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14. ABSTRACT
**Hydrogen systems infrastructure development and fuel cell vehicles (FCVs) have the potential to replace the gasoline internal combustion engine vehicles thus increasing energy security and reducing greenhouse gas emissions. Hydrogen fueling infrastructure development is critical for the commercialization and consumer acceptability of the FCVs, thus recognizing hydrogen as an affordable transportation fuel. This paper presents the conceptual design of a scalable and reproducible hydrogen fueling station in Santa Monica, California. The various hydrogen production technologies have been evaluated and the usage of renewable energy sources such as biogas and landfill gas has been emphasized. The technical specifications of the hydrogen fueling station components and the transportation of hydrogen fuel have been discussed. Cascade simulations were conducted for different compressor capacities and storage bank configurations. Hydrogen dispensing using the 3-bank cascade configuration has been discussed. Well-to-wheel analysis, comparing the emissions of harmful gases and total energy consumption of conventional gasoline engine vehicles and fuel cell vehicles, has been performed. Early market customers, including material handling vehicles, stationary back-up power and portable power systems have been identified and their daily hydrogen fuel requirements have been computed. This article discusses the safety codes and standards, identifies the significant failure modes and suggests precautionary measures to be taken to mitigate them. The economic impact of employing such hydrogen technologies has been studied.**

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# DESIGN OF A HYDROGEN COMMUNITY FOR SANTA MONICA

by

VIJAY MOHAN

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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Approved by

Dr. John W. Sheffield, Advisor
Dr. Scott Grasman
Dr. Lokeswarappa R. Dharani

## PUBLICATION THESIS OPTION

This thesis consists of following articles that have been submitted and presented as follows:

The paper presented in pages 3-17 titled “DESIGN OF A HYDROGEN COMMUNITY” has been submitted as a short-communication paper to International Journal of Hydrogen Energy (IJHE) 2011.

The design report presented in pages 18-62 titled “DESIGNING A HYDROGEN COMMUNITY”, secured the Grand Prize in the Hydrogen Student Design Contest organized by the Fuel Cell & Hydrogen Energy Association (FCHEA). The design was selected for presentation at the National Hydrogen Association (NHA) Conference at Long Beach, California in May 2010 and World Hydrogen Energy Conference (WHEC) 2010 at Essen, Germany in May 2010.

# ABSTRACT

Hydrogen systems infrastructure development and fuel cell vehicles (FCVs) have the potential to replace the gasoline internal combustion engine vehicles thus increasing energy security and reducing greenhouse gas emissions. Hydrogen fueling infrastructure development is critical for the commercialization and consumer acceptability of the FCVs, thus recognizing hydrogen as an affordable transportation fuel.

This paper presents the conceptual design of a scalable and reproducible hydrogen fueling station in Santa Monica, California. The various hydrogen production technologies have been evaluated and the usage of renewable energy sources such as biogas and landfill gas has been emphasized. The technical specifications of the hydrogen fueling station components and the transportation of hydrogen fuel have been discussed. Cascade simulations were conducted for different compressor capacities and storage bank configurations. Hydrogen dispensing using the 3-bank cascade configuration has been discussed. Well-to-wheel analysis, comparing the emissions of harmful gases and total energy consumption of conventional gasoline engine vehicles and fuel cell vehicles, has been performed. Early market customers, including material handling vehicles, stationary back-up power and portable power systems have been identified and their daily hydrogen fuel requirements have been computed.

This article discusses the safety codes and standards, identifies the significant failure modes and suggests precautionary measures to be taken to mitigate them. The economic impact of employing such hydrogen technologies has been studied.

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### 1. INTRODUCTION

According to U.S. Department of Energy (DOE), hydrogen and fuel cell development are key elements to address energy challenges today and in the future. According to the U.S. DOE, the cost per kilowatt of automotive fuel cell power systems has been reduced from $275/kW in 2002 to $94/kW in 2007 and is expected to reach $30/kW by 2015 [1]. California Fuel Cell Partnership (CaFCP) released an Action Plan in February 2009, according to which, by 2017, automotive manufacturers plan to have nearly 50,000 fuel cell vehicles in California, including 80% of those in Southern California. It also plans on developing hydrogen communities inclusive of fuel cell vehicles and retail hydrogen refueling stations, in four Southern California locations: Santa Monica, Irvine, Torrance and Newport Beach [2]. The primary objective of this paper is to identify, select and design hydrogen technologies for a community located in Santa Monica, California, to reduce the dependence on petroleum and decrease pollution and greenhouse gas emissions. The hydrogen technologies and systems selected in the project are commercially available and possible to implement for practical, real-world use from May 2010.

This paper discusses the design of a reproducible and scalable hydrogen fueling station, hydrogen production using renewable energy sources and potential early market customers for the site located in Santa Monica. The benefits of incorporating hydrogen technologies when compared to conventional sources are higher energy efficiency, reliability and fuel flexibility. Hydrogen technologies were selected based on these benefits and steam methane reformation, on-site and centralized hydrogen production were evaluated. The hydrogen station technical design describes the specification of compressors, storage tanks, dispensers, fuel cell to provide back-up power and other safety equipment. Early market applications are critical for the development and acceptance of any niche technologies. Potential early market customers including material handling vehicles, stationary back-up power systems and portable power systems for emergency and security purposes are also discussed.

According to U.S. Department of Energy and Energy Efficiency and Renewable Energy (EERE), safe practices in the production, compression, storage, distribution and usage of hydrogen is necessary to sustain the safety requirements for a developing hydrogen economy [3]. During the design of the hydrogen fueling station, safety analysis was performed to identify the various failure modes and the safety precautions to be taken to mitigate them. The safety codes and standards to be followed during the installation of the hydrogen systems and operation of the hydrogen fueling station have been listed.

An environmental analysis was conducted to study the emissions of forklift propulsion systems. A well-to-wheel analysis was performed on Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) analysis software to compare the emissions and total energy consumption of fuel cell vehicles with gasoline internal combustion engine vehicles. An economic analysis was performed to estimate the impact of implementing the concept of hydrogen community on the economy of Santa Monica. It includes the capital cost for all hydrogen equipment, operating cost and maintenance cost of hydrogen fueling station equipment. A business plan encouraging collaboration with the industry was formulated to implement the hydrogen technologies in Santa Monica.

Public acceptance of hydrogen as a sustainable energy fuel is one of the main challenges faced by promoters of this idea. A successful marketing campaign and education of the public should help in popularizing and generating interest regarding the concept. The design outlines the initiatives undertaken to promote and educate the Santa Monica public. Some of the marketing programs include organizing “open house” day within the community and by advertising about the concept at public locations. The education plans include conducting workshops and introducing the concept of hydrogen as a sustainable fuel in school curriculum.

# PAPER

## I. DESIGN OF A HYDROGEN COMMUNITY

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Abstract:

This paper discusses the conceptual design of a scalable and reproducible hydrogen fueling station at Santa Monica, California. Hydrogen production using renewable energy sources such as biogas, which accounts for 100% of the total production, has been discussed. The fueling station consists of a DFC 300 fuel cell for on-site generation of 136 kg/day of hydrogen and 300 kW of electric power, five hydrogen storage tanks (Storage capacity of 198 kg of $H_2$ at 350 and 700 bar), four compressors which assist in dispensing 400 kg of hydrogen in 14 hours, two hydrogen dispensers operating at 350 bar and 700 bar independently and a SAE J2600 compliant hydrogen nozzle. Potential early market customers for hydrogen fuel cells and their daily fuel requirements have been computed. The safety codes, potential failure modes and the methods to mitigate risks have been explained. A well-to-wheel analysis is performed to compare the emissions and the total energy requirements of conventional gasoline and fuel cell vehicles.

Keywords: Hydrogen fueling station; biogas; early market customers; safety; well-to-wheel

# 1. INTRODUCTION

In recent years, a number of innovative alternative energy projects have been encouraged across the United States to reduce the dependence on oil imports, leading to increased environmental benefits and better energy security. Communities play an important role in the pre-commercial deployment of emerging hydrogen technologies. The hydrogen infrastructure development is critical for the commercialization of fuel cell vehicles and transition to a sustainable hydrogen economy [4]. According to the Action Plan released in February 2009, California Fuel Cell Partnership (CaFCP) has plans for developing hydrogen communities in Southern California [5]. This paper discusses the conceptual design of a reproducible and scalable hydrogen fueling station, and outlines the strategic development of a hydrogen community in Santa Monica, California [6]. Water electrolysis, steam methane reformation and on-site hydrogen production are some of the hydrogen production methods which are being evaluated. Usage of local renewable energy sources such as biogas is also emphasized for these production processes. Potential early market customers in material handling vehicles, stationary back-up power and portable power systems at various utilities are identified [2]. The hydrogen fueling station technical design including hydrogen production, compression, storage and dispensing is discussed. Significant failure modes, and the safety codes and standards to mitigate risks associated with hydrogen are identified. The greenhouse gases (GHG's) emitted during the generation of hydrogen is compared with the gasoline generation through a well-to-wheel analysis.

## 2. HYDROGEN PRODUCTION EVALUATION

The potential for hydrogen production from various sources is evaluated and identified within 25 miles of Santa Monica city limits. Two existing facilities are listed below:

1. Hyperion Treatment Plant, Playa del Rey

2. Terminal Island Water Reclamation Plant, San Pedro

Biogas (50% - 75% methane) is produced at Hyperion Treatment Plant and Terminal Island Water Reclamation Plant. The methane produced at these plants is separated and further processed at steam methane reformer to generate hydrogen. The hydrogen is compressed on-site and transported to the hydrogen station through tube trailers. Table 2.1 shows a description of the hydrogen production at each plant.

Table 2.1 – Hydrogen production plants

| NAME OF PLANT | PRODUCTION METHOD | HYDROGEN PRODUCTION | PRODUCTION FACILITY AVAILABILITY |
|---|---|---|---|
| Hyperion Treatment Plant | Steam Methane Reformation of Biogas | 544 kg/day | >97% |
| Terminal Island Water Reclamation Plant | Steam Methane Reformation of Biogas | 544 kg/day | >97% |

The Hyperion Treatment Plant is Los Angeles' oldest and largest wastewater treatment plant. It produces 650 tons of bio-solids and 226,534 cubic meter of biogas per day. Due to the high volume of bio-gas production, the facility is considered as a major hydrogen production location [7]. The biogas produced at the facility is used to generate hydrogen through combined heat, hydrogen and power process (CHHP) using a molten carbonate fuel cell [8]. Biogas produced at the waste water treatment is converted to energy using a steam turbine at the City of Los Angeles, Department of Water and Power's Scattergood Steam Power Plant. The plant employs a DFC 1500 fuel cell from FuelCell Energy (FCE) to internally reform natural gas to produce power, heat and hydrogen. The power generated by the fuel cell will be sold to local utility company and the heat produced will be sent to the facility.

The Terminal Island Water Reclamation Plant is located in San Pedro, CA and produces 50 wet tons of bio-solids and 6,768 cubic meter/day of biogas [9]. This facility employs similar equipment as the Hyperion Treatment plant to produce 544 kg/day of hydrogen using DFC 1500 FCE fuel cell. The usage of same system at both locations will aid in lowering the cost and will benefit the design in various ways. The power produced from the Hyperion Treatment plant will be sold to the local utility company and the heat generated will be transferred to the fueling station. The Terminal Island Water Reclamation Plant was developed by the Bureau of Sanitation and Department of Water and Power to harness the renewable hydrogen produced using biogas. A 250 kW molten carbonate fuel cell has been installed to generate renewable energy to provide the power to the city of Los Angeles.

Hydrogen produced at the Hyperion Treatment Plant and Terminal Island Water Reclamation plant is compressed by employing a two-stage diaphragm compressor from PDC machines and the compressed hydrogen is transported by tube trailers.

# 3. HYDROGEN STATION TECHNICAL DESIGN

This section explains the design of the proposed hydrogen fueling station in Santa Monica which includes the hydrogen production, compression, storage and dispensing of fuel. Renewable sources account for 100% of the supplied hydrogen. Several options were considered but the on-site hydrogen production with tube trailer delivery of renewable hydrogen was chosen [10, 11]. The station has a dispensing capacity of 400 kg of $H_2$ per day at 350 bar and 700 bar. It can continuously dispense upto 240 kg of hydrogen without recharging the storage tanks with a high customer service level.

Figure 3.1 shows the conceptual hydrogen fueling station at Olympic Boulevard, a suitable location chosen for the installation. The decision was based on its proximity to existing hydrogen stations, potential customers and easy access from the roads and nearby highways.

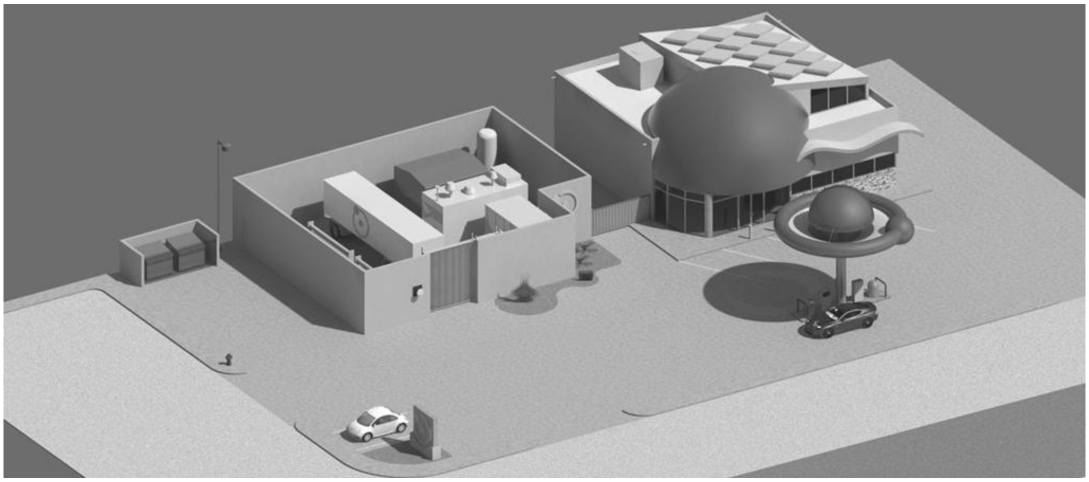

Figure 3.1. Hydrogen fueling station

The Piping and Instrumentation Diagram shown in Figure 3.2, illustrates the major equipment employed in the design. The figure also shows the pathway of hydrogen from the tube trailer to the dispenser at the hydrogen station.

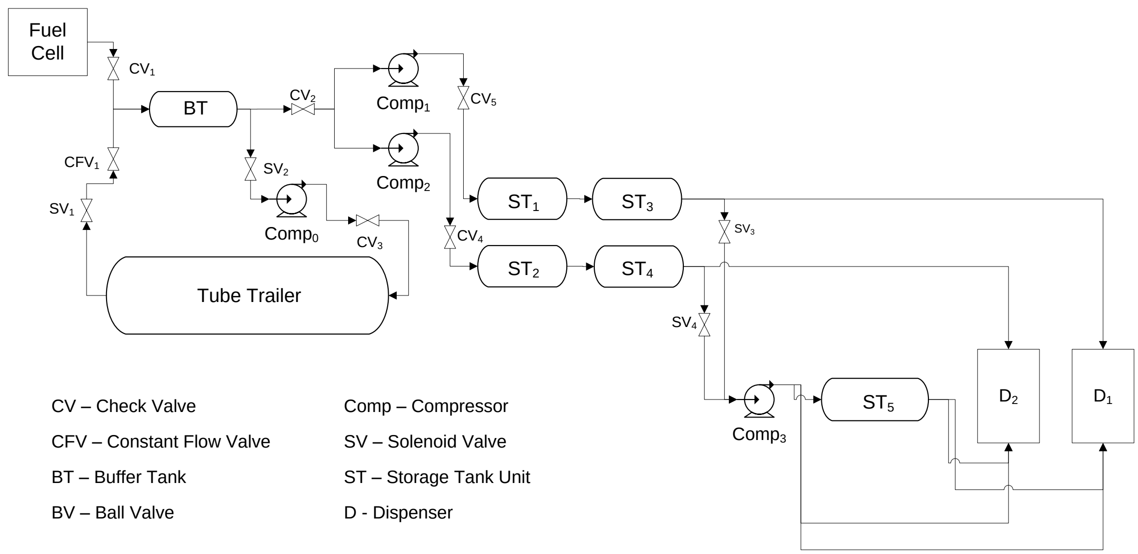


Figure 3.2. Major components of hydrogen fueling station

The main sources of hydrogen include renewable hydrogen from Hyperion Treatment Plant and Terminal Island Water Reclamation Plant which will be transported to the station through a tube trailer. The total amount of hydrogen dispensed during the three day time period using renewable energy sources was estimated to be approximately 100% of the total fuel supplied during the period. DFC 300 FCE fuel cell generates approximately 136 kg/day of hydrogen. It runs 24 hours a day and is stored in the buffer tank. The fuel cell produces a maximum of 300 kW of electric power when the tank is full. The total storage capacity at the fueling station is around 198 kg with the capability of reaching 240 kg of hydrogen. The heat produced from the fuel cell is used at the fueling station and the convenient store. The four storage tanks $ST_1$, $ST_2$, $ST_3$ and $ST_4$ can accumulate 11 kg of hydrogen at 450 bar. The storage tank $ST_5$ consists of three tanks which can store up to 22 kg each at 700 bar. Table 3.1 provides the specifications of the major components of the hydrogen fueling station.

