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Quantitative analysis of a successful public hydrogen station

Tim Brown*, Shane Stephens-Romero, G. Scott Samuelsen

Advanced Power and Energy Program University of California, Irvine, California 92697-3550, USA

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ABSTRACT

Reliable hydrogen fueling stations will be required for the successful commercialization of fuel cell vehicles. An evolving hydrogen fueling station has been in operation in Irvine, California since 2003, with nearly five years of operation in its current form. The usage of the station has increased from just 1000 kg dispensed in 2007 to over 8000 kg dispensed in 2011 due to greater numbers of fuel cell vehicles in the area. The station regularly operates beyond its design capacity of 25 kg/day and enables fuel cell vehicles to exceed future carbon reduction goals today. Current limitations include a cost of hydrogen of \$15 per kg, net electrical consumption of 5 kWh per kg dispensed, and a need for faster back-to-back vehicle refueling.

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1. Introduction

Global climate change, air quality concerns, and the geopolitical and economic instability associated with petroleum fuel are driving manufacturers, and society, to find alternatives to gasoline and diesel powered automobiles. Hydrogen powered fuel cell vehicles offer a potential solution to all three major problems because hydrogen can be generated and consumed with little or no carbon footprint, pollutant emissions, or oil usage.

The California Hydrogen Highway was the first large-scale governmental foray into the provision of hydrogen infrastructure and provided the needed refueling capacity for early vehicle deployment programs [1]. Thanks in part to the efforts of California and the availability of fueling stations, automakers have made remarkable advances in fuel cell vehicle development and are projecting commercialization in the 2015 timeframe [2]. As this deadline approaches, attention turns to establish a sufficient refueling infrastructure for early consumers. This reality is reinforced by the California Energy Commission's allocation of \$22 million for hydrogen station funding for 2010, and another \$14 million designated for 2011 [3].

A significant and globally researched part of this potential infrastructure rollout is fueling station placement [4–7]. The initial California Hydrogen Highway plan envisioned well-spaced fueling stations positioned along major transportation corridors [1]. Current planning for initial commercialization focuses on a “cluster” approach whereby several stations are clustered around the geographic fuel cell vehicle deployment regions [8,9]. An early cluster is developing in Orange County, California centered on the existing University of California (UC) Irvine station that will include a Shell Hydrogen station in Newport Beach that is undergoing initial fueling trials as of December 2011, a station operating on wastewater treatment digester gas at the Orange County Sanitation District in Fountain Valley that became operational in August 2011, and two planned stations that have been funded by the California Energy Commission: a second Irvine station operated by Air Products and Chemicals, Inc. and a Linde, LLC. station in Laguna Niguel.

Station capacity is also a critical issue for the planning of station networks. To date, most hydrogen fueling stations have been designed and characterized by daily average fuel dispensation rate (kg/day) [10,11]. However, most vehicle

* Corresponding author. Tel.: +1 949 824 0088.

E-mail addresses: tmb@apep.uci.edu (T. Brown), ssr@apep.uci.edu (S. Stephens-Romero), gss@apep.uci.edu (G. Scott Samuelsen).
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fueling occurs during predictable periods of the day, leading to capacity and utilization problems. Society of Automotive Engineers standard SAE J2601 [12] develops more realistic hydrogen station characterization metrics (e.g. peak kg/hr), but few public data exist on actual station performance.

2. Background

The National Fuel Cell Research Center (NFCRC) was commissioned at the University of California, Irvine in 1998 by the U.S. Department of Energy and the California Energy Commission. On December 2, 2002, Toyota delivered the first fuel cell hybrid vehicle (FCHV 1) to the NFCRC, a transaction that provided the first delivery of a fuel cell vehicle to a paying customer, Orthodyne Electronics, for daily “real-world” use and mileage accumulation.

In conjunction with the Toyota FCHV deployment, the NFCRC established, in collaboration with Air Products, a hydrogen fueling station in Irvine on the corner of Jamboree Road and Campus Drive in January of 2003 capable of delivering a few kilograms of hydrogen each day at 35 MPa pressure. The UCI Hydrogen Station was upgraded in November of 2003 to provide more fuel and a better user interface. FCHV 3 was delivered in December of 2003 and sub-leased to Horiba Ltd. in March of that year. The FCHV program was off and running with increasing numbers of cars delivered in subsequent years.

In February 2007, the existing UCI Hydrogen Station was again upgraded with additional capacity and dual dispensing pressures (35 and 70 MPa), both provided from one dispenser. In collaboration with the NFCRC, Air Products and Chemicals (APCI) of Allentown, Pennsylvania, designed, engineered and installed the station with funding from the U.S. Department of Energy and the South Coast Air Quality Management District, and automakers Nissan, Honda, and Toyota.

Due in part to the upgraded hydrogen station, General Motors and Honda both began leasing fuel cell vehicles in Irvine and nearby Newport Beach in 2008, through the Project Driveway and Clarity lease programs, respectively. The California Fuel Cell Partnership (CaFCP), a public-private organization, designated Irvine and Newport Beach as 2 of the 4 initial Hydrogen Communities in California [13]. One notable

lessee of the GM Equinox fuel cell vehicle is the Irvine branch of the US Postal Service which currently delivers mail using the vehicle.

3. Usage data

Throughout 2009, 2010 and 2011, the UCI Hydrogen Station experienced heavy use and multiple car back-ups as users waited for fuel. The station is currently used by Toyota FCHV-adv fuel cell vehicles leased from Toyota Motor Sales, Inc., test vehicles associated with Toyota Motor Engineering & Manufacturing North America, Inc., customers of the Honda FCX Clarity lease program, Chevrolet Equinox Fuel Cell drivers involved with General Motors Project Driveway (including the Irvine Postal Service), engineering vehicles from the Hyundai America Technical Center including the Hyundai Tucson and Kia Borrego, Mercedes-Benz fuel cell vehicles from their growing California vehicle deployment of the F-Cell, and Mazda RX-8 hydrogen combustion outreach and marketing vehicles operated by Mazda USA.

