideal Gas Stations are produced (Melaina and Penev 2013):

\[ C' = C^0 \left( \frac{Q'}{Q^0} \right)^\alpha \left( \frac{V'}{V^0} \right)^\beta \]

Where:

- \( C' \) = station capital cost ($/station)
- \( C^0 \) = base station capital cost ($/station); assumed $2.80M
- \( Q' \) = station capacity (kg/day)
- \( Q^0 \) = base station capacity (kg/day); assumed 450 kg/day
- \( V' \) = cumulative capacity (kg/day)
- \( V^0 \) = cumulative capacity at cost status of base station (kg/day); assumed 20,000 kg/day
- \( \alpha \) = scaling factor; assumed 0.707
- \( \beta \) = learning factor; assumed -0.106