Table 3.1 Specifications of major components

| # | Item | Specifications | Company |
|---|---|---|---|
| 1 | Fuel Cell – DFC 300 | 250 kW/136 kg$H_2$/day | Fuel Cell Energy |
| 2 | Buffer Tank | ~ 5 kg @ 14 bar | - |
| 3 | Tube trailer (rent) | 300 kg @ 207 bar | APCI |
| 4 | Hydrogen Compressor | 8 bar – 207 bar @ 6 kg/hr | APCI |
| 5 | Hydrogen Compressor | 8 bar – 415 bar @ 13 kg/hr | APCI |
| 6 | Hydrogen Compressor | 415 bar – 830 bar @ 18.5 kg/hr | Hydro-Pac |
| 7 | Storage unit (350 bar) | 33 x 4 = 132 kg | APCI |
| 8 | Storage unit (700 bar) | 66 kg | APCI |
| 9 | Hydrogen Dispenser | 350 bar & 700 bar | APCI |

The compressors listed in the above table are oversized to achieve high customer service level at the fueling station. The dispensing capability can go up to 400 kg of hydrogen in 14 hours due to the presence of compressors and storage tanks. The two dispensers provided by Air Products and Chemicals, Inc. (APCI) are capable of dispensing at 350 bar and 700 bar. The fueling time for vehicles varies from 5 minutes for 350 bar to 7 minutes for the 700 bar vehicle. The hydrogen fueling process shown in Figure 3.3 and Figure 3.4 is simulated for 350 bar and 700 bar fueling using Cascade fueling system analysis engineering software to select the components for the hydrogen station. Forty one vehicles are fueled continuously in 7 hours using the 350 bar hydrogen dispenser. The 700 bar hydrogen dispenser fuels twenty vehicles continuously in 4 hours.

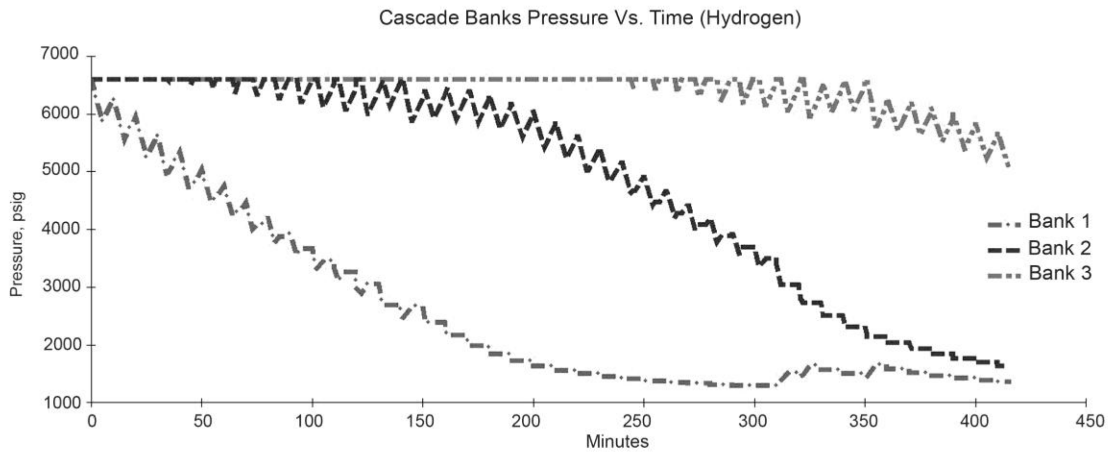


Figure 3.3. Cascade simulation results for 350 bar fueling

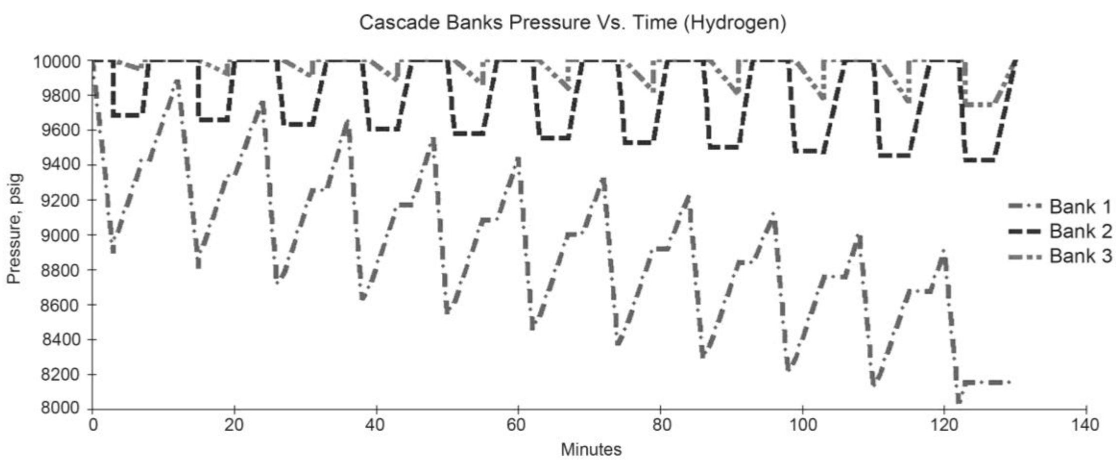


Figure 3.4. Cascade simulation results for 700 bar fueling

## 4. EARLY MARKET APPLICATIONS

Early market customers play an important role in providing an accurate picture of the market conditions and spreading awareness about the applications of hydrogen technologies. In Southern California, Santa Monica is a leader in the area of fuel cell vehicles with around 87 of them operating on hydrogen [2, 12]. Table 4.1 discusses the early market applications including material handling at warehouses and distribution centers, back-up power and portable power [13, 14].

The concept considers material handling equipment including forklifts, gators, lift-trucks, palter jacks and stock pickers as one of the fastest growing applications for fuel cell technologies [15]. They are used by large manufacturing units, warehouses and airports for transporting heavy materials at high efficiency. Hydrogen fuel cells are also a great source of back-up power at various locations including schools, universities, banks and hospitals. Another area where fuel cells are used is in portable power applications such as law enforcement, security cameras, emergency response system, telecommunication and recreational purposes [16]. The advantages of operating with fuel cells include lower maintenance cost, longer running times, higher reliability and higher energy efficiency.

Table 4.1 Early market applications of fuel cells

| Purpose | Customer | Model | Average hydrogen consumption |
|---|---|---|---|
| Material Handling | LA International Airport, City of Santa Monica, Lowe's Home Improvement | Hydrogenics HyPM HD12 PEM fuel cell | 88 kg/day |
| Back-up Power | Crossroads School, LA Orthopaedic Hospital, Will Rogers State Historic Park, Wachovia Bank | Altergy Freedom Power FCM 5 PEM fuel cell | 153 kg/day |
| Portable Power | City TV 16, UCLA Medical Center, Boy Scout Camping | Jadoo Power XRT N-Gen180 fuel cell | 9 kg/day |

## 5. SAFETY ANALYSIS

Hydrogen safety is a primary concern for the implementation of any hydrogen energy system in a community. Precautionary measures have to be in place during the production, compression, storage and dispensing of hydrogen gas. Hydrogen has proved to be safe for industrial applications but the handling of the gas by untrained personnel may increase the initiation of hydrogen-related accidents. This will result in slower growth of hydrogen system applications leading to challenges in the commercialization of the technology. Therefore special care is required to not only identify the probable failure modes of hydrogen systems but also mitigate risks and provide the community with the necessary instructions to operate the various hydrogen systems.

A failure mode effect analysis has been performed to identify the different failure modes, causes of failure and steps taken to mitigate the risks associated with the application of hydrogen technologies [17]. Important failure modes considered are the fire caused due to static electric discharge and improper connection leading to hydrogen leakage in piping and storage tanks [18]. Some of the steps taken to alleviate these risks are to install infrared sensors which can detect a flame in the vicinity of hydrogen systems and also proper and timely inspections of the piping and connections. The usage of hydrogen leak detectors is another option to identify the presence of hydrogen in the area. The failure of the pressure relief devices on the dispenser and storage tanks leads to dispenser cascade control failure and piping failure. This issue can be resolved by regular inspection of the hydrogen dispenser. Some of the other possible failure modes considered are hardware failure, electrical power outage, human operator error, fire and combustion of hydrogen and natural disasters [17]. This design of the hydrogen fueling station was chosen over the others due to its ability to reduce the occurrence of failure. Some of the safety regulations followed at the hydrogen fueling station comply with National Fire Protection Association 55 (NFPA), NFPA 52, NFPA 853, Society of Automotive Engineers (SAE) J2600, SAE Technical Information Report (TIR) J2601 and International Codes Council [19].

## 6. ENVIRONMENTAL ANALYSIS

Well-to-wheel analysis shown in Figure 6.1, compares the emissions of a fuel cell and a gasoline vehicle using GREET analysis software. The carbon emissions of a hydrogen fuel cell vehicle (124 g/km) is 55.7% lesser than a gasoline vehicle (279.1 g/km). In addition, nitrous oxide and green house gas emissions are also reduced.

Table 6.1 Well-to-wheel analysis

| **Gasoline Vehicle: Conventional Gasoline and Reformulated Gasoline** | | | |
|---|---|---|---|
| | **kJ/km or g/km** | | |
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** |
| Total Energy | 178 | 631 | 3,218 |
| Fossil Fuels | 163.4 | 499 | 2,986 |
| Coal | 0.6 | 56 | 0 |
| Natural Gas | 127.4 | 188.3 | 0 |
| Petroleum | 35.4 | 254 | 2,986 |
| $CO_2$ (w/ C in VOC & CO) | 9.4 | 35.4 | 234.3 |
| $CH_4$ | 0.3 | 0 | 0 |
| $N_2O$ | 0 | 0 | 0 |
| GHGs | 16.8 | 36.7 | 237 |

| **FCV: grams of $H_2$** | | | |
|---|---|---|---|
| | **kJ/km or g/km** | | |
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** |
| Total Energy | 92 | 1,038 | 1,399 |
| Fossil Fuels | 86.4 | 805.3 | 1,179 |
| Coal | 0 | 0 | 0 |
| Natural Gas | 78.3 | 798 | 1,179 |
| Petroleum | 8 | 7.5 | 0 |
| $CO_2$ (w/ C in VOC & CO) | -21 | 145 | 0 |
| $CH_4$ | 0.2 | 0.1 | 0 |
| $N_2O$ | 0 | 0 | 0 |
| GHGs | -16.2 | 149 | 0 |

## 7. RESULTS AND CONCLUSION

This article describes the conceptual design of a hydrogen community at Santa Monica, California. The main focus of the design is the production of hydrogen using renewable energy sources. Biogas serves as an ideal renewable energy source for the production of hydrogen contributing to 100% clean hydrogen to be dispensed during the three day period. The four compressors are coupled with three-bank cascade storage system configuration to assist in the fueling using both the dispensers.

The concept identifies forklift propulsion systems, back-up power in the telecommunication sector and portable power for emergency purposes as potential early market customers in the near term. Early market customers account for approximately a total of 250 kg/day of hydrogen. A well-to-wheel analysis is performed to compare the total energy consumption and emissions of $CO_2$ and other harmful gases of fuel cell and gasoline vehicles. The total energy consumption of the fuel cell vehicle is approximately 37% lesser than the gasoline vehicle.

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# SECTION

## 2. CONCLUSION

This article describes the design of a scalable and reproducible hydrogen fueling station for a community located in Santa Monica, California. Different hydrogen production methods were evaluated and the requirement of producing 33% hydrogen using renewable energy sources was achieved. Biogas produced at the Hyperion Treatment Plant and Terminal Island Water Reclamation Plant served as an ideal renewable energy source. Various hydrogen technologies were considered for the hydrogen fueling station and the appropriate ones have been selected.

Early market customers including forklifts, back-up power systems in telecommunication firms and portable power for emergency and security purposes have been identified. The daily requirements of these customers are approximately 250 kg/day of hydrogen. Hydrogen safety is a critical area and has been extensively addresses through this article. The design considers various failure modes and the safety procedures have been followed in and around the hydrogen fueling station. The emissions of a fuel cell vehicle and gasoline vehicle have been compared using GREET analysis software. The carbon emissions and the total energy consumption of a hydrogen fuel cell vehicle are significantly lesser than a gasoline internal combustion engine vehicle. The total cost of the design has been calculated and a business plan formulated. Onboard vehicle storage of hydrogen, cost and durability of fuel cells are some of the challenges facing the commercialization of fuel cell vehicles. Thus, the introduction and maintenance of hydrogen technologies in Santa Monica can not only keep the environment clean but also lead by example for future hydrogen communities.

# APPENDIX A

# FUEL CELL AND HYDROGEN ENERGY ASSOCIATION STUDENT DESIGN CONTEST REPORT ON

# "DESIGNING A HYDROGEN COMMUNITY"

## 1. ABSTRACT

Hydrogen and hydrogen technologies have the potential to increase energy security, stimulate economic growth, and reduce greenhouse gas emissions. Even though there have been many projects worldwide that have proven the feasibility, durability, and reliability of hydrogen technologies, they are still in the demonstration phase. To promote the transition of hydrogen technologies to real-world commercial operation, California Fuel Cell Partnership (CaFCP) released an Action Plan that outlines the strategies for the development of early “hydrogen communities” in the State of California. This report focuses on the design of one such hydrogen community located in Santa Monica, California.

The design includes reproducible and scalable hydrogen fueling stations, renewable hydrogen sources in the community, and potential customers for early market hydrogen applications. Different hydrogen production technologies, including steam methane reforming, electrolysis, on-site hydrogen production, and centralized hydrogen production, were evaluated and technologies appropriate for the hydrogen demand in Santa Monica were selected. Emphasis was given to hydrogen produced from renewable sources such as biogas and landfill gas. Other hydrogen technologies selected in the design include materials handling vehicles, stationary back-up power systems, portable power, and other niche products powered by hydrogen. The design also includes a unique hydrogen system dedicated for public education.

Ultimately, public safety and public perception of hydrogen technologies are the biggest challenge. All hydrogen systems selected will meet or exceed existing safety codes and standards. Significant failure modes have been identified and measures have been taken to mitigate them. An economic and environmental analysis was conducted to evaluate the benefits of deploying hydrogen technologies in the Santa Monica community. Finally, implementation of the design will initiate the transition from demonstration phase of the hydrogen technologies to a real-world commercial operation.

## 2. HYDROGEN PRODUCTION EVALUATION

Numerous programs around the world demonstrated hydrogen vehicle and fueling station technologies in the past decade which are now ready to begin the transition to commercial operation. In February 2009, the California Fuel Cell Partnership (CaFCP) released an Action Plan that outlines a near term strategy for the development of early "hydrogen communities" with clusters of retail hydrogen stations in four Southern California communities: Santa Monica, Irvine, Torrance and Newport Beach. The design report illustrates the design of a hydrogen community in Santa Monica, California. During the project, one scalable fueling station was designed and renewable hydrogen sources in the community and customers for early market hydrogen applications were identified. The hydrogen technologies and systems selected in the project plan will be commercially available and possible to implement for practical, real-world use by May 2010.

Hydrogen can be produced from a variety of sources like water, biomass, natural gas, coal, etc and has the potential to increase energy security, reduce green house gas emissions, and stimulate economic growth. During the contest, the team evaluated and identified the potential for production of hydrogen from renewable or byproduct sources near Santa Monica, CA. Three existing facilities within 25 miles of Santa Monica city limits capable of producing of renewable hydrogen were identified (Figure 2.1) and are listed below.

1. Hyperion Treatment Plant, Playa Del Rey

2. Terminal Island Water Reclamation Plant, San Pedro

3. Palos Verdes Gas-to-Energy Facility, Rolling Hills Estates

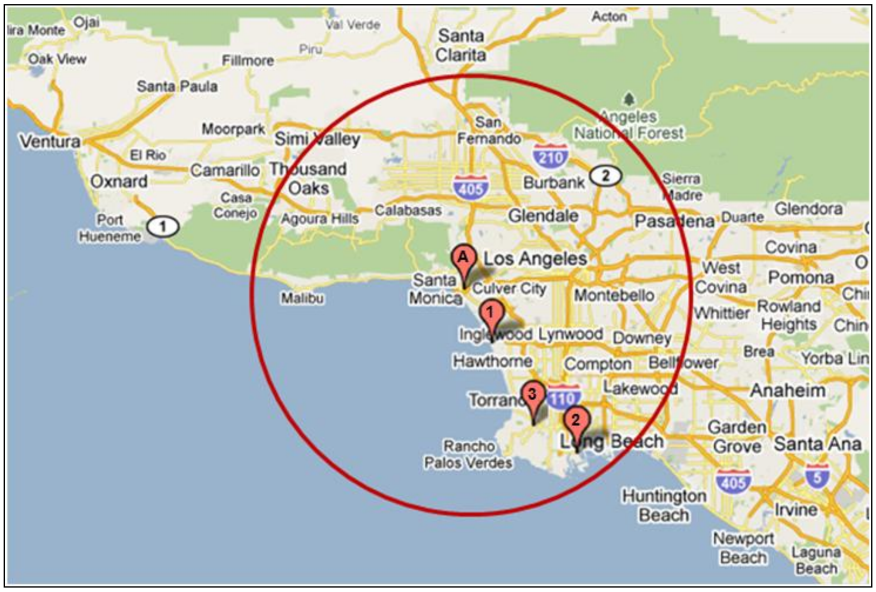


Figure 2.1. Hydrogen production locations within 25 miles of Santa Monica [1]

Hyperion Treatment Plant and Terminal Island Water Reclamation Plant produce biogas (50% - 75% methane) [2] during water treatment process while the Palos Verdes Gas-to-Energy Facility generates landfill gas (50% - 55% methane) [3] at its facility. Methane present in these gases will be separated and will be used to produce hydrogen via steam methane reformation. Hydrogen generated at these facilities is considered to be renewable hydrogen since it uses biogas and landfill gas as feedstock. Hydrogen will be compressed on-site and will be transported to the proposed hydrogen fueling station in Santa Monica via a tube trailer. The total hydrogen production from these facilities adds up to approximately 1,200 kg/day. A description of each facility can be found in Table 2.1.

Table 2.1 Hydrogen production facilities

| ***Name of Producer*** | ***Location*** | ***Production Method*** | ***Hydrogen Produced per day*** | ***Production Facility Availability*** |
|---|---|---|---|---|
| **Hyperion Treatment Plant** | 12000 Vista del Mar, Playa Del Rey, CA 90293 | Steam methane reformation of biogas | 544 kg | > 97% |
| **Terminal Island Water Reclamation Plant** | 445 Ferry St, Los Angeles, CA 90731 | Steam methane reformation of biogas | 544 kg | > 97% |
| **Palos Verdes Gas-to-Energy Facility** | 25706 Hawthorne Boulevard Rolling Hills Estates, CA 90274 | Steam methane reformation of landfill gas | 88 - 115 kg | 65% - 85% |

Hydrogen production and process at the three facilities is explained in the following sections.