Fig. 1 shows the quantity of hydrogen dispensed at the UCI Hydrogen Station for each of the past five years. The usage nearly tripled from 2007 to 2008, and doubled from 2008 to 2009. However, the quantity of hydrogen dispensed increase by only 15.5% in 2009, and 18.2% in 2010 because the station has been operating above the design capacity. There has not been a single safety incident in any of the 8976 refuelings performed at the UCI station.

Interestingly, the quantity of hydrogen dispensed increased at a faster rate than have the number of filling events in 2007, 2008, and 2009. In 2007 and 2008, many users new to hydrogen fueling had difficulty successfully completing a fill on the first attempt due to cumbersome safety regulations requiring personal protective equipment (PPE) such as a fire resistant jacket and eye protection. Resultantly, several discrete fills were often recorded for each refueling event. Upon the removal of the PPE requirement, the data show more consistency in the ratio between number of fills and mass of hydrogen dispensed.

The station is open 24 h a day, 7 days a week, but not surprisingly, most users fill their vehicles during normal waking hours between Monday and Friday. Fig. 4 shows the

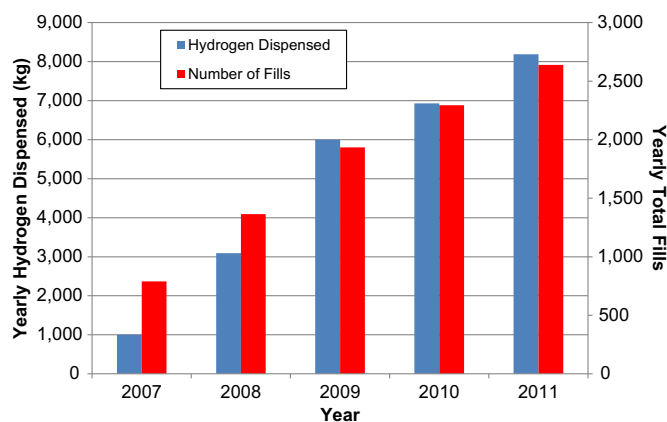


Fig. 1 – Mass of hydrogen dispensed and number of refuelings at UCI station per year.

yearly average hydrogen dispensed per hour across all weekdays for 2007–2011. The plot shows consistent usage spikes at 6:00 am or 7:00 am, between 9:00–11:00 am, and during 2:00–3:00 pm in the afternoon. Additionally, the plot shows that usage tapers off gradually after 4:00 pm, and that there is virtually no usage between midnight and 4:00 am. As shown, weekday usage is higher than weekend usage, particularly in the morning and afternoon hours.

The average profile shown here differs from one estimate presented in the literature [14] where refuelings occur in sharp morning and afternoon peaks but show a lull during midday. One explanation may be that relatively long wait times due to heavy station usage has forced drivers to fill their vehicles at less than ideal times. As explained in detail later, the UCI Hydrogen Station cannot consistently fill multiple vehicles back-to-back, as opposed to a typical gasoline station which is limited solely by the number of dispensers. Therefore, drivers tend to refuel when they think they have the best chance of avoiding other drivers, as demonstrated by the 4 am spike in Fig. 2.

Fig. 3 shows the weekly hydrogen dispensation trends observed for 2007–2011. For each year, usage is consistently low on Saturday and Sunday compared to other days. Year-to-year usage is relatively consistent during weekdays. 2011 shows small peaks on Monday and Friday.

Table 1 shows data for quantity of hydrogen dispensed per day and per year, as well as the number of fills per day and per year for 2007–2011. Table 1 also presents the maximum mass of hydrogen dispensed on a single day for each year.

4. Station configuration

Hydrogen is delivered to the UCI station as a liquid and is stored onsite as a liquid in a 1500 gallon (385 kg) insulated vessel, as depicted in Fig. 4. As needed, the liquid is vaporized and compressed by the main compressor to 54 MPa and stored in three equally sized storage tubes capable of holding a combined 52 kg of hydrogen at 54 MPa. Hydrogen vehicles are equipped with onboard storage tanks pressurized to either 35 MPa or 70 MPa, depending on the vintage and the manufacturer. When

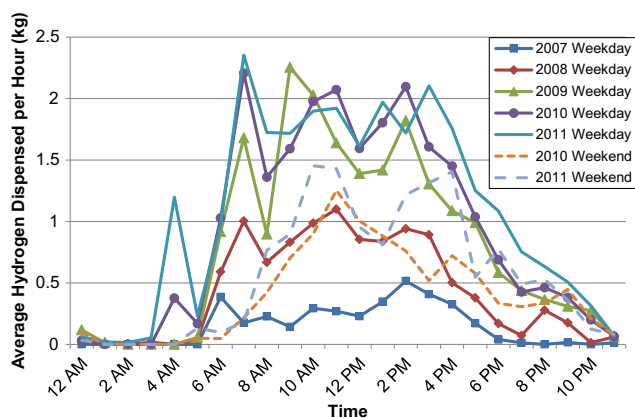


Fig. 2 – Average H₂ dispensed per weekday hour at UCI station from 2007 to 2011 (weekend rates for 2010 and 2011).

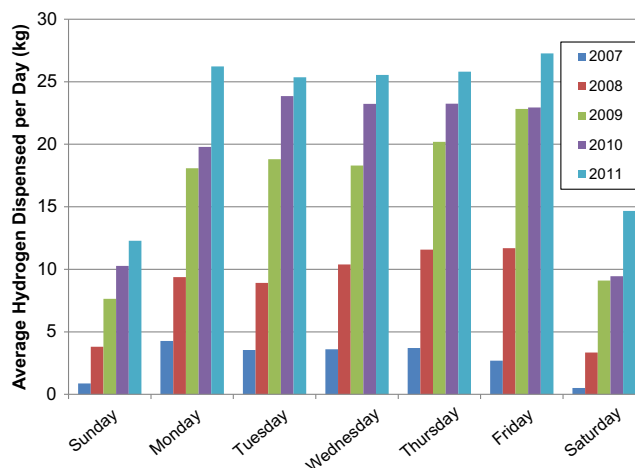


Fig. 3 – Average H₂ dispensed per day at UCI station from 2007 to 2011.

a 35 MPa vehicle refuels, hydrogen is cascaded directly from the 54 MPa storage tubes to the vehicle's tank. Hydrogen is drawn from the lowest pressure storage tube first. As the vehicle tank pressure nears parity with the first station tube, the second storage tube is activated. If this pressure is insufficient to completely fill the vehicle, the third tube is used.

Two additional steps are required to fill a 70 MPa vehicle. The stored 54 MPa hydrogen is further compressed with a reciprocating piston compressor up to a final pressure of nearly 80 MPa. However, the extra compression and high pressure require that the fuel be cooled substantially in order to accomplish quick vehicle refueling without overheating the vehicle tank. The high pressure hydrogen therefore passes through a heat exchanger (cooling block) which cools the gas just before it enters the vehicle. The cooling block is cooled by an onsite refrigeration unit.

The station has a nominal daily maximum capacity of 25 kg which is limited by the 54 MPa compressor capable of compressing roughly 2 kg per hour, with a 50% duty cycle. However, as shown by actual usage data, vehicle fueling does not take place consistently throughout a 24 h period. As a result, even though the station only dispensed an average of 22.4 kg per day throughout 2011, the 52 kg of onsite compressed storage was often depleted at a rate greater than 2 kg/hour during common refueling times, resulting in a shortage of compressed hydrogen.

The “bottleneck” to more hydrogen dispensation at the UCI Hydrogen Station varies depending on the type, rate, and timing of filling events. Two bottlenecks are possible for 35 MPa vehicle filling. The first is due simply to waiting in line when other vehicles are filling at the one dispenser. The second bottleneck occurs when the onsite storage is consumed so quickly by multiple filling events that the pressure in the high pressure bank drops below 35 MPa. As shown Table 2, 35.3% of 35 MPa fill attempts did not result in a full vehicle fill in 2011 because the onsite compressed gas pressure dropped too low.

Vehicles refueling with 70 MPa hydrogen can experience the same two bottlenecks that impact 35 MPa vehicles, plus an

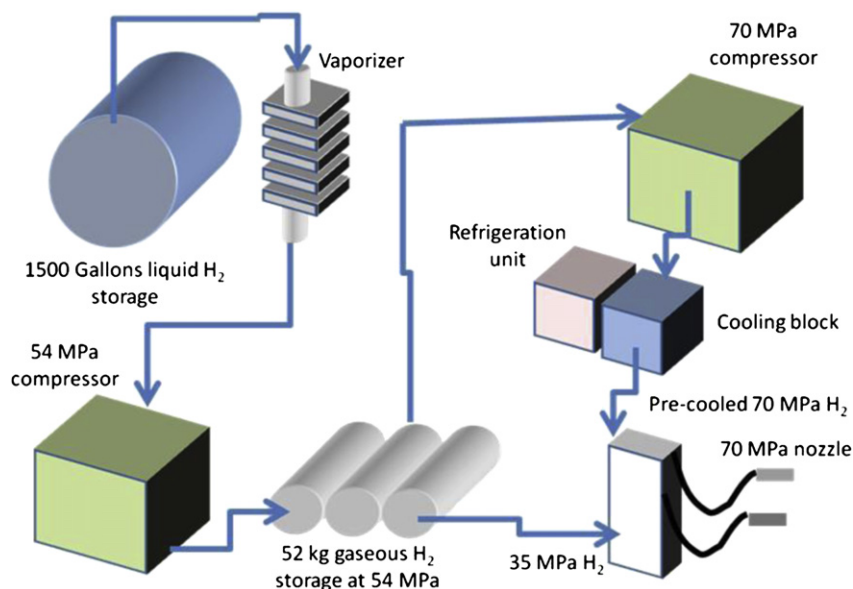


Fig. 4 – UCI hydrogen station having liquid and gaseous hydrogen storage, 35 MPa and 70 MPa compression and dispensing, and 70 MPa pre-cooling.

additional constraint due to the necessary pre-cooling of 70 MPa fill. If the pre-cooler temperature rises above a set threshold due to a combination of ambient temperature and hydrogen throughput, safety protocol prevents further 70 MPa refuelings until the temperature drops back down to the pre-determined level. Because the pre-cooling bottleneck does not allow a fill to begin if the cooling block is at an unacceptable temperature, no quantitative data have been collected on these events. Anecdotal data from drivers indicate that this is a frequent issue, particularly in the warmer summer months, with wait times as long as 1 h for the cooling block temperature to drop so the next fill can begin.

In 2011, only 2.3% of 70 MPa fills failed to deliver a full tank due to insufficient compressed gas storage. The percentage of incomplete 70 MPa fills is substantially lower than that of 35 MPa fills because the 80 MPa booster compressor can accept input hydrogen from the 54 MPa storage tubes at pressures as low as 27.5 MPa, whereas the pressure must be above 35 MPa for completion of 35 MPa filling.