## 2.1 HYPERION TREATMENT PLANT

Waste water treatment plants are ideal for utilizing biogas as a renewable energy source. The Hyperion Treatment Plant is Los Angeles' oldest and largest wastewater treatment facility. The plant has been operating over a century and produces 650 tons of bio-solids and 8 million cubic feet of biogas per day [4]. The sludge accumulated during the wastewater treatment process is treated and stabilized for safe disposal by using anaerobic digestion. During this process microorganisms convert organic materials to biogas in the absence of oxygen. Biogas produced during the waste water treatment is sent to the City of Los Angeles, Department of Water and Power's Scattergood Steam Power Plant through a pipeline where it is converted to energy using a steam turbine.

Since biogas is available in high volume, the team recommends the facility to be a major hydrogen production location. The design proposes to use biogas generated at the treatment plant to produce hydrogen through a combined heat, hydrogen, and power (CHHP) process where heat, hydrogen and power will be produced on-site using a molten carbonate fuel cell. Biogas from the facility will first undergo pretreatment through a gas processing unit to remove harmful compounds before being fed into the fuel cell.

The DFC 1500 fuel cell from Fuel Cell Energy (FCE) has the capacity to internally reform natural gas or anaerobic gas to produce power, heat, and hydrogen. It has high efficiency, low environmental impact, high reliability, quiet operation and a 20 year power-plant life with overhaul at the end of five years [2]. The fuel cell can operate in two modes (i) combined heat and power (CHP), (ii) combined heat hydrogen and power (CHHP). During the CHP mode it is capable of producing 1.4 MW of electric power at 47% efficiency and the heat energy available for recovery (to 250°F 2,216,000 Btu/h (to 120°F) 3,730,000 Btu/h [5]. During the CHHP mode it is capable of providing 1 MW of electric power at 47% efficiency and 544 kg of hydrogen per day [6]. Hydrogen produced during CHHP is made at the expense of the power. A total of 554 kg of hydrogen (~160 scfm) will be produced at this facility and the power produced from the fuel cell will be sold to the local utility company. The heat generated in the fuel cell will be fed into the facility. The facility is assumed to be working 24 hours a day with a production facility availability of greater than 97% [6]. The reactions inside the fuel cell during the hydrogen production and power generation are as follows.

Hydrogen production:

*Steam-Reforming Reactions*

*Water-Gas Shift Reaction*

Power generation:

*Anode Reaction:*

*Cathode Reaction:* –

## 2.2 TERMINAL ISLAND WATER RECLAMATION PLANT

The Terminal Island Water Reclamation Plant is located at 445 Ferry St, San Pedro, CA and produces 50 wet tons of bio-solids, and 239,000 cubic feet per day of biogas [7]. This facility will employ the same systems (fuel cell, compression, storage, control, safety, etc) as the Hyperion Treatment Plant and will produce 544 kg of hydrogen per day using the DFC 1500 FCE fuel cell. Using the same systems at both the facilities will lower cost and will be beneficial in many aspects. The fuel cell provides increased energy efficiency, 42% to 47% net electrical efficiency and has the capability to cogenerate heat making the combined efficiency (electric + heat) nearly 80% [2]. The power produced from the fuel cell will be sold to the local utility company and the heat generated will be transferred to the facility. The design estimates the facility to be working 24 hours a day with a production facility availability of greater than 97% [6].

Realizing the potential of producing renewable energy using biogas at water treatment facilities, Bureau of Sanitation and the Department of Water and Power developed Terminal Island Fuel Cell Power Plant in 2003[8]. It has installed a molten carbonate fuel cell that generates 250 kW of renewable energy which provides power to city of Los Angeles. This program is a clear indication that using fuel cell power plant for co-production of electricity, heat, and hydrogen at waste water treatment plants is a good option.

## 2.3 PALOS VERDES GAS-TO-ENERGY FACILITY

Palos Verdes Gas-to-Energy Facility is located at the Palos Verdes Landfill, Rolling Hills Estates. The facility has steam power plants using landfill gas as fuel and produces approximately 4 MW of electric power [9]. The power is used to meet onsite landfill needs and the excess power is sold to the local utility company. In October 2007, Sanitation Districts of Los Angeles County proposed a project to replace the existing Gas-To-Energy Facility at Palos Verdes Landfill with new technologies including fuel cell and microturbine that will produce approximately 2 MW of renewable energy using landfill gas [9, 10].

The design will take advantage of the proposal by Sanitation Districts of Los Angeles County [10] and will install a DFC 300 FuelCell Energy (FCE) fuel cell capable of producing 250 kW of electric power and 136 kg of hydrogen per day. The fuel cell power will be used to power the on-site gas collection equipment as proposed by Sanitation Districts of Los Angeles County [10] .The fuel cell will use catalytically upgraded landfill gas [11] or treated landfill gas which is free from compounds that can harm the fuel cell. The facility is anticipated to have fluctuations in methane level and the production facility availability is considered to be 65% - 85% with hydrogen production of 88-115kg (~26-34 scfm) per day.

## 2.4 HYDROGEN COMPRESSION AND TRANSPORTATION

Hydrogen produced at Hyperion Treatment Plant and Terminal Island Water Reclamation Plant will be compressed on-site using a two-stage diaphragm compressor from Pdc Machines (PDC-13-1000-3000) [12] and will be transported to the proposed hydrogen station via a hydrogen tube trailer. Excess hydrogen will be sold commercially and the facility will have provisions for refilling hydrogen tube trailers belonging to major gas providers. Palos Verdes Gas-to-Energy Facility will have a hydrogen bottling plant capable of refilling hydrogen cylinders which will be used by the early market customers identified in Section 2. It will also have the capability to refill the mobile hydrogen refueler which will dispense hydrogen to the material handling vehicles described in Section 3. Figure 2.2 illustrates different operations at the three facilities including hydrogen production, compression, storage, and transportation.

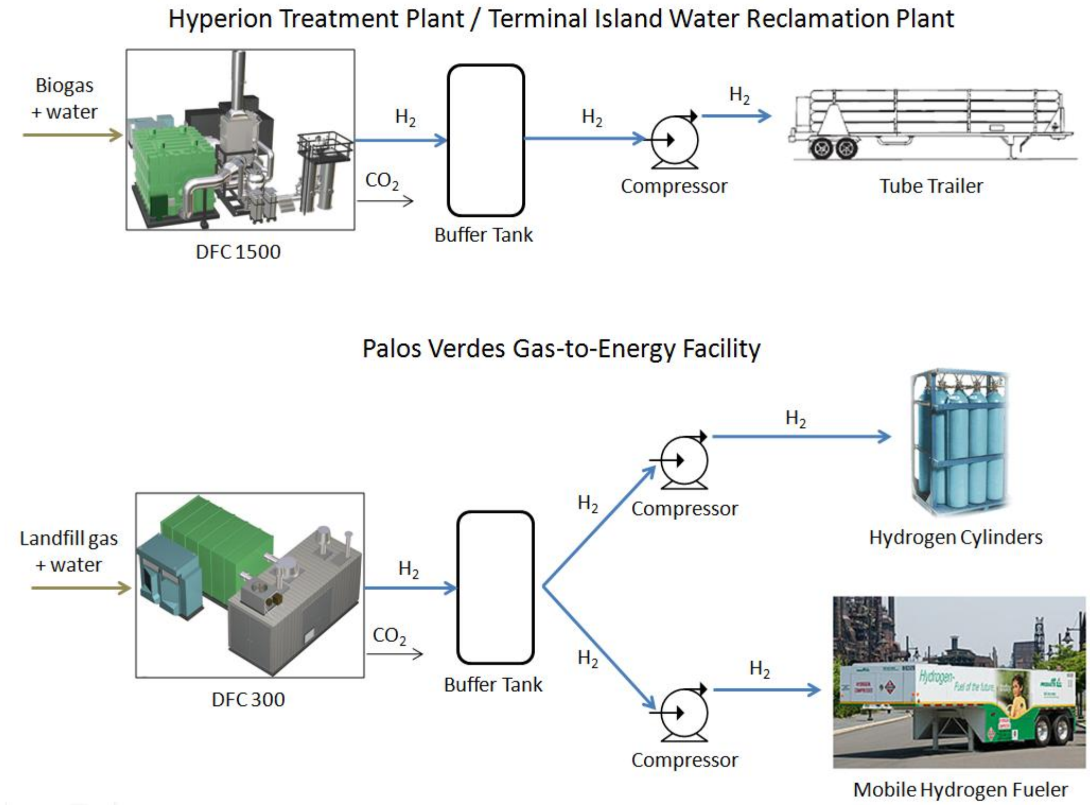


Figure 2.2. Hydrogen production, compression, and transportation [13]

The utilization of compressed hydrogen inside the tube trailer, hydrogen cylinders, and mobile hydrogen unit will be discussed in the following sections.

# 3. EARLY MARKET CUSTOMER IDENTIFICATION

Early market customers play a very important role in providing a timely and an accurate picture on the market conditions. They assist in spotting fatal flaws early and hence the whole process is inexpensive and fast. The city of Santa Monica is already a leader in alternative fuels with 87 vehicles operating using fuel cell technologies. One of the potential customers, Rick Sikes, Fleet Superintendent, City of Santa Monica says "We are in discussions to participate in a project of two 56,000 pound solid waste collection vehicles that will have electric motors powered by fuel cells to drive hydraulic pumps for the body/packer systems and propulsion". The move towards alternative fuels has received significant attention and also helped in considerably reducing the Green House Gas (GHG) emissions. He adds "We are committed to reduce our GHG and other emissions and hydrogen will certainly play a role. We typically use the money we earmark for replacements toward alternative fuel projects and supplement that with grants. We are willing to sometimes pay more for alternative fuel vehicles because there are other costs and benefits other than the purchase price of a vehicle."

## 3.1 BACK-UP POWER

Hydrogen powered fuel cells can be used as a source of back-up power at different locations including schools, universities, banks, hospitals, communication towers, etc. Currently, most of the backup power equipments are powered by batteries and generators which are mechanically driven and hence incur a high maintenance cost. Fuel cells offer a longer running time and also have high reliability and durability along with lower maintenance cost and noise pollution.

To support the different customers and their critical operations, Proton Membrane Exchange (PEM) fuel cell manufactured by Altergy Freedom Power, shown in Figure 3.1, was selected. Back-up power will be provided using a stack of five FCM 5 fuel cells generating a total output of 25 kW. For areas requiring more power, more than one stack of 6 fuel cells can be used. One unit of fuel cell weighs 158 pounds and is rated for 0-5,000 W. It can reach its maximum power overload of 6250 W in 30 seconds. It is fueled by 99.95% pure gaseous hydrogen pressurized at 15-100 psig and consumes 75 slpm [14] or 9 kg/day. The ambient temperature for its application is 32°F to 104°F. Sensors for fuel leak detection are included and these are equipped with remote communication and control ability [14]. Table 3.1 lists the early market customers that can employ fuel cells for back-up power applications.

Figure 3.1. FCM 5 fuel cell

The customers selected for providing the back-up power are:

Table 3.1 Early market customer information - back-up power

| ***Customer*** | ***Name and Location*** | ***Contact Information*** | ***Estimate of Daily Hydrogen Consumption and Usage of Hydrogen*** | ***Hydrogen Production Method*** |
|---|---|---|---|---|
| **School** | **Crossroads School**<br>1714 21st Street<br>Santa Monica, CA<br>90404-3917<br>Ph:310- 828-1196 | Eileen Gilbert<br>Administrative Assistant<br>Program Assistant/Rentals<br>ext 564 | Estimate: Five stacks of FCM 5 fuel cells will be used to generate 25 kW of back-up power consuming 45 kg/day of hydrogen.<br>Usage: This power can be used to run UPS and computers. | Delivered on-site using hydrogen cylinders |
| **Bank** | **Wachovia Bank**<br>729 Montana Avenue, Santa Monica<br>Ph:310- 451-8944 | Shantel G<br>Online Services Team | Estimate: Five stacks of FCM 5 fuel cells will be used to generate 25 kW of back-up power consuming 45 kg/day of hydrogen.<br>Usage: Back-up power generated can be used for computers, servers, alarms, communication lines security cameras, token generator, etc | Delivered on-site using hydrogen cylinders |
| **Hospital** | **LA Orthopedic Hospital**<br>1530 Arizona Avenue<br>Santa Monica, CA<br>90404-1208<br>Ph:310- 395-4814 | James V. Luck, Jr., M.D.<br>Chief Executive Officer and Medical Director<br>info@laoh.ucla.edu<br>Ph:213-) 742-1000 | Estimate: Five stacks of FCM 5 fuel cells will be used to generate 25 kW of back-up power consuming 45 kg/day of hydrogen.<br>Usage: Various uses are emergency lights, equipments in operation theatre, critical units, elevators, surveillance cameras, etc | Delivered on-site using hydrogen cylinders |
| **State Park** | **Will Rogers State Historic Park**<br>1501 Will Rogers Park Road<br>Pacific Palisades, CA 90272 | Will Rogers SHP<br>1501 Will Rogers Park Road<br>Pacific Palisades, CA<br>Ph:310-454-8212 | Estimate: Two stacks of FCM 5 fuel cells will be used to generate 10 kW of back-up power consuming 18 kg/day of hydrogen.<br>Usage: Raise public awareness about hydrogen technologies, provides power to the building, demonstration of fuel cell | Delivered on-site using hydrogen cylinders |
| **Hospital** | **LA Orthopedic Hospital**<br>1530 Arizona Avenue<br>Santa Monica, CA<br>90404-1208<br>Ph:310- 395-4814 | James V. Luck, Jr., M.D.<br>Chief Executive Officer and Medical Director<br>info@laoh.ucla.edu<br>Ph:213- 742-1000 | Estimate: DFC 300 FCE fuel cell will provide 300 kW of power<br>Usage: High quality and reliable auxiliary power. | Uses natural gas to produce hydrogen which will power the fuel cell |

Total Consumption: Hydrogen consumption for back-up power in the above mentioned places comes out to be 153 kg/day.

### 3.2 MATERIAL HANDLING

Lift trucks, gators and the other material handling equipments are used by large manufacturing units, warehouses and also airports for transporting heavy material at increased operational efficiency. Forklifts are commonly powered by batteries and internal combustion engines. But now, hydrogen fuel cell can be used to power these material handling equipments. PEM fuel cells are the ones that are being targeted for this material handling segment. PEM fuel cells are comparatively cost effective than batteries which have to be constantly replaced while running two or three shifts per day. The need for a battery charging room can also be avoided by using fuel cell powered forklifts.

The model chosen for material handling is HyPM HD12, manufactured by Hydrogenics.  This fuel cell is PEM, supplying an output of 21 kW which can be integrated to power a Class 1 forklift. The fuel cell requires 1.6 kg of hydrogen stored at 5,000 psig. The temperature at which it can be operated is around 41° to 95°F [15]. Table 3.2 lists the early market customers that can employ fuel cells for material handling purposes.

### 3.3 PORTABLE POWER

Fuel cells can also be used in portable power applications such as law enforcement, surveillance/security cameras, emergency response and telecommunication purposes. Fuel cells are extremely energy efficient and have significantly longer run-times than batteries and also provide a clean and a reliable way of generating portable power. The fuel used in the design for producing portable power is XRT N-Gen180TM fuel cell shown in Figure 3.3, manufactured by Jadoo Power. N-Gen 180 is a

Table 3.2 Early market customer information - material handling vehicles

| ***Customer*** | ***Name and Location*** | ***Contact Information*** | ***Estimate of Daily Hydrogen Consumption and Usage of Hydrogen*** | ***Method of hydrogen production*** |
|---|---|---|---|---|
| **Airport** | **Los Angeles International Airport** Los Angeles, CA 90045 | LAX Public Relations Division One World Way Administration East Ph: 424- 646-5260 | Estimate: Twenty forklifts each using 3.2 kg of hydrogen/day, consuming total of 64 kg/day. Usage: Forklifts can be used for handling baggage. | On-site fueling using mobile hydrogen fueler |
| **Santa Monica City** | **Santa Monica City** 1685 Main Street Santa Monica, CA 90401 Ph:310-458-8411 | Stuart Cooley, Energy Efficiency Engineer Office of Sustainability and the Environment 1212 Fifth Street, First Floor Santa Monica, CA 90401 Ph: 310- 458-2238 | Estimate: Ten forklifts are to be powered each using 1.6 kg of hydrogen/day, this means total consumption of 16 kg/day. Usage: Transportation of heavy duty material for Public Works Department. | On-site fueling using mobile hydrogen fueler |
| **Warehouse** | **Lowe's Home Improvement** -Ph:310- 787-1469 | Desiree Poro Manager, Ph: 310- 602-209 | Estimate: Five forklifts are to be powered resulting in consumption of 8 kg /day of hydrogen. Usage: Transportation of hardware. | On-site fueling using mobile hydrogen fueler |

Total Consumption: Total hydrogen consumption of three customers for fuel cell powered forklifts in material handling is 88 kg/day.

PEM fuel cell shown in Figure 3.4, supplies 180Amp hours of run time with no self discharge. The power output of the fuel cell is 100 W. Figure 3.5 shows N-Stor 130™ hydrogen canisters stored at pressure of 400 psig, which is used to run the fuel cell. Table 3.3 lists the early market customers that can employ fuel cells for portable power applications.