Interestingly, Table 2 shows that the mix of 35 MPa and 70 MPa fuelings has shifted from year to year. The initial shift toward 70 MPa in 2008 and 2009 is due to the increasing portion of 70 MPa capable vehicles (i.e. Toyota, Mercedes and Hyundai) compared to 2007, as shown in Fig. 5. The trend

away from 70 MPa observed in 2010 is due to a 50% increase in Honda (35 MPa) usage and a 60% decrease in GM (70 MPa) usage resulting from shifts in the Honda Clarity lease and GM Project Driveway programs, respectively. General Motors' share of fuel was substantially larger in the past due to their deployment of vehicles to customers in the Irvine area through the Project Driveway program, though the project has recently ended [15]. Similarly, Mercedes' share of fuel has increased beyond 2010 due to a public lease program beginning in December of 2010 [16], again raising the portion of 70 MPa fueling.

High cooling block temperatures present an additional bottleneck to 70 MPa customers. If the cooling block temperature is too high, the driver must wait an indeterminate time (up to 1 h) for the cooling block temperature to drop in order to get a full 70 MPa fill. Alternatively, many 70 MPa vehicles can accept 35 MPa fuel pressure (resulting in approximately half the range) which enables drivers to immediately get a partial fill. This situation is observed in 2009, 2010, and 2011. For example, Table 2, 51.7% of fills were 70 MPa in 2010, yet Fig. 5 shows that 70% of the hydrogen was dispensed to vehicles capable of receiving 70 MPa (all except for Honda and Other). Likewise in 2011, 60.1% of fills were 70 MPa, yet 69% of hydrogen was dispensed to 70 MPa vehicles. The data are

Table 1 – Total and average hydrogen and filling data for 2007–2011.

Year	Total H ₂ dispensed per year (kg)	Average H ₂ dispensed per day (kg)	Total number of fills	Average number of fills per day	Average H ₂ per fill (kg)	Maximum H ₂ dispensed in 1 Day (kg)
2007	1003	2.75	744	2.04	1.35	25.2
2008	3093	8.45	1364	3.73	2.27	32.8
2009	5998	16.43	1934	5.30	3.10	54.5
2010	6928	18.98	2295	6.29	3.02	59.9
2011	8186	22.43	2639	7.23	3.10	51.3

Table 2 – Distribution of 35 MPa and 70 MPa fills and percentage of fills that ended prematurely.

Year	2007	2008	2009	2010	2011
Portion 35 MPa (%)	71.5	48.9	39.7	48.3	39.9
Portion 70 MPa (%)	28.5	51.1	60.3	51.7	60.1
Incomplete 35 MPa fills (%)	2.3	4.2	11.9	21.4	35.3
Incomplete 70 MPa fills (%)	3.3	3.2	6.1	3.1	2.3

more difficult to analyze in 2007 and 2008 when manufacturers such as Toyota and Mercedes simultaneously operated both 35 MPa and 70 MPa vehicles.

The load duration curve of Fig. 9 shows the mass of hydrogen dispensed at the station each day for five years, in descending order. As shown, the station was only used 209 days in 2007 compared to 324, 353, 358, and 362 days for 2008, 2009, 2010, and 2011, respectively. It is important to note that station repair and maintenance is responsible for several days of station inoperability each year. Fig. 6 also displays a horizontal line indicating the 25 kg/day design point of the station based on compressor capacity of roughly 2 kg/hour with a 50% duty cycle. Roughly 50 kg/day is possible if the compressor operates non-stop, and even greater quantities can be dispensed daily (as demonstrated several times in 2009, 2010, and 2011) due to the capacitive effect of the onsite storage, but all such operation is beyond the intended design. As shown, the numbers of days above the 25 kg/day threshold were 1, 7, 80, 98, and 150 for 2007–2011, respectively.

Each driver at the UCI Hydrogen Station is assigned a unique PIN code to allow access only to trained users and to enable data collection. Some users share a PIN code and a vehicle (e.g. husband and wife) and some users have access to more than one vehicle (e.g. automaker employees), though these instances are rare. Assuming that each driver represents one vehicle, the fleet of vehicles supported by the UCI station averaged 30.4 per month in 2009, 31.8 per month in 2010, and 32.4 per month in 2011, equating to 0.54 kg/car/day, 0.60 kg/car/day, and 0.69 kg/car/day for 2009, 2010, and 2011, respectively. This matches well to daily hydrogen consumption estimates used in the literature [13,17]. For the entire year of 2011, 64 different drivers filled at the UCI station.