Figure 3.3. XRT Extended Runtime adaptor [16, 17]


Figure 3.4. N-Gen Fuel cell [16, 17]

Figure 3.5. N-Stor hydrogen canisters [16, 17]

Table 3.3 Early market customer information - portable power

| ***Custome r*** | ***Name and Location*** | ***Contact Information*** | ***Estimate of Daily Hydrogen Consumption and Usage of Hydrogen*** | ***Method of hydrogen production*** |
|---|---|---|---|---|
| **News Channel** | **City TV 16**<br>1717 4th Street, Suite 100 Santa Monica, CA 90401 | Robin Gee<br>Manager<br>Ph:310-458-8590 | Estimate: Five portable fuel cells can be used to power consuming total of 2 kg/day.<br>Usage: To provide power to recording equipments in remote and urban areas. | Canister refilled using delivered $H_2$ cylinders |
| **Hospital** | **UCLA Medical Center - Santa Monica**<br>1250 16th Street Santa Monica, CA 90404<br>Ph:310- 319-4000 | Posie Carpenter<br>Chief Administrative Officer<br>- - | Estimate: Ten fuel cells consuming a total of 4 kg/day of hydrogen.<br>Usage: Providing emergency medical services to remote areas. | Canister refilled using delivered $H_2$ cylinders |
| **Camps** | **Boy Scout Camping WLACC**<br>16525 Sherman Way, Unit C-8, Van Nuys, CA<br>Ph:818- 785-8700 | Barry Swenson<br>Training Chairperson<br>SZonian@yahoo.com | Estimate: Eight portable fuel cells can be used to power consuming total of 3 kg/day.<br>Usage: Portable fuel cell can be used to power field communication. | Canister refilled using delivered $H_2$ cylinders |

Total Consumption: Total hydrogen consumption of customers for portable fuel cell is 9 kg/day. A total of 250 kg/day of hydrogen will be used by the early market customers that are identified in the report.

# 4. HYDROGEN STATION TECHNICAL DESIGN

This section illustrates the design of the proposed hydrogen station in Santa Monica including production, compression, storage, and dispensing of hydrogen. To attract state funding, at least 33% of hydrogen supplied will be produced from renewable sources. Different options were evaluated during the hydrogen station design including use of liquid hydrogen delivery, pipeline delivery, tube trailer delivery, on-site production, etc. The design finally selected on-site hydrogen production with tube trailer delivery of renewable hydrogen for the reasons shown in Table 4.1.

Table 4.1 Station design options

| ***Technologies evaluated during design*** | ***Observations*** |
|---|---|
| **Liquid delivery of renewable hydrogen** | Expensive way to produce, store, transport hydrogen |
| | Losses from vaporization adds significant costs |
| **Tube trailer delivery via two trailers** | Daily delivery will be needed |
| | Connecting and disconnecting the trailer daily is not practical |
| **On-site hydrogen production** | Cannot provide 33% of renewable hydrogen |
| **Pipeline** | High infrastructure cost |
| **On-site hydrogen production with tube trailer delivery of renewable hydrogen** | Tube trailer rotation only at the end of third day, 33% renewable hydrogen supply, fuel cell eligible for 100% incentive |

The station will be capable of dispensing 400 kg of hydrogen per day and will have the capacity to dispense hydrogen at both 5,000 and 10,000 psi. It was designed to dispense up to 240 kg of hydrogen continuously without suspending operations to recharge the storage tanks and will have a high customer service level. Each dispenser can operate independently and can function even if one of the sources (fuel cell or tube trailer is down for maintenance) is not functioning. The hydrogen station operation will be discussed in detail in the following sub-sections.

## 4.1 SITE LOCATION

Current real estate locations throughout Santa Monica, CA were researched, both with and without existing structures on site. The top locations were scrutinized for their proximity to current hydrogen refueling stations, potential area customers, as well as access and visibility from freeways through the city. A location was found off Olympic Boulevard that allowed the best site layout and the potential to acquire more land to the west as needed. The site has two existing warehouses. The one closest to Olympic Boulevard would be demolished, while the warehouse at the back would be partially demolished reusing the existing foundation and the majority of the walls to save materials. Additionally, the site offered complete visibility from the road and Highway 10 immediately behind the property. The proposed hydrogen station located at 1710 12th Street in Santa Monica, shown in Figure 4.1, is an industrial type property with a lot size of 14,994 square foot and is priced at $3,995,000 [18].

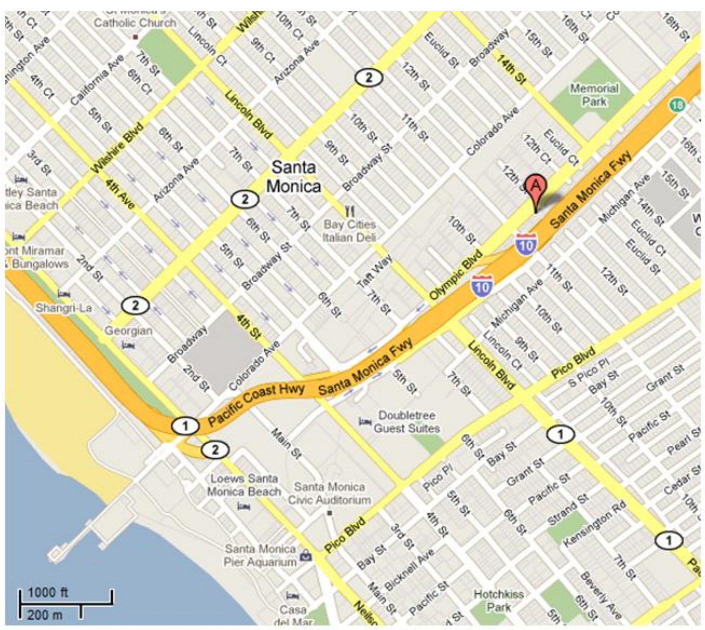


Figure 4.1. Location of the proposed hydrogen fueling station [19]

## 4.2 SITE PLOT

The hydrogen refueling station was designed on a rectangular lot that would accommodate the refueling area for vehicles, maximum hydrogen storage capabilities and a sustainably designed convenience store.

A popular architectural phenomenon that occurred through southern California starting in the early 1920's was the use of novelty, or 'programmatic,' architecture. This style of architecture essentially takes the form of the products that a particular building sells. The inspiration behind the hydrogen refueling station design was to capture the essence of the hydrogen atom in a shape that would be recognized by everyone passing on Olympic Boulevard in Santa Monica. The blue hydrogen atom can be seen emerging into the Santa Monica community, bursting from the existing status quo of conventional gas stations. This concept was refined to include sustainable building components including a rain water collection system from the refueling island canopy for site irrigation and utility needs as well as solar panels on the convenience store roof.

The awning over the refueling pumps further carries the hydrogen theme by displaying the $H_2$ logo to traffic traveling Northeast on Olympic Boulevard. The site layout accommodates both convenience store customer parking as well as parking for customers who are refueling their hydrogen vehicles. The station refueling area boasts of two hydrogen pumps available to either the left or right side of a vehicle. Additional employee parking is available to the Northeast corner of the site. Great attention to detail was spent on the layout of the site. The design of the hydrogen storage area was located so that a hydrogen delivery truck would be able to easily place a trailer within the equipment area for the hydrogen delivery.

The vehicle refueling area as well as the gated entrance next to the hydrogen storage area both provides highly visible shut off buttons in the case of an emergency. The island incorporates fabric architecture into the design of the canopy. The canopy shields drivers from rain or intense sun while refueling their vehicles and illuminates the refueling area at night. The island canopy provides a clearance of 14 feet to accommodate large vehicles or trucks.

A two-hour fire wall surrounds the hydrogen storage area, shielding the convenience store and local sidewalks in the event of failure. There is no roof over the hydrogen storage arena allowing for ample ventilation. The electrical control panel for the hydrogen area is located within the convenience store, keeping it safe and can be accessed easily by any clerk or attendant. As a precaution a flame sensor system as well as security cameras were placed within the hydrogen storage area. The site plot and the different views of the hydrogen station and convenience store can be found in Figures 4.2 – 4.6.


Figure 4.2. Plot layout

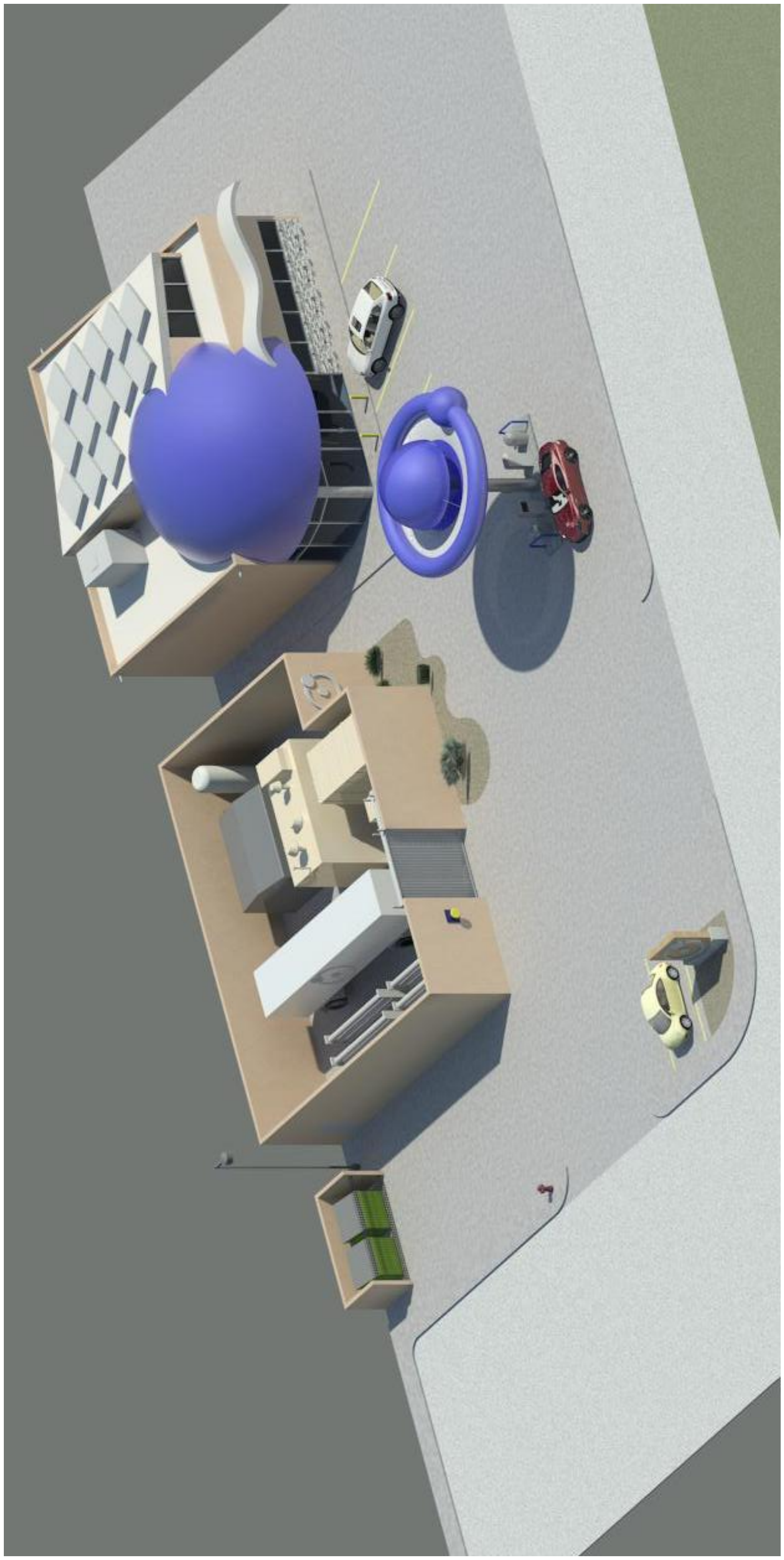

Figure 4.3. Hydrogen station and convenience store

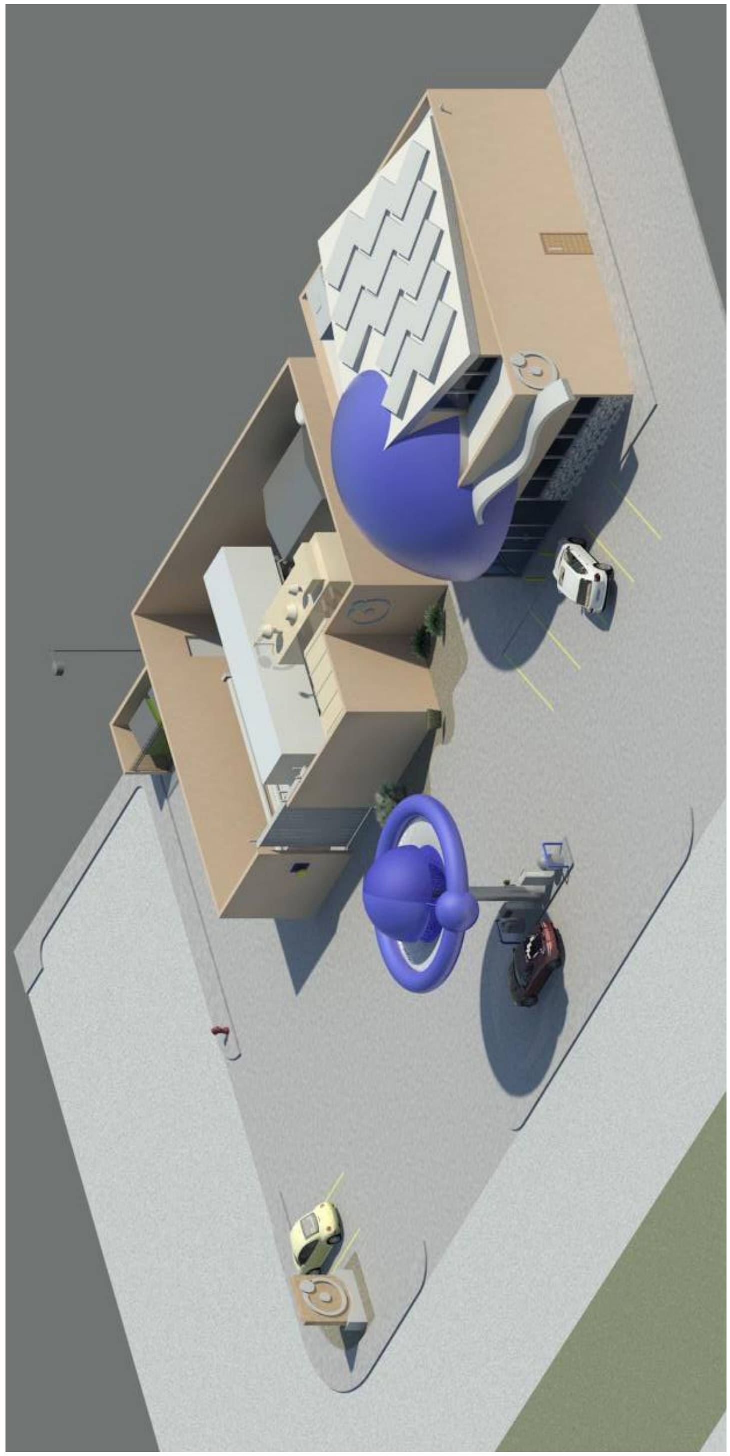

Figure 4.4. Hydrogen station and convenience store Alternate View

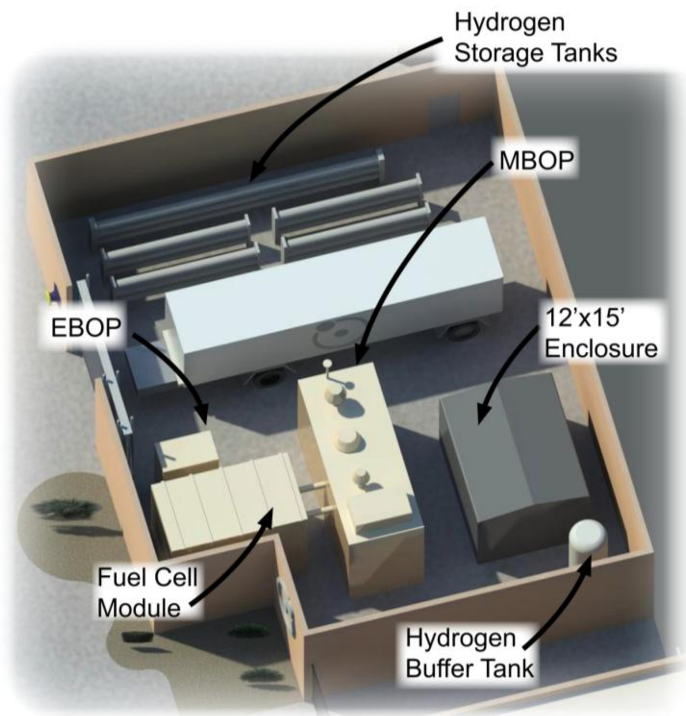


Figure 4.5. Hydrogen production, compression and storage area

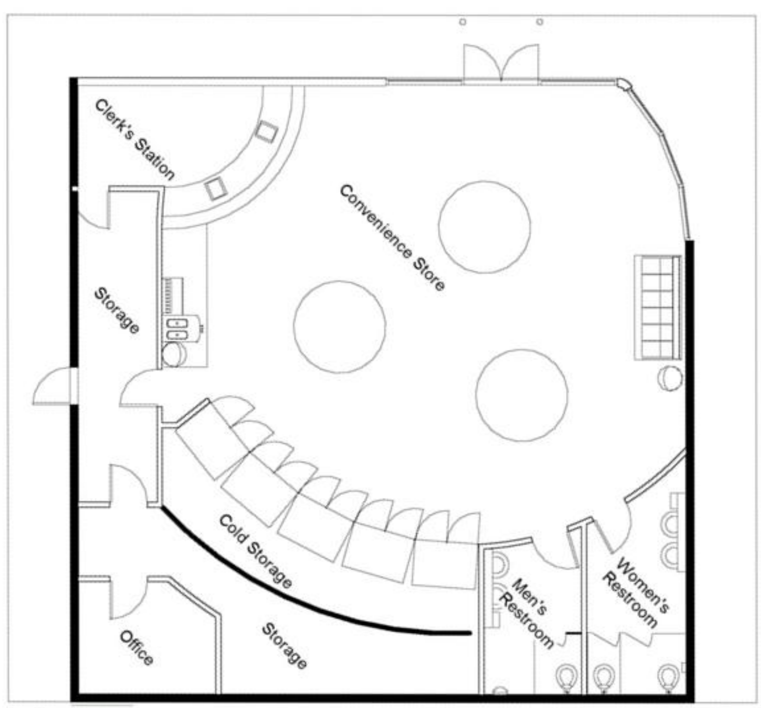


Figure 4.6. Floor plan - Convenience store

## 4.3 HYDROGEN FUELING STATION COMPONENTS

This section explains delivery of compressed hydrogen from tube trailer, on-site hydrogen production, compression, storage, and dispensing at the hydrogen station. A major portion of the equipments including compressors, storage tanks, dispenser, etc will be provided by APCI [20]. Figure 4.7 shows the major components at the station. However, it should be noted that it does not include all the piping and valves and it explains the fueling station operation illustrated in Section 4.5.

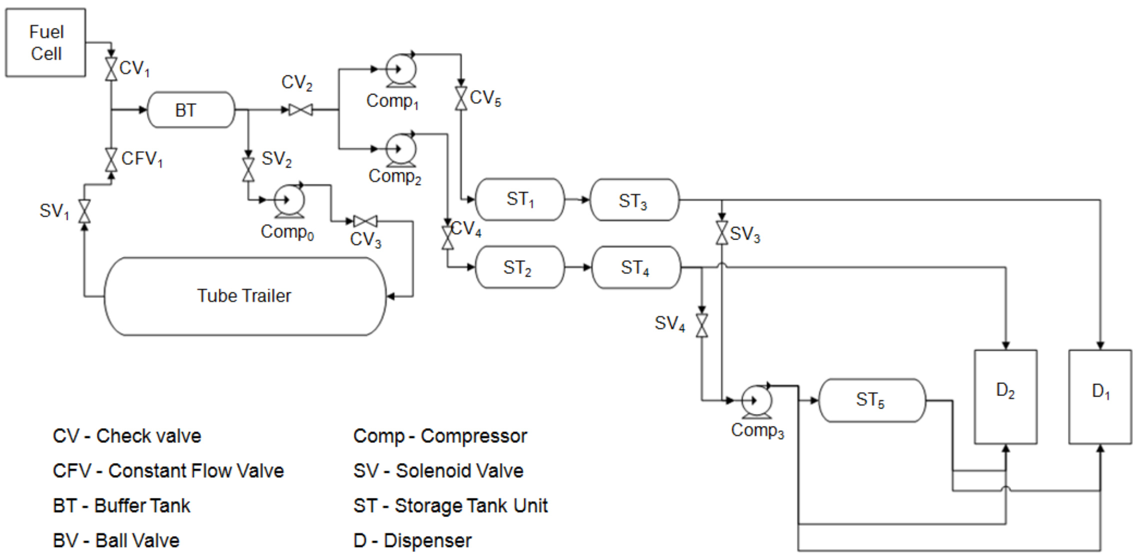


Figure 4.7. Major components at the hydrogen fueling station

Table 4.2 provides the specification and other details of the major components at the fueling station.

Table 4.2 Specifications of major components [20]

| # | Item | Specification | Company |
|---|---|---|---|
| 1 | Fuel Cell – DFC 300 | 250kW / 136 kg $H_2$/day | Fuel Cell Energy |
| 2 | Buffer Tank | ~ 5 kg @ 200 psi | - |
| 3 | Tube trailer (rent) | 300 kg @ 3,000 psi | APCI |
| 4 | Hydrogen compressor | 120 psi - 3000 psi @ 40 scfm | APCI |
| 5 | Hydrogen compressor | 120 psi - 6000 psi @ 90 scfm | APCI |
| 6 | Hydrogen compressor | 6,000 psi – 12,000 psi @ 130scfm | Hydro-Pac |
| 7 | Storage unit (5000 psi) | 33 x 4 = 132 kg | APCI |
| 8 | Storage unit (10,000 psi) | 66 kg | APCI |
| 9 | Hydrogen dispenser | 5,000 psi & 10,000 psi | APCI |

**4.3.1 Delivery of Compressed Hydrogen.** As mentioned earlier, hydrogen supplied at the station will be coming from two sources i.e. renewable hydrogen (produced off-site from biogas and landfill gas) and non-renewable hydrogen (produced on-site from natural gas). Renewable hydrogen from Hyperion Treatment Plant and Terminal Island Water Reclamation Plant will be transported to the station via a tube trailer leased from APCI. The tube trailer can carry 300 kg of hydrogen at 3,000 psi and will be exchanged for a new one every three days to meet the 33% renewable hydrogen criteria. The total amount of renewable hydrogen dispensed during the three day time period was estimated to be approximately 270 kg which is more than 33% of the total fuel supplied during the period.

**4.3.2 On-site Production**. A DFC 300 FCE fuel cell will be installed at the hydrogen station which generates 136 kg/day of hydrogen and 1MW of power using steam methane reformation of natural gas. The fuel cell will run 24 hours a day and the hydrogen produced from it will be fed to the buffer tank BT shown is Figure 3.7.There will be some instances during the operation of the station when the station does not require hydrogen from the DFC 300 fuel cell. For example, during the tube trailer exchange and when the storage is full, the fuel cell will run at its maximum capacity and will produce 300 kW of electric power. The heat produced from the fuel cell will be used at the fueling station and convenience store.

**4.3.3 Storage.** Hydrogen will be stored on-site in five hydrogen tank units provided by APCI. The station will have total storage capacity of 198 kg (132 kg at 5,000 psi and 66 kg at 10,000 psi) with capability of dispensing over 240 kg of hydrogen continuously without recharging the cascade. Storage tank units $ST_1$, $ST_2$, $ST_3$, and $ST_4$ represented in Figure 3.7 have 3 tanks each that can hold 11 kg of hydrogen at 6,600 psi. Storage tank unit $ST_5$ consists of 3 tanks with a storage capacity of 22 kg each at 10,000 psi. Storage tank units $ST_1$ and $ST_3$ will provide 5,000 psi hydrogen to dispenser 1 and $ST_2$ and $ST_4$ will provide hydrogen to dispenser 2. $ST_1$, $ST_2$, $ST_3$, and $ST_4$ are also connected to $ST_5$ which is at a pressure of 10,000 psi.

**4.3.4 Compression.** The hydrogen fueling station has four compressors with specifications shown in Table 3.2. The compressors were oversized to achieve high customer service level at the hydrogen station. Using these compressors and storage, the station will be able to dispense up to 400 kg of hydrogen in 14 hours. Two compressors of the same size were selected to have redundancy in the system. Compressor 3, labeled as "$Comp_3$" in Figure 3.7, will do direct filling after the cascade during a 10,000 psi fill.

**4.3.5 Dispenser.** Air Products will be providing two dispensers capable of dispensing hydrogen at both 5,000 psi and 10,000 psi. The maximum allowable time for fueling the vehicles is 5 minutes for the 5,000 psi vehicle and 7 minutes for the 10,000 psi vehicle. The system is designed such that both dispensing units can work independent of each other.

## 4.4 HYDROGEN DISPENSING

Several simulations were run before selecting the components for the hydrogen station. Figure 4.8 shows the simulation of hydrogen fueling process using Cascade [21] gaseous fueling system sizing/analysis engineering tool.

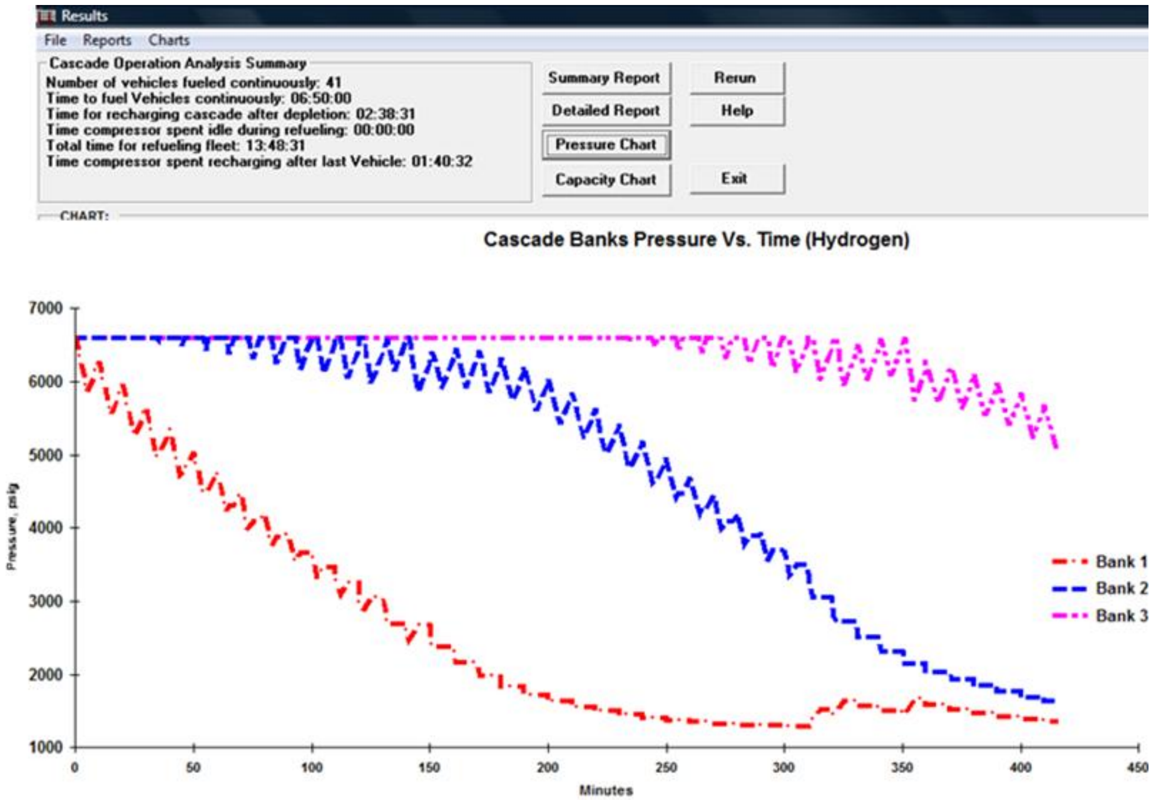


Figure 4.8. Results from Cascade simulation for 5,000 psi fueling

The team ran a simulation were the total demand was 201 kg (67 vehicle with 3 kg demand) of hydrogen at 5,000 psi. The simulation started with three banks, each containing 22 kg of hydrogen at 6,600 psig (cascading $ST_1$ and $ST_3$) and with the compressor running throughout the fueling process. Simulation for dispensing 10,000 psi hydrogen was also performed and the results are shown in Figure 4.9. The compressor providing 130 scfm hydrogen will run continuously during the fueling process and the recharging time of the cascade is only 8 minutes. If there was a demand for 3 kg per vehicle and hydrogen was dispensed at 10,000 psi, the number of continuously fueled vehicle was found to be two with recharge time of roughly 8 minutes. But the number of 10,000 psi fills is considered to be significantly less than the number of 5,000 psi fills.

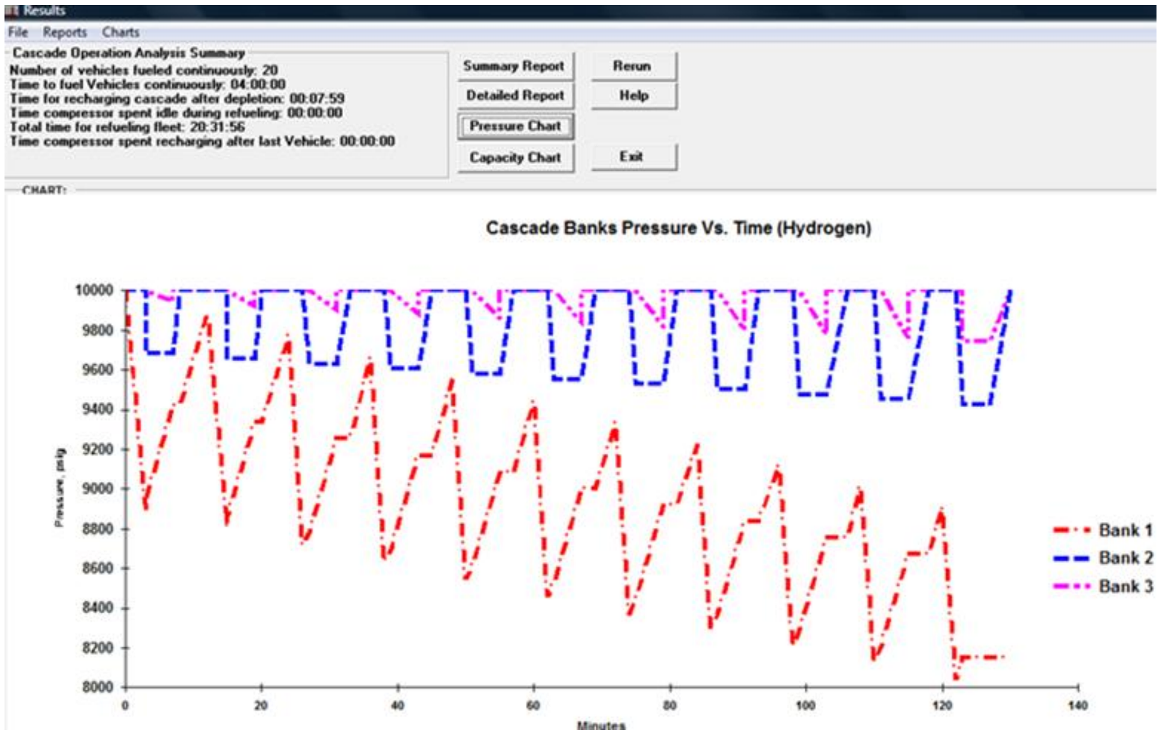


Figure 4.9. Results from Cascade simulation for 10,000 psi fueling

## 4.5 HYDROGEN FUELING STATION OPERATION

This section will explain how the station will be operated. Even though the station has the capacity to operate 24 hours, the normal station operating hours will be 6:00 a.m. to 8:00 p.m. During regular station operation, both fuel cell and tube trailer will provide hydrogen at a constant rate of 40 scfm and 140 scfm at 150 psi to the 1,060 gallon buffer tank BT as shown in Figure 4.8. The system will be designed such that hydrogen flow from the tube trailer will be stopped when the pressure in the buffer tank reaches a particular point corresponding to the hydrogen outlet pressure from the fuel cell. At this point, $Comp_0$ will come online and will start recharging the tube trailer using hydrogen from the fuel cell. If there is a hydrogen demand from the storage tank units, $Comp_0$ will seize operation and hydrogen flow from the tube trailer will be restored. The compressors $Comp_1$ and $Comp_2$ were sized based on the flow rate from the fuel cell and tube trailer and will result in fueling operations as shown in Figure 4.9 and Figure 4.10. By the end of day three, the tube trailer will be almost empty and will have to be replaced by a new one. During the 10,000 psi fueling operation, $ST_5$ will demand hydrogen from the storage bank having highest pressure. The booster compressor $Comp_3$ will fill the vehicle directly after the cascade fill.

## 4.6 SAFETY EQUIPMENTS

Safety was the most important item during the design of the station and will not be compromised in any way. Different safety equipments will be installed to prevent and/or mitigate possible dangerous events at the fueling station. These include hydrogen and flame detection systems, safety cameras, hydrogen storage isolation systems, pressure relief devices, etc. Safety barriers and walls will be built to protect the dispenser and hydrogen equipments at the station. Emergency shutdown switches will be strategically located at the fueling station and will terminate all operations at the station instantly. Other safety features like break away hoses, fire extinguishers, safety signs, etc will also be installed at the station.

# 5. SAFETY ANALYSIS

Safe practices in production, storage and distribution of hydrogen is vital for a growing hydrogen economy. Mitigating risk and danger associated with hydrogen will help in accepting it as a revolutionary fuel. To avoid safety hazards, it is necessary to implement practices that if adopted early in the development of a fueling station project will provide a safe environment component. One such safe practice is to develop a plan which identifies the failure modes and the magnitude of its damage and frequency. Some of the most significant risks associated with the hydrogen refueling station, with their source, controls and the measures taken to mitigate risks were identified and listed in Table 5.1. All systems selected during the design will meet or exceed existing safety codes and standards.

Table 5.1 Failure Mode Effect Analysis

| ***Failure Mode*** | ***Source/Cause*** | ***Effects*** | ***Potential Damage*** | ***Frequency*** | ***Design to mitigate risks*** |
|---|---|---|---|---|---|
| **Fire or combustion of hydrogen** | High flammability, static electricity discharge | Potential fire | 10 | 2 | Appropriate signs near hydrogen areas and flame detection sensors |
| **Hydrogen leak in piping** | Mechanical failure/improper connections | Potential fire | 8 | 5 | Piping and connections inspected periodically and use of leak detectors |
| **Storage tank leak** | Mechanical failure | Loss of vacuum within vessel | 6 | 4 | Pressure Safety Valve (PSV) vents at elevated location. |
| **Vehicle crash into dispenser, storage area, etc** | Release of high pressure hydrogen | Potential fire/explosion | 5 | 4 | Physical barriers to protect these equipments |
| **Dispenser cascade control and piping failure** | Pressure relief device on dispenser and storage tanks fails | Overpressure vehicle fuel tank. Relief valve on vehicle tank vents. | 4 | 2 | Checking of dispenser every time before use. |

It is to be noted that the table shown above is not a complete analysis of factors that can contribute to an incident at the fueling station. Other possible factors leading to failure modes are human/operator error or equipment misuse, natural disaster, hardware/software, communication failure, etc. A range of hydrogen fueling station design options was considered before coming up with this design to reduce the occurrence of a failure. As hydrogen and fuel cell technology gather pace, new safety challenges are expected to arise and should be avoided by following best practices in the handling of hydrogen. Table 5.2 lists the codes and standards that will be followed during the installation and operation of the hydrogen production facilities, hydrogen fueling station, and fuel cells.