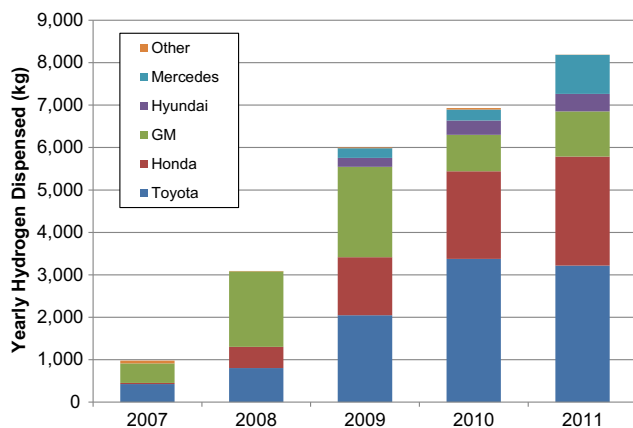
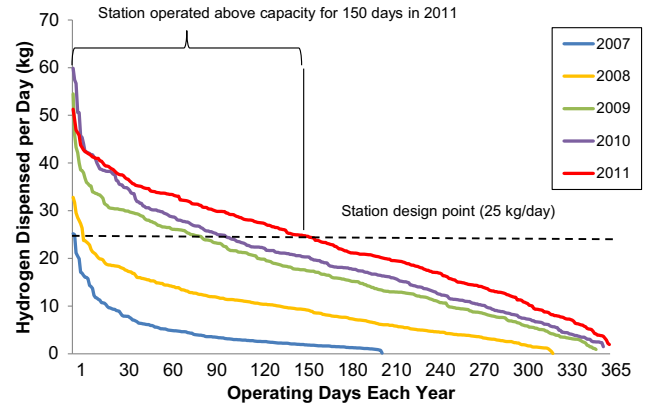
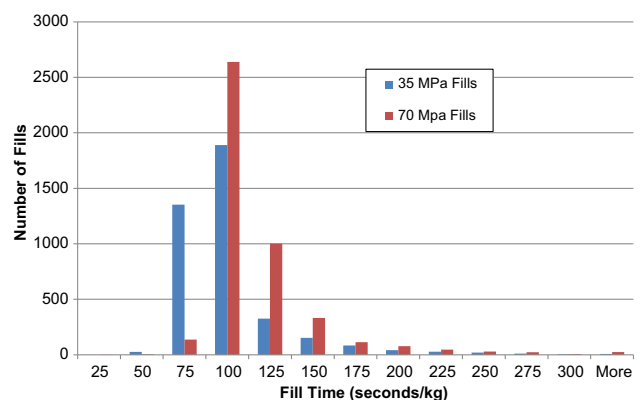
**Fig. 5 – Hydrogen dispensed per year allocated by automaker.****Fig. 6 – Hydrogen Station load duration curve showing the relationship between daily dispensing capacity and capacity utilization for 5 years.**

Fig. 7 shows a histogram of fueling time in seconds/kg for both pressures of fuel across all 5 years of station operation for every fueling event registering more than 0.25 kg. The small quantity refuelings were discarded from the data because they are often the result of station demonstrations, automaker engineers who are testing tanks and filling systems, or inexperienced users who inadvertently stop the fill prematurely. As shown, 83% of fill times for 35 MPa fueling range between 50 and 100 s per kg, and 63% of 700 bar fill times require between 75 and 100 s per kg. All recorded fill rates are easily below the maximum allowable rate of 16.67 s/kg outlined in SAE J2601.

Fig. 2 shows a peak in 2011 of 2.35 kg/hour for the hour between 7:00 am and 8:00 am. Based on an average fill rate of 93 s/kg for all fills conducted at UCI, the 2011 peak hour only resulted in 219 s of dispenser usage; a utilization factor of just 6.1%. This low utilization is due in part to factors including the time required to begin and end the refueling process including entering user identification number, connecting the nozzle, etc., but primarily due to the inability of the system to consistently perform back-to-back refuelings.

Ongoing, informal polling of drivers using the UCI Hydrogen Station has revealed several common observations. Waiting to refuel or the inability to refuel due to low pressure

**Fig. 7 – Histogram of refueling time.**

or station maintenance events are chief complaints. Additionally, the fill rate, particular for 70 MPa vehicles during warm weather can be burdensome. And lastly, drivers, even very early adopters, desire the common attributes of rest-rooms, beverages, and snack food provided at commercial gasoline stations, but lacking at UCI.

5. Electricity consumption

Station electricity consumption was measured as a function of hydrogen dispensed over the period from March 18, 2011 to March 22, 2011. During this time, 43 kg were dispensed through thirteen 35 MPa fills, and 37 kg were dispensed with eight 70 MPa fills. Current was recorded with 30 s resolution at the three-phase, 208 V feed line to the station and integrated to give electrical energy for all station loads, including compression, cooling block refrigeration, dispenser and control hardware, and even station lighting. The resulting electricity usage is a relatively linear relationship of 5.18 kWh consumed per kg of hydrogen dispensed.

Fig. 8 shows the hydrogen station electrical load and fill events over the course of four days in March of 2011. As shown, a 30–35 kW peak load is associated with each 70 MPa fill, and a roughly 12 kW peak load occurs during each 35 MPa fill.

Fig. 9 presents a high resolution portion of electric power data for a 15 h period containing baseline nighttime load, baseline daytime load, and two 35 MPa fills. As shown, a periodic trend for both nighttime and daytime base loads dithers between roughly 1.7 kW and 2.5 kW due to electrical consumption of the cyclic cooling system for the 70 MPa dispenser.

In Fig. 9, the main compressor starts as each 35 MPa fill begins and continues to run after each fill is complete in order to refill the hydrogen storage tubes. For the first fill shown, 2.26 kg was dispensed to a vehicle in 193.1 s. The compressor ran for 54 min resulting in a storage tube replenishing compression rate of 0.042 kg/min. The second fill dispensed 3.41 kg in 251.8 s, and the compressor ran for 67 min resulting in a replenishing rate of 0.051 kg/min. The difference in replenishing compression rate is not clear from the data,

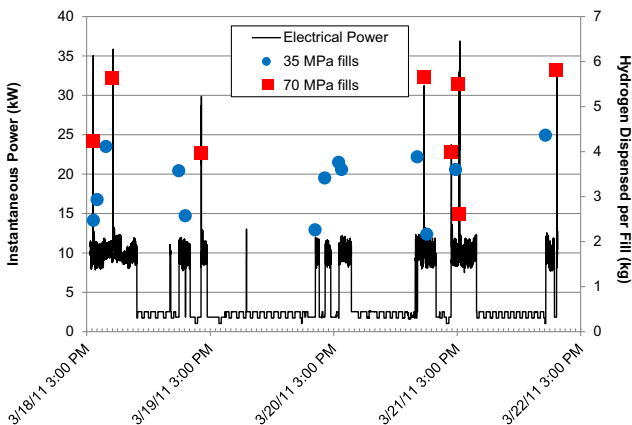


Fig. 8 – Station power demand and refuelings over a 5-day period.