Table 5.2 List of safety codes and standards

| **Equipment & Vehicles** | **Codes & Standards** |
|---|---|
| DFC Fuel Cell | CSA No. 5.99, UL 2264B, ISO 16110-1, ASME PTC 50, NFPA 70, NFPA 110 |
| Low Pressure Hydrogen cylinders | ASME BPVC |
| Air Products Hydrogen Dispenser | NFPA 52, SAE J 2600 |
| Fuel cell lift truck | SAE J 2572, 2574, 2578, NFPA 52, SAE J 2600, SAE J 2719 |
| Altergy Freedom Power Fuel Cell | CSA FC 1, CSA No. 33, UL 1741, NFPA 853, NFPA 70 Art 692, NFPA 110 |
| Portable Fuel Cells | CGA H-2, NFPA 52, CGA H-2, CSA FC 3 |
| Hydrogen piping and pipelines | ASME B31, CGA G 5.4, CGA 5.6 |
| Hydrogen vent systems | CGA G-5.5 |
| Hydrogen fueling station | ISO/PAS 15594, NFPA 52, NFPA 55 |
| Installation & operation | OSHA: 29 CFR 1910.103 |

# 6. ECONOMIC/BUSINESS ANALYSIS

The economic and business plan analysis includes capital cost for all equipments, operating cost, and maintenance cost for the hydrogen community at Santa Monica. It includes both capital investments in purchased equipment as well as lease agreements. The leased equipment will help to keep the initial investment low while creating flexibility to change with emerging and improving hydrogen technologies. The component selection during the design was driven by the incentives and rebates. The capital cost shown in Table 6.1 was calculated based on the information gathered from different industry leaders and the sources are cited in the reference section.

The installation, commissioning, and training cost were calculated based on fuel cell case study [23] and is considered to be 20% of the capital cost. The team will take advantage of the Assembly Bill AB 2778 Renewed by the Self Generation Incentive Program and will apply for incentives during the purchase of DFC FCE fuel cells. The DFC 300 FCE fuel cell will receive a 100% of incentives while DFC 1500 FCE fuel cell will receive 50% of incentives as seen in Table 6.2. These incentives will make the program economically feasible and will cut the payback period. During the case study of City of Tulare [2] which installed three DFC 300 FCE fuel cells, it was noted that the total cost of the project was $7 million, with state & federal incentives of $4.05 million. The net cost of the project to the city was $2.95 million and the payback period was only 4.5 years. The design encourages applying for similar state and federal incentives to significantly reduce the payback period.

Table 6.1 Capital cost summary [22]

| | *Item* | *Quantity* | *Cost ($)* | *Cost after incentives/ Rebates ($)* |
|---|---|---|---|---|
| 1 | **Hydrogen Production Facilities** | | | |
| **1.1** | FCE Fuel Cell - DFC 1500/300 | 3 | 13,330,000 | 6,020,000 |
| **1.2** | Compressor | 4 | 1,000,000 | 1,000,000 |
| **1.3** | Buffer Tank | 3 | 75,000 | 75,000 |
| **1.4** | Installation, commissioning, training, etc. | n/a | 2,881,000 | 2,881,000 |
| 2 | **Hydrogen Fueling Station** | | | |
| **2.1** | FCE Fuel Cell - DFC 300 | 1 | 1,290,000 | 0 |
| **2.2** | Compressor | 4 | 910,000 | 910,000 |
| **2.3** | Buffer tank | 1 | 25,000 | 25,000 |
| **2.4** | Storage tanks (5,000 psig and 10,000 psig) | 132 kg | 240,000 | 240,000 |
| **2.5** | Hydrogen dispenser (5,000 psig and 10,000 psig) | 2 | 500,000 | 500,000 |
| **2.6** | Air compressor | 1 | 8,000 | 8,000 |
| **2.7** | Safety equipments | n/a | 50,000 | 50,000 |
| **2.8** | Installation, commissioning, training, etc | | 604,600 | 604,600 |
| 3 | **Early Market Applications** | | | |
| **3.1** | 5 kW fuel cell unit | 17 | 340,000 | 85,000 |
| **3.2** | FCE Fuel Cell - DFC 300 | 1 | 1,290,000 | 0 |
| **3.3** | Forklift fuel cell kit + installation + vehicles | 35 | 350,000 | 350,000 |
| **3.4** | Portable fuel cells, extra cartridges, refueling station | n/a | 202,000 | 202,000 |
| **3.5** | Installation, commissioning, training, etc | n/a | 728,000 | 728,000 |
| 4 | **Real Estate / Building Structure** | | | |
| **4.1** | Hydrogen fueling station plot | | 3,955,000 | 3,955,000 |
| **4.2** | Hydrogen fueling station construction | | 600,600 | 600,600 |
| **4.3** | Shipping container hydrogen education center | | 75,000 | 75,000 |
| | **Total** | | **28,202,000** | **18,057,000** |

Table 6.2 Self–Generation Incentive levels [24]

| *Incentive Levels* | *Eligible Technologies* | *Incentive Offered ($/watt)** | *Minimum System Size (kW)* |
|---|---|---|---|
| **Level 2 Renewable** | Renewable fuel cells | 4.50 | 30 |

* 0 - 1 MW - 100% of incentive 1 - 2 MW -- 50% of incentive 2 - 3 MW -- 25% of incentive

Additionally, California Energy Commission through its Emerging Renewables Program (ERP) is offering rebates on grid-connected small wind and fuel cell renewable energy electric-generating systems [25]. From Table 6.3, it can be observed that 5 kW fuel cells that use renewable hydrogen produced at the facilities discussed earlier will be eligible for $3.00/W rebate.

Table 6.3 Rebates available for Emerging Renewable Systems [25]

| *Technology Type* | *Size Category* | *Rebate Offered($/watt)* |
|---|---|---|
| **Fuel Cells using a renewable fuel** | <30 kW | 3.00 |
| **Wind** | First 7.5 kW | 2.50 |
| | Increments between >7.5 kW and <30 kW | 1.50 |

Operating cost of hydrogen production facilities and fueling station was calculated and is given in Table 6.4.

Table 6.4 Operating cost

| | *Item* | *Cost/year ($)* |
|---|---|---:|
| **1** | Biogas / Natural gas | 1,147,281 |
| **2** | Labor and driver | 193,815 |
| **3** | Water & sewer | 183,595 |
| **4** | Tube trailer (rent + fuel) | 76,772 |
| **5** | Mobile fueler rent | 234,000 |
| **6** | Maintenance | 389,360 |
| | **Total** | **2,224,823** |

During the calculation of the operating cost, it was assumed that three facilities will sell biogas, landfill gas at the same rate as the natural gas. The design used Southern California Gas Company's commercial and industrial rate with commodity charge GN-10 and rate type Tier III with rate average effective rate 49 cents/therm (procurement charge + transmission charge) [26]. In reality, the facilities may offer biogas and landfill gas at a cheaper rate than the natural gas rate, since it is a byproduct at their site. Labor was estimated to be $0.27/kg [27] of hydrogen produced and an additional amount of $30/hr was also included towards bottling plant which would require constant monitoring. The water and sewer cost were calculated based on the total water usage by the fuel cells and non-residential water and sewer rates from Santa Monica Public Works [28]. Two tube trailers with 300 kg of hydrogen storage at 3,000 psi will be leased from Air Products. Three mobile fueler units will also be rented from Air Products to supply hydrogen to the material handling vehicles at the three facilities mentioned earlier. Maintenance cost per year was estimated to be 2% of the capital cost of the equipment.

The design employs five fuel cells with a total capacity of 2.8 MW with 1,200 kg of hydrogen per day production. The power generated from the fuel cells are sources of revenue and will be sold to different customers and are tabulated in Table 6.5. Equipments including compressors, safety devices, control panels, and other equipments at the hydrogen generation facilities and the hydrogen station will be powered using the power generated by the fuel cell. The excess power will be sold to the local utility at a rate of 8 cents/kWh.

Cost of hydrogen based on the cost analysis of production (biogas charges, water and sewer charges, labor) and delivery systems (truck rent, driver expenses) was estimated to be $3.55/kg. Selling price of hydrogen based on a discounted cash flow analysis with an after-tax (tax rate 35%) internal rate of return of 10% for a 10-year analysis was calculated and was found to be $10.48/kg for a capital cost of $18,016,600. The high cost can be directly related to the high capital cost including the $4 million hydrogen station plot.

Table 6.5 Revenue from selling power generated from fuel cell

| *Location* | *Power generated (kWh/ year)* | *Power consumed (kWh/ year)* | *Power sold (kWh/ year)* | *Sellin g Price (cents /kWh)* | *Revenue ($/year)* |
|---|---|---|---|---|---|
| **Hydrogen Production Facilities** | 19,710,000 | 1,978,300 | 17,731,700 | 0.08 | 1,418,536 |
| **Hydrogen Fueling Station** | 2,190,000 | 868,700 | 138,2133 | 0.08 | 110,571 |
| **Early Market Applications** | 2,190,000 | 9,125 | 2,180,875 | 0.08 | 174,470 |
| **Total** | **24,090,000** | **2,856,125** | **21,233,875** | **n/a** | **1,703,577** |

A comparison of the cost in $/mile of hydrogen fuel for the fuel cell vehicle compared to the $/mile for comparable conventional vehicle using gasoline was also done during the design and is summarized in Table 6.6. The fuel economy of the fuel cell vehicle was fixed at 60 mile/kg of hydrogen while the cost per mile for conventional vehicles or Internal Combustion Engine (ICE) vehicles was assumed to be $0.058/mile.

Table 6.6 Cost comparison between FC vehicles and ICE vehicles

| *Category* | *cost/mile($/mile)* |
|---|---|
| **Fuel cell vehicle (cost of $3.55/kg)** | 0.059 |
| **Fuel cell vehicle (selling price $10.84/kg)** | 0.181 |
| **Conventional vehicle** | 0.058 |

# 7. ENVIRONMENTAL ANALYSIS

Energy security is a major issue concerning the world today. As the developing countries consume more energy, the industrialized nations have to come up with alternative energy solutions to offset this potential crisis. Hydrogen and fuel cells have the potential to be one of the key solutions to the energy crisis, allowing clean and efficient production of power and heat. Hydrogen based energy systems have had a positive impact in meeting the energy requirements but challenges regarding a cost-effective and efficient transition is being researched.

A well-to-tank analysis of the greenhouse gas (GHG) emissions performed during the generation of hydrogen is compared with that of gasoline generation. The Life-cycle energy usage and the GHG emissions of various fuel and vehicle technologies are shown in Table 7.1. The total energy usage and the total GHGs emissions of the hydrogen fuel cell is considerably lower than a Gasoline ICE and thus offer a clean and sustainable energy option [29].

Table 7.1 Life-cycle energy use and GHG emissions for fuel and vehicle technologies

| *Fuel and Vehicle Technology* | *Total Energy (MJ/km)* | *Total GHG emitted g C/km* |
|---|---|---|
| **Gasoline ICE** | 2.34 | 47 |
| **Diesel ICE** | 1.77 | 37 |
| **Hybrid gasoline ICE** | 1.53 | 30 |
| **Hybrid CNG ICE** | 1.45 | 24 |
| **Hybrid gasoline Fuel cell** | 2.44 | 49 |
| **Hybrid hydrogen Fuel cell** | 1.69 | 34 |

## 7.1 LIFE CYCLE ENERGY USE AND GHG EMISSIONS FOR FORKLIFTS

Forklift propulsion systems have been identified as one of the potential early market customers for hydrogen fuel cell applications. In this section a comparative study on the forklifts operated by hydrogen fuel cells, batteries and Internal Combustion Engines (ICEs) is being taken up and the total energy usage and GHG emissions are shown.

Figure 7.1 compares the total energy usage per kWh supplied to the wheels/fork. The fuel cycle total energy for hydrogen forklifts includes the energy usage for the recovery and transportation of the feedstock to the hydrogen production site, the conversion of the feedstock to hydrogen fuel, the compression of hydrogen, and the hydrogen use aboard the forklift. The fuel cycle total energy for electric or battery operated forklift includes the energy used due to the recovery, processing and transportation of fuels to the power plant, the use of fuels for electricity generation, the charger and battery energy losses, and the energy use by the forklift. The fuel cycle total energy for ICE forklift includes the energy use associated with the recovery, processing and transportation of fuels to the forklift, and the energy use by the forklift. The total energy usage by the ICE forklifts is considerably high due to significant engine inefficiency. The usage of wind and biogas as a source of clean power to generate hydrogen considerably reduces the total energy requirements for the fork.

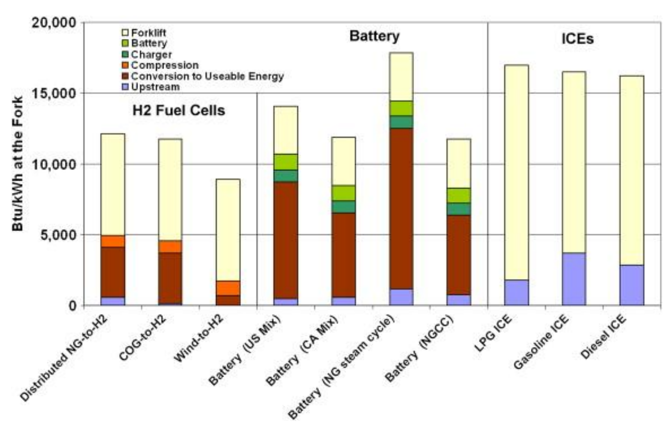


Figure 7.1. Fuel cycle total energy use for forklift technologies

Figure 7.2 compares GHG impacts for the different forklift types. The ICE-powered forklifts produce the highest full fuel-cycle GHG emissions, but the battery-powered forklifts that rely on the average U.S. electricity mix produce almost as much. This is because of the U.S. grid's heavy reliance on coal, which results in more GHG per unit energy consumption. The GHG emissions from the use of coke oven gas (COG) are low, because COG is a byproduct of coke production and typically contains 55% $H_2$. Natural gas pathways as the primary energy source, are areas of interest. Of these, the path using the single cycle power plants results in the highest GHG emissions and the combined cycle the lowest. The path using steam reforming is only slightly higher, but is still well below the path using batteries charged with the average U.S. generation mix [30].

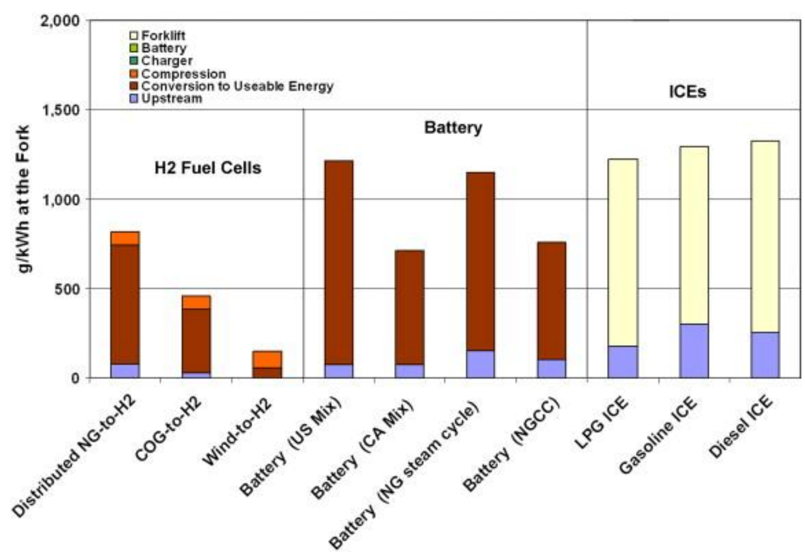


Figure 7.2. Comparison of fuel cycle GHG emissions for forklift technologies

## 7.2 FUEL CELLS FOR HYDROGEN PRODUCTION

FuelCell Energy's DFC1500 FCE fuel cells are the electrical power generation systems being used to produce hydrogen from Natural gas (NG) or anaerobic gas at the

Hyperion Water Treatment plant and Terminal Island Water Reclamation Plant. Also DFC300 fuel cells are being deployed at hydrogen fueling station and at the landfill site of Palos Verdes Gas-to-Energy Facility. The advantage of DFCs is they internally reform fuels such as natural gas and anaerobic gas into hydrogen, thus increasing the electrical efficiency. Table 7.2 gives the data regarding the GHGs emissions and the noise levels associated with DFCs.

Table 7.2 Emissions data of DFC fuel cells [5, 31]

| ***Parameters*** | *DFC300* | *DFC1500* |
|---|---|---|
| **Fuel consumption (NG)** | 39 scfm | 181 scfm |
| **Water Consumption** | 0.9 gpm | 4.5 gpm |
| **Pollutant Emissions** | NOx - 0.01 lb/MWh<br>Sox - 0.0001 lb/MWh<br>PM10 - 0.00002 lb/MWh | NOx - 0.01 lb/MWh<br>Sox - 0.0001 lb/MWh<br>PM10 - 0.00002 lb/MWh |
| **GHGs Emissions** | $CO_2$ - 980 lb/MWh<br>$CO_2$ - (with waste heat recovery) 520-680 lb/MWh | $CO_2$ - 980 lb/MWh<br>$CO_2$ - (with waste heat recovery) 520-680 lb/MWh |
| **Noise Level** | Standard - 72 dB(A) at 10 feet<br>Optional - 65 dB(A) at 10 feet | Standard - 72 dB(A) at 10 feet<br>Optional - 65 dB(A) at 10 feet |

### 7.3 WELL-TO-TANK ANALYSIS

A well-to-tank analysis was performed to compare grams of $CO_2$/mi produced by a hydrogen fuel cell vehicle to grams of $CO_2$/mi produced by gasoline vehicle. It was assumed that the fuel cell vehicles have a fuel efficiency of 60mi/kg of hydrogen with zero emissions and that the gasoline vehicle emits 422g $CO_2$/mi. Amount of $CO_2$ emitted by the truck used for transporting hydrogen was assumed to be 169g/mi per ton. It was estimated that production of one kg of hydrogen will emit 2.753 kg of $CO_2$ and the truck will emit 0.0313 kg of $CO_2$ per kg of hydrogen during transportation. Emissions of the fuel cell vehicle and gasoline vehicle were estimated and are compared in Table 7.3. It was noticed that there was an 89% reduction in $CO_2$ emissions with the use of fuel cell vehicles.

Table 7.3 Vehicle emission comparison

| *Vehicle Type* | *g $CO_2$/mile* |
|---|---|
| **Fuel Cell** | 45 |
| **Light duty gasoline** | 422 |

# 8. MARKETING AND EDUCATION PLAN

The design of the hydrogen community at Santa Monica, CA has to be environmentally sustainable and economically viable in the long term. A successful marketing strategy and an intensive education program would go a long way in popularizing the concept of hydrogen and its applications to the citizens of Santa Monica in particular and the country as a whole. The initiatives that will be taken up by the Missouri S&T team to promote and educate the people of Santa Monica are explained below.

## 8.1 MARKETING PLAN

1. Use a hydrogen vehicle to advertise the community or a vehicle with large logo decals. This would help not only advertise the community, but by using a hydrogen vehicle, it shows the sustainability of the community. The vehicles could drive in various target locations to help garner support and interest. This would help in getting the awareness among the general public.
2. Have an "open house" day for the hydrogen community, where people among different age groups can come and learn about new hydrogen technologies.
3. Form reciprocal web link agreements with state government agencies to disseminate the idea of hydrogen as a clean source of energy. The state government in turn could generate interest by promoting the idea of hydrogen as a sustainable source of energy to the visitors of Santa Monica by advertising about hydrogen in airport terminals, Santa Monica Union Station and other public locations.

The advertisement that will be used during the marketing campaign is shown in Figure 8.1

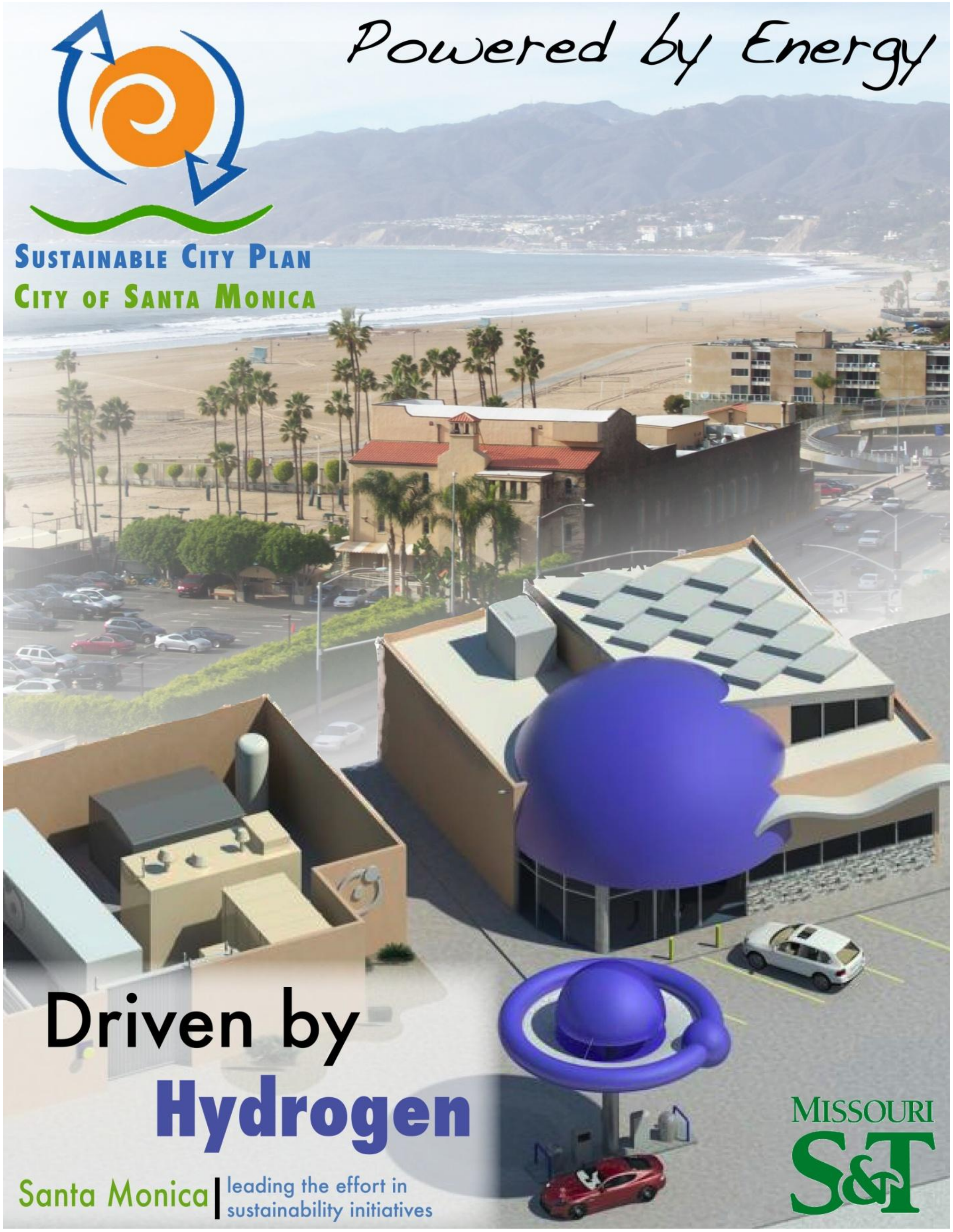


Figure 8.1. Advertisement

## 8.2 EDUCATION PLAN

1. Conduct public workshops on the benefits of hydrogen technologies at auto shows, science fairs and other public events. This would also include real-time demonstrations of some of the applications of hydrogen, thus helping in the better understanding among the general public of Santa Monica and also acting as an eye-opener to foreign visitors to the city.
2. Introduce the concept of hydrogen as a fuel and fuel cell technology in school and college curriculum. Organize seminars and conferences on topics related to clean energy in general and hydrogen and fuel cells in particular. A series of pamphlets will be made to give detailed information about the various components such as the fuel cell, electrolyzer, hydrogen dispenser, safety equipments and products run on hydrogen.
3. Creating an awareness regarding the nuances of hydrogen among the general public through local newspapers and other means of mass media.
4. Establish a public education center at one of the State parks near Santa Monica. The team has selected Will Rogers State Historic Park for this purpose and will build a hydrogen education facility using recycled shipping containers. The Hydrogen Education Center proposed is designed from six cargo containers and conventional building materials with concrete masonry unit walls.  It boasts an open lobby, large educational classroom, men’s and women’s restrooms, green roof observation deck and multi-purpose space on the second floor. In addition to being environmentally friendly, the Hydrogen Education center also includes space capacity for eight large solar panels. The ideal location for this conceptual building would be at the entrance grounds to a park and being near a bike path. Due to the modular nature of these containers, it can be easily transported to other locations if necessary.