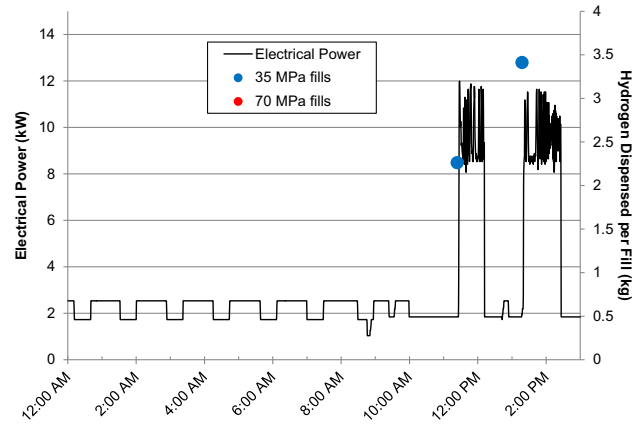


Fig. 9 – High resolution power demand for a period containing nighttime base load, daytime base load, and two 35 MPa refueling peaks.

though it may be due to differences in head pressure in the storage tubes, ambient temperatures, or compressor inlet pressures. The energy consumed for compression resulting from the two refueling events (after subtracting the power required to meet the base load) is 5.89 kWh (2.61 kWh/kg) for the first fill and 8.41 kWh (2.47 kWh/kg) for the second fill. These measured data fall between literature assumptions which range from 0.7 to 5.0 kWh/kg [14,18–21].

Fig. 10 shows a high resolution portion of electric power data for a 2 h period containing one 3.97 kg 70 MPa fill. When the fill started, an initial electrical spike occurred with a peak of slightly more than 10 kW corresponding to the start of the main compressor and continued for approximately 2.5 min as the vehicle tank was partially filled with hydrogen cascaded from the station’s compressed storage tubes. When the vehicle tank pressure equilibrated with the onsite compressed storage (at roughly 2.5 min) the operation of the high pressure booster compressor was required. The main compressor continued to operate with a power draw of 10 kW while the booster compressor was activated, resulting in a second,

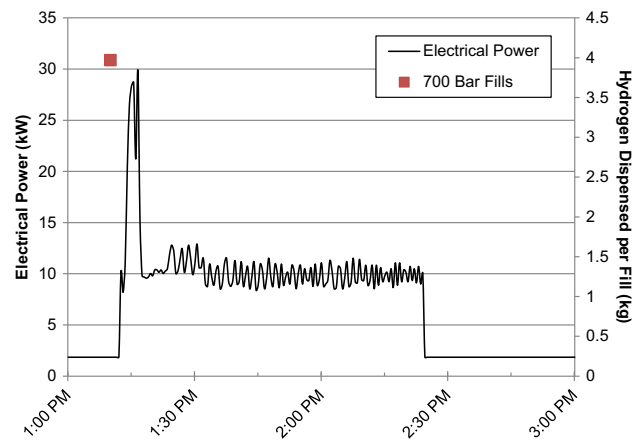


Fig. 10 – High resolution power demand data showing peak power consumption associated with one 70 MPa fueling.

larger combined power spike of nearly 30 kW. The booster compressor operated for approximately 3 min, ending when the vehicle tank was full. The main compressor continued to run for a total of 72 min to refill the onsite storage (rate of 0.055 kg/min). The total energy consumption for both fills (after subtracting base load demand) was 10.63 kWh, leading to 2.68 kWh/kg required for compression. This equates to only 11% more compression energy than that required for 35 MPa filling.

The average power consumption over the course of 80 kg of dispensed gas (5.18 kWh/kg) is significantly higher than the compression energy component alone due to other loads. The cooling system load averaged 0.54 kW for the analysis period in March with an average ambient temperature of 13.5 °C resulting in the addition of 1.40 kWh per kg of 70 MPa hydrogen dispensed. The remaining station electrical loads average 1.79 kW resulting in slightly more than 2 kWh per kg of hydrogen dispensed (both 35 and 70 MPa). These energy consumption figures indicate that the compression energy required for hydrogen dispensation is just one of several energy intensive processes.

6. Environmental analysis

The Preferred Combination Assessment (PCA) tool was developed to analyze resource consumption and emissions of hydrogen supply chains [22]. Using historical UCI station usage data including dispensing pressure and vehicle mixes, combined with knowledge that each liquid hydrogen delivery originated at Air Products Sacramento based liquefaction facility (~435 miles from UCI), the PCA model was used to generate greenhouse gas emissions as shown in Table 3. As shown, the well-to-wheel greenhouse gas emissions have always been lower than those of the California projected gasoline vehicle fleet for the year 2015 (376.95 g/mi) [23], and have dropped substantially from 2007 to 2011. The primary reason for the decline in emissions is due to higher utilization of the station which distributes the fixed electrical energy (e.g. lighting) over more vehicle miles. For 2010 and 2011, the increased utilization is offset by a slightly less efficient vehicle fleet mix (Table 4).

In November of 2010, the California Energy Commission awarded APCI a grant to upgrade the UCI Hydrogen Station. The upgraded station will utilize high pressure composite tube trailer technology which enables more efficient distribution and dispensing of gaseous hydrogen with a throughput

capability of 180 kg/day [24]. Consequently, no electricity is required for liquefaction and hydrogen can be delivered from local gaseous supply facilities 35 miles away (although more deliveries will be needed as the gaseous truck does not carry as much hydrogen as the liquid tanker). Using the same vehicle mix and throughput data for 2011, the reduced energy consumption and reduced travel distance would result in an average value of just 201 g CO₂e/mile. This is well below the 2016 combined car and truck goal of 250 g CO₂e/mile promulgated by the U.S. Environmental Protection Agency [25].