# APPENDIX B

# CASCADE ANALYSIS RESULTS

1. Compressor – 80 scfm, vehicle storage pressure – 9500 psig

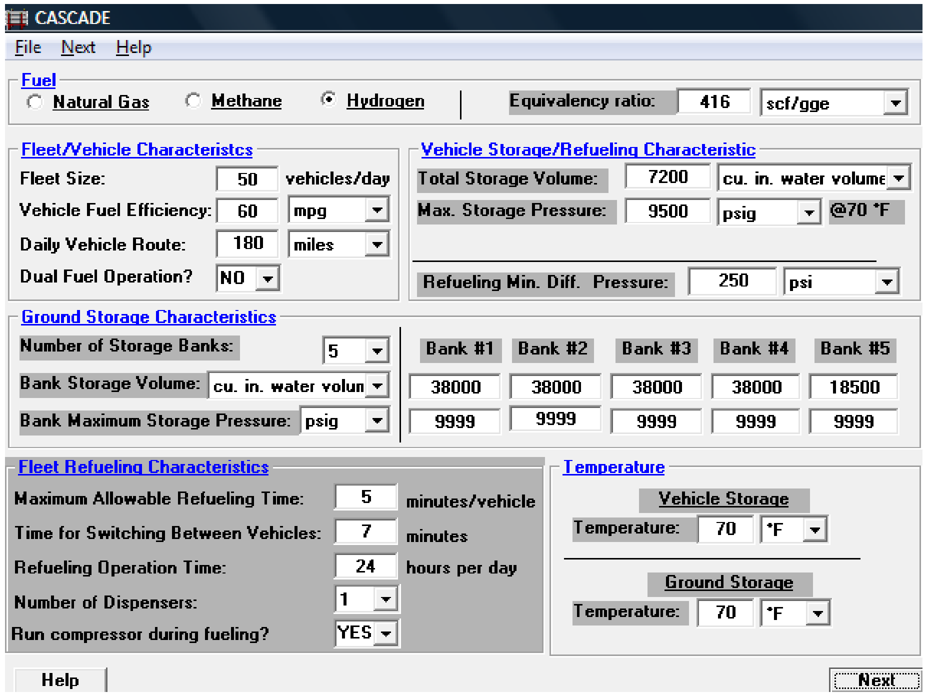


Figure B.1. Cascade simulation input – 80 scfm

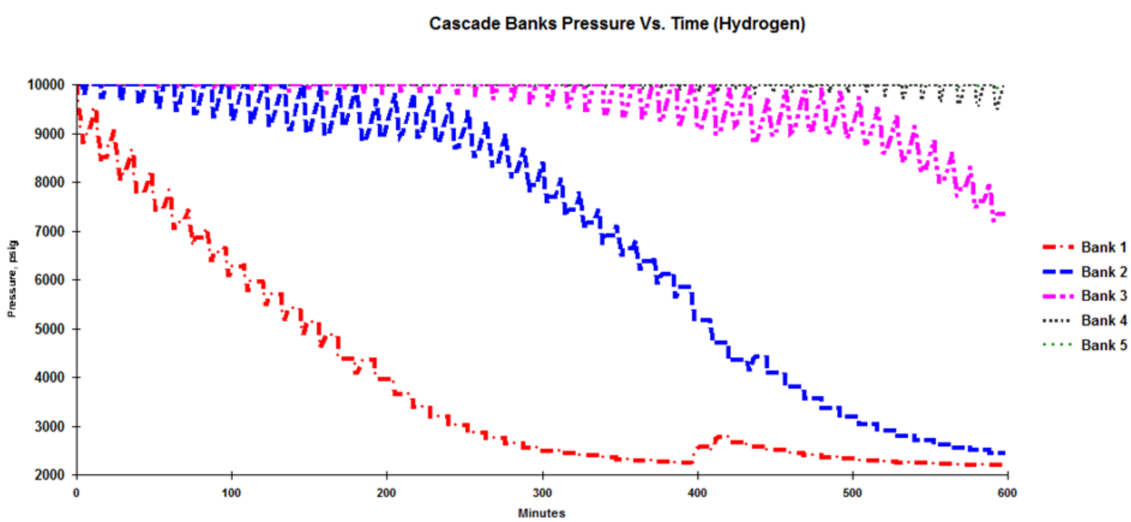


Figure B.2. Cascade banks Pressure v/s Time – 80 scfm

2. Compressor – 70 scfm, vehicle storage pressure – 9500 psig

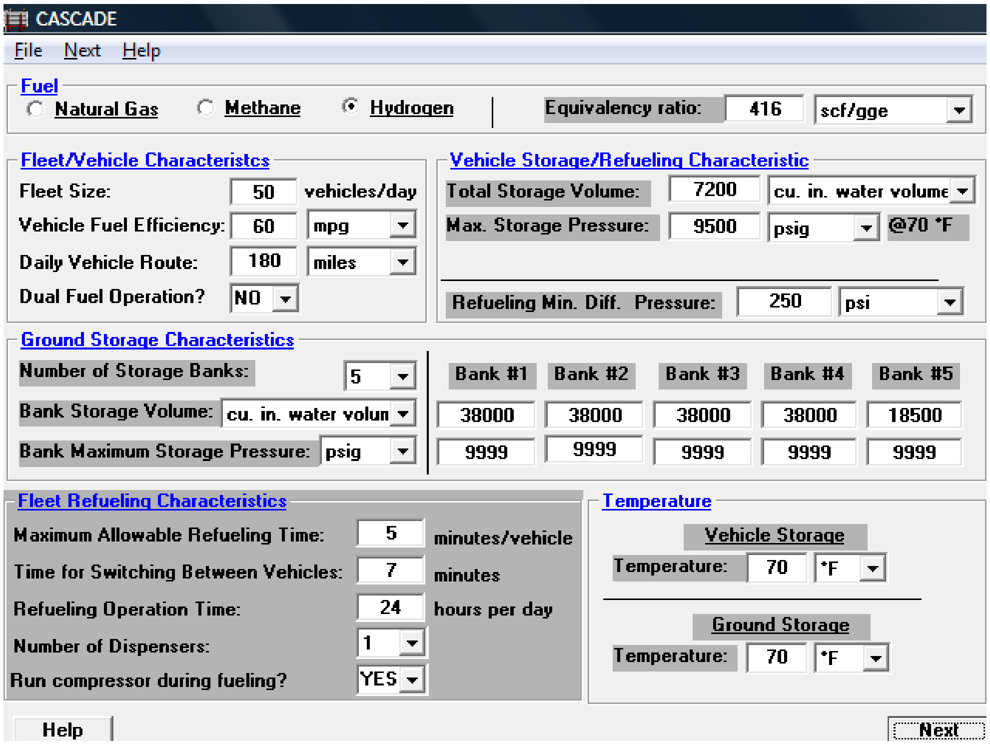


Figure B.3. Cascade simulation input – 70 scfm

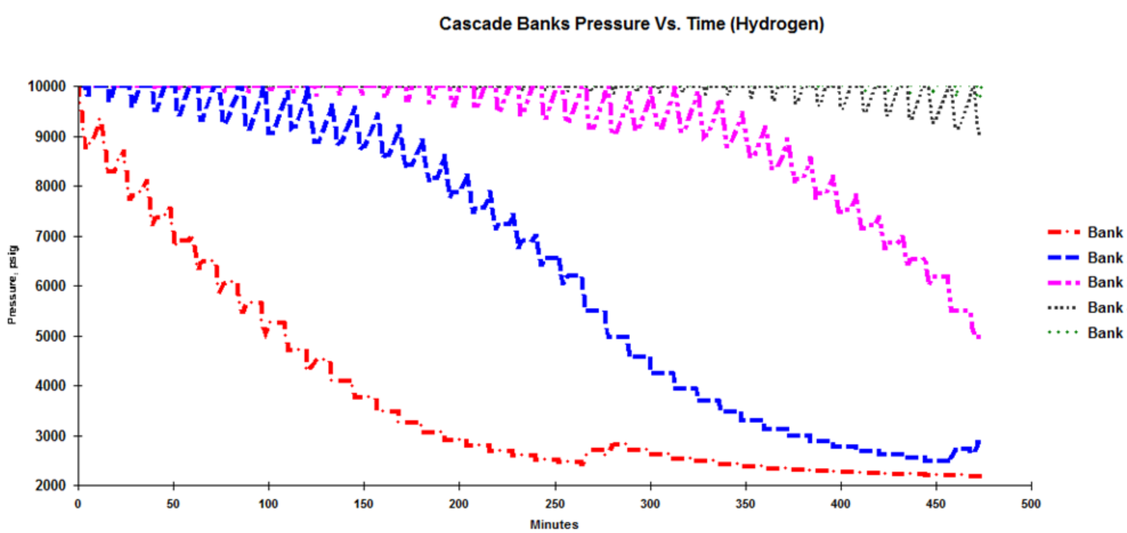


Figure B.4. Cascade banks Pressure v/s Time – 70 scfm

3. Compressor – 100 scfm, vehicle storage pressure – 9500 psig

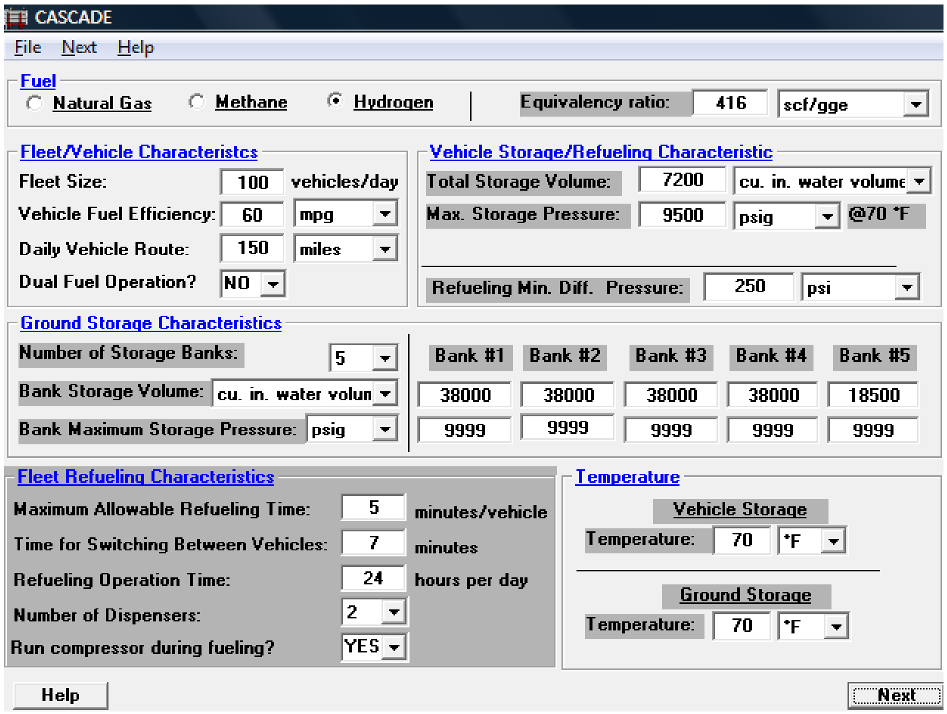


Figure B.5. Cascade simulation input – 100 scfm

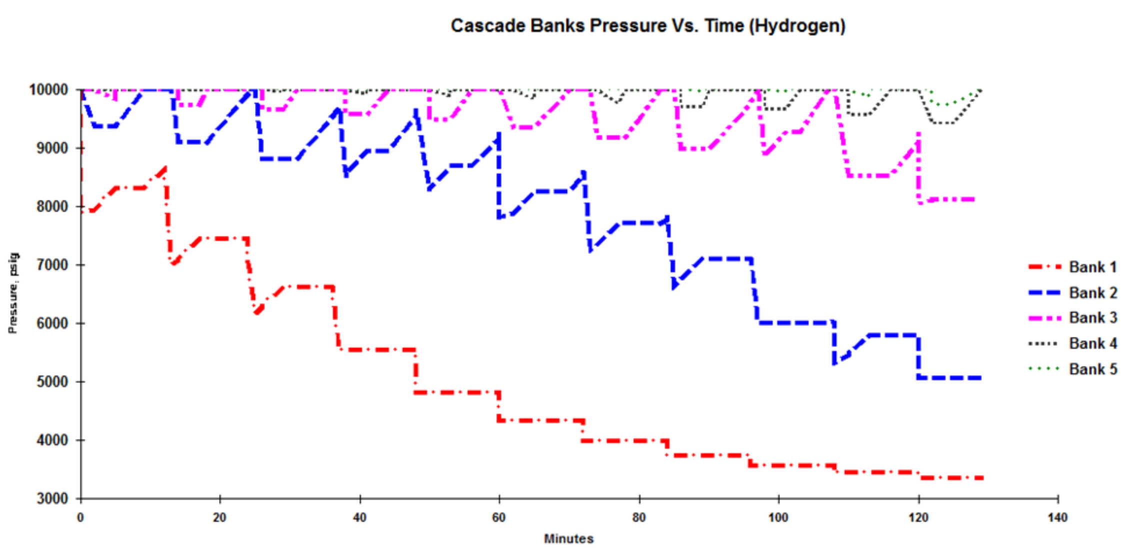


Figure B.6. Cascade banks Pressure v/s Time – 100 scfm

4. Compressor – 120 scfm, vehicle storage pressure – 9500 psig

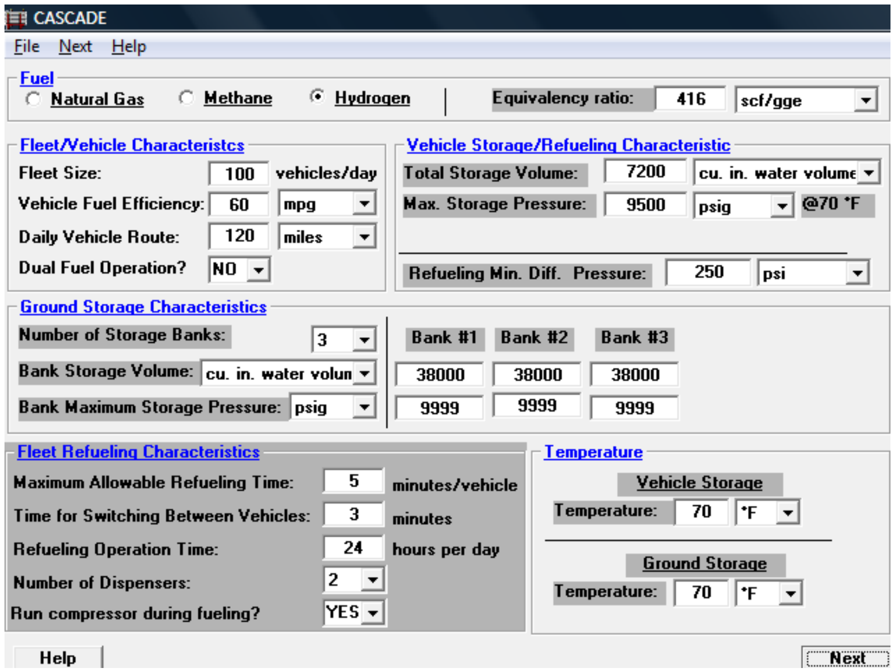


Figure B.7. Cascade simulation input – 120 scfm

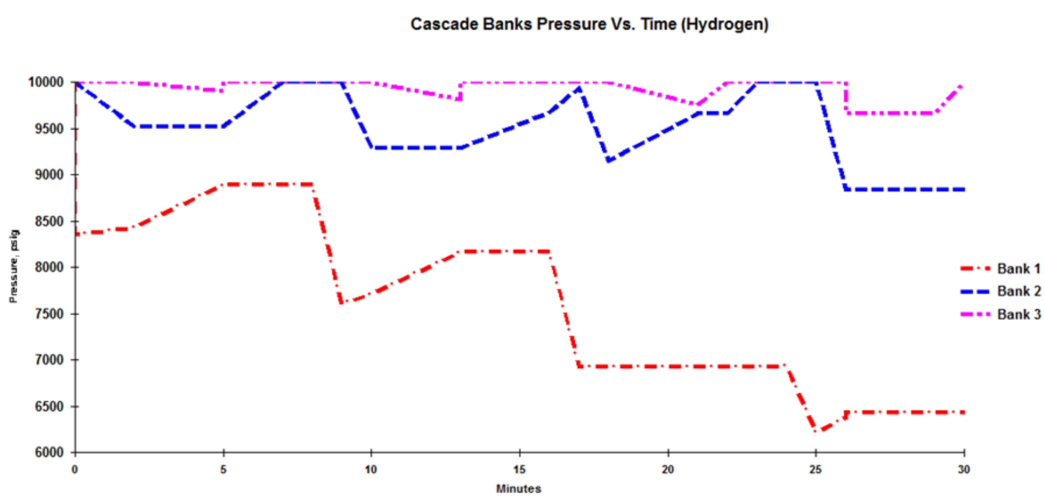


Figure B.8. Cascade banks Pressure v/s Time – 120 scfm

5. Compressor – 90 scfm, vehicle storage pressure – 9500 psig

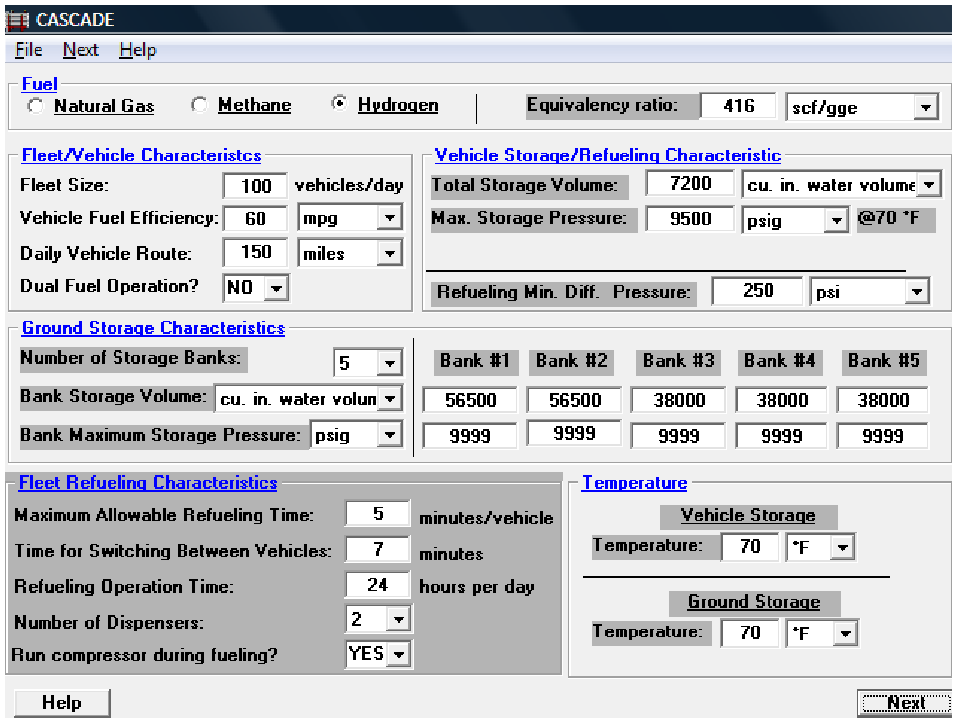


Figure B.9. Cascade simulation input – 90 scfm

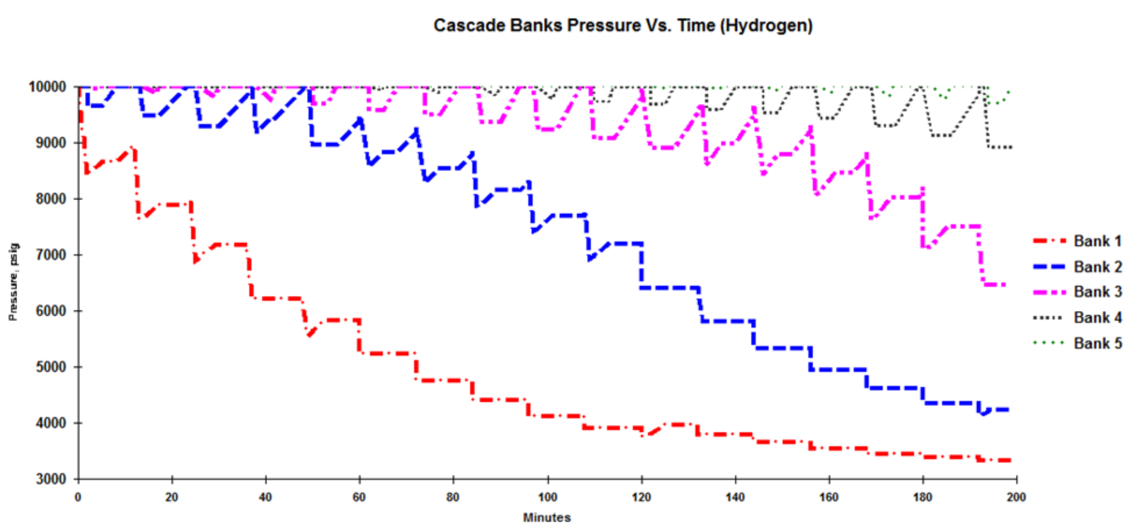


Figure B.10. Cascade banks Pressure v/s Time – 90 scfm

6. Compressor – 110 scfm, vehicle storage pressure – 9500 psig

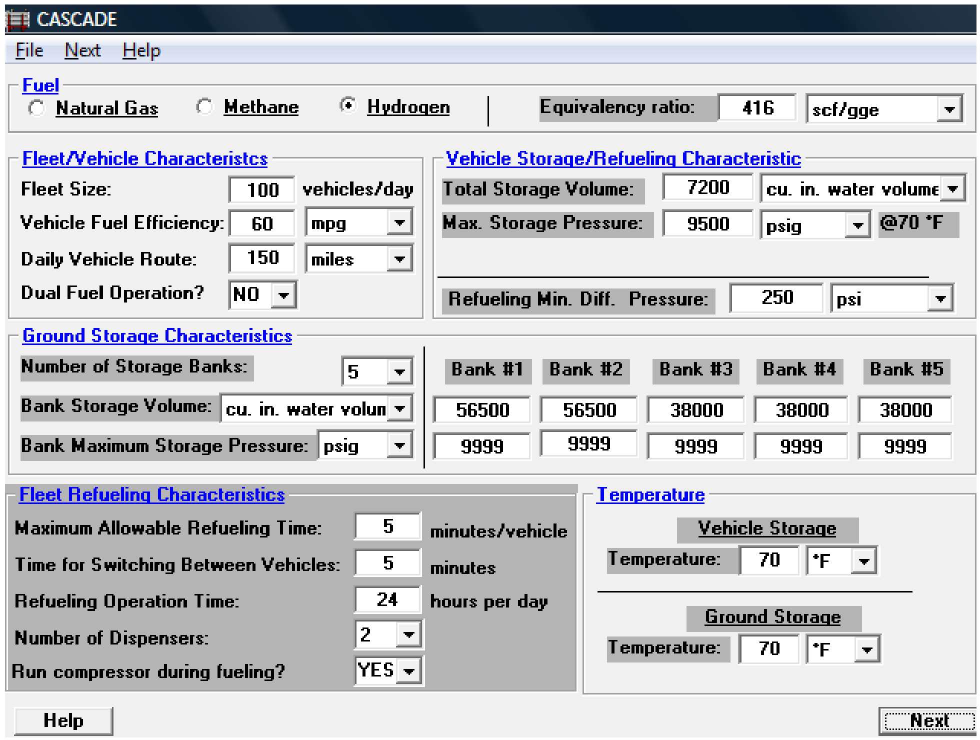


Figure B.11. Cascade simulation input – 110 scfm

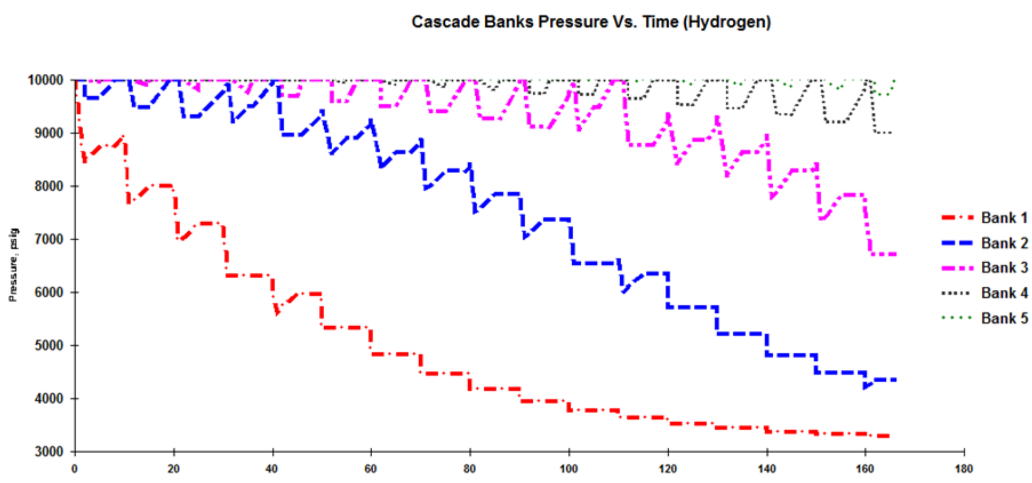


Figure B.12. Cascade banks Pressure v/s Time – 110 scfm

7. Compressor – 130 scfm, vehicle storage pressure – 9500 psig

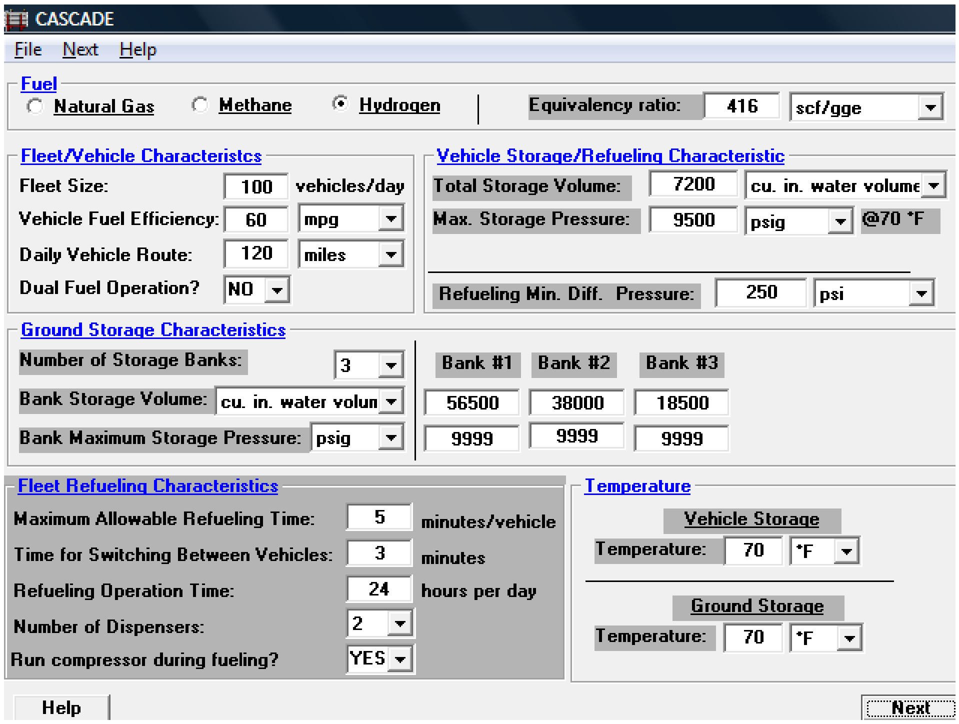


Figure B.13. Cascade simulation input – 130 scfm

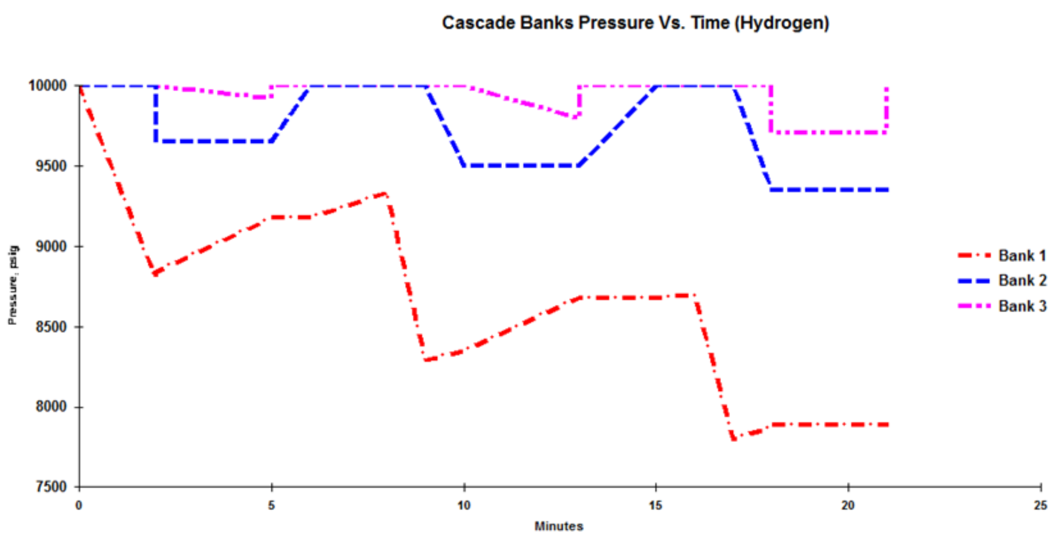


Figure B.14. Cascade banks Pressure v/s Time – 130 scfm

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