The station upgrade which will incorporate both a significant capacity increase and a change in hydrogen delivery and storage method should overcome many of the performance limitations of the current station. By storing all of the hydrogen in a high pressure tube trailer, the station will no longer depend on an onsite compressor to accomplish 35 MPa fueling. Secondly, an additional stationary, onsite carbon composite storage tank will be capable of storing hydrogen at sufficient pressure (>80 MPa) to fuel 70 MPa vehicles. Currently, the high pressure compressor operates only during the fueling of 70 MPa vehicles and the fill rate is directly coupled to the compression rate. With the addition of the onsite composite storage tube, the high pressure compressor operation is no longer coupled directly to vehicle fueling, allowing for both faster refueling and less strenuous compressor operation. As a third benefit, the change in duty cycle of the high pressure compressor and the absence of a low pressure compressor reduces electrical requirements such that a higher power cooling system can be installed without significant electrical upgrades at the station site. As a result, many, if not all, of the current refueling delays due to the cooling system should be overcome. It is also expected that that higher station throughput (up to 180 kg/day) will distribute station ancillary loads over a greater number of refueling events, ultimately reducing the electricity consumption per kilogram of hydrogen dispensed.

7. Hydrogen and operation costs

The per kilogram price of hydrogen depends on a number of factors including staffing, equipment lease, maintenance, electricity and natural gas pricing, hydrogen production costs, delivery cost, hazardous material (liquid H₂) fees, and sales tax.

In line with the university charter, the UCI Hydrogen Station is operated without profit motive, but does require real staffing and overhead costs associated with management and campus land procurement. Likewise, insurance costs can be significant. These costs are not considered herein.

Much of the UCI station equipment was purchased through grant money awarded by the Department of Energy, but some equipment is leased from APCI on a monthly basis, as shown in Table 3. Additionally, a monthly fee is paid to APCI for a maintenance agreement. This cost will likely rise substantially for new stations with significantly higher daily capacity.

As shown in the third column of Table 3, throughput data from 2011 results in a yearly cost of \$122,351.75 for 8186 kg dispensed, or \$14.95 per kg. Correspondingly, similar analysis

Table 3 – Historic well-to-wheel greenhouse gas emissions for UCI Hydrogen Station operation.

Scenario	Greenhouse gas emissions
Gasoline Baseline (CARB)	377 g/mile
2007 UCI H ₂ Station	367 g/mile
2008 UCI H ₂ Station	305 g/mile
2009 UCI H ₂ Station	273 g/mile
2010 UCI H ₂ Station	248 g/mile
2011 UCI H ₂ Station	248 g/mile
Future UCI H ₂ Station	201 g/mile

for the lower 2008 throughput (3093 kg) amounted to a hydrogen cost of \$25.50 per kg. Even without the inclusion of labor, land, or insurance, this price is not yet competitive with gasoline on a per mile basis. Higher throughput and reduced capital costs through technology advancements aim to bring hydrogen to parity with, or below the cost of gasoline per mile in the 2015 timeframe.

8. Station optimization

The UCI Hydrogen Station always maintains a sufficient supply of bulk, liquid hydrogen due to careful level monitoring and timely deliveries. However, it is clear from the premature fill stoppage data that the station is commonly operating near its maximum threshold, particularly with respect to 35 MPa refueling. This is particularly alarming because the station is often characterized as having the capability to deliver 25 kg/day (nominal compressor rating), but is currently operating at a slightly lower average of 22.43 kg/day. As hydrogen infrastructure planning matures, properly characterizing and optimizing hydrogen station capacity will become a necessity.

The Society of Automotive Engineers (SAE) has been working with industry partners to develop guidelines for hydrogen vehicle refueling. SAE J2601, Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles, specifies average daily station capacity as the total mass of hydrogen that can be delivered to 7 kg capacity vehicles over a 12 h period (expressed in kg/day). Peak fueling capacity is defined as the number of 7 kg capacity vehicles that can be fueled in 1 h (expressed in kg/hour).

The UCI Hydrogen Station is constrained by compressor rate and compressed gas storage. If either is increased, the mass of hydrogen that can be dispensed will be improved. A model of the station has been constructed using MATLAB to simulate the compressor, onsite storage, and vehicle fuel tank. Inputs to the model include fill start times (date/time), fill durations (seconds), fill rates (kg/second), vehicle tank pressure at the beginning and end of each fill (MPa), and total mass of hydrogen transferred per fill (kg) for a given time period, typically one week. Actual station data is used to validate the model. Whenever the storage tube having the highest pressure drops below the 35 MPa threshold during

a 35 MPa filling event, the model records an incomplete fill. Likewise, if the pressure drops below 27.5 MPa during 70 MPa fueling, the fill is deemed incomplete. The model derived incomplete fills can be compared to actual incomplete fills observed in the data.

The compressor is modeled as a constant source producing 54 MPa hydrogen at a rate of 25 kg/day anytime that the storage tubes are not completely full. Each of the 3 onsite storage tubes is modeled as a volume capable of holding 17.33 kg of hydrogen at 54 MPa. The Van der Waals gas equation is used throughout to model the pressure, mass, and volume of hydrogen under the very high pressures used in vehicle fueling. The Van der Waals equation accounts for both intermolecular forces and molecular size:

$$\left(p + \frac{\left(\frac{m}{M}\right)^2 a}{V^2} \right) \left(V - \frac{m}{M} b \right) = \frac{m}{M} RT$$

where p is pressure, m is mass, M is molecular weight, a is a measured quantity of the attraction between molecules, V is volume, b is the volume of a mole of molecules, R is the universal gas constant, and T is temperature. In the model, hydrogen is transferred from the storage tubes to a simulated vehicle fuel tank at a rate consistent with that recorded from actual station data. No data is available for vehicle tank capacity or initial fill level for each filling event. However, starting and ending tank pressure is available. An iterative loop using the Van der Waals equation solves for tank volume and initial tank mass given starting pressure, ending pressure, and mass transferred. The model neglects gas dynamic effects and heat transfer.

The model is effective at predicting insufficient station pressure situations. For example, during a particularly busy week in 2009 (172.77 kg dispensed over 53 fills), the model correctly predicted 7 out of 7 low pressure events during the week and only incorrectly predicted 1 low pressure event that did not occur.

Fig. 11 shows the simulated pressure in each storage tube during the same week in 2009. The low pressure tube shown as a dotted line is reduced to under 15 MPa by the third day of the week, never fully recovers, and ends the week at nearly 10 MPa. The middle pressure tube (dashed line) is depleted to 17 MPa on Friday and early Saturday, but recovers to nearly

Table 4 – Hydrogen station costs.

Item	Cost	Contribution per kg of H ₂ in 2011 (8186 kg dispensed)
1500 gallon liquid hydrogen tank lease	\$1800 per month	\$2.64
3 high pressure compressed gas storage tubes	\$900 per month	\$1.32
Maintenance contract	\$1467 per month	\$2.15
H ₂ product price (current; varies based on natural gas and diesel fuel indices)	\$17.58 per 1000 SCF	\$7.31
HAZMAT fee	\$48 per delivery (average roughly 1 delivery per week)	\$0.30
Electricity (\$0.12 per kWh)	5.18 kWh per kg	\$0.62
State sales tax	8.25%	\$0.60

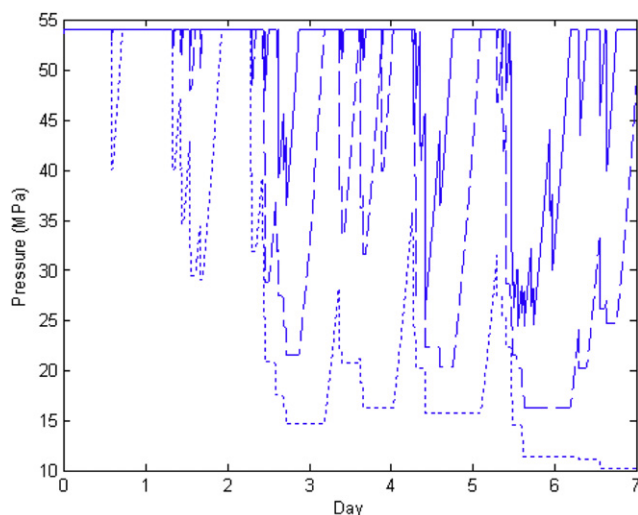


Fig. 11 – Simulated pressure of each of the 3 onsite hydrogen station storage tubes during the week of heaviest usage for 2009. Solid line: high pressure bank, dashed line: middle pressure, dotted line: low pressure.

full pressure by Saturday night. The high pressure tube (solid line) is continually depleted and fully replenished throughout the week. Anytime that the high pressure tube falls below 35 MPa during a 35 MPa fill, or below 27.5 MPa during a 70 MPa fill, the fill stops and it is recorded as incomplete.

The model can be used to assess the SAE kg/hour and kg/day specifications for the UCI station (ignoring any bottle-necks associated with the hydrogen cooling system). Applying repeated 7 kg refueling every 2 h results in 5 complete fills. The 6th fill is incomplete due to low storage tube pressure, as shown in Fig. 12. Reducing the time between fills does not improve the number of complete fills. As a result, the UCI station would be classified as 35 kg/day (5 fills at 7 kg each).

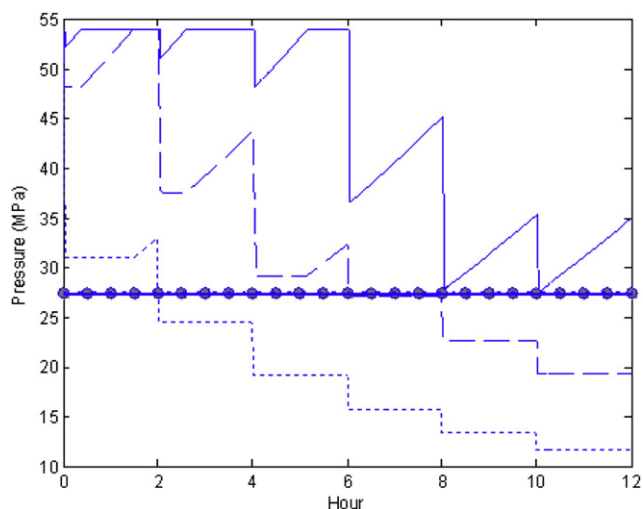


Fig. 12 – Storage tube pressures for repeated 7 kg fills per SAE kg/day guidelines. Solid line: high pressure bank, dashed line: middle pressure, dotted line: low pressure. The dark solid line at 27.5 MPa represents the booster compressor threshold.

Similar analysis for a 1 h period results in 4 complete fills, or a 28 kg/hour rating. Both of these specifications are somewhat misleading as they result in severely depleted storage tubes precluding the potential repetition of the predicted performance in the following day or hour.

9. Conclusions

The UCI Hydrogen Station has successfully dispensed over 25,000 kg of fuel to over 8900 vehicles in the course of 5 years without any safety issues. This does not minimize the potential hazard associated with flammable gas stored at high pressure, but does indicate that the hydrogen vehicle refueling process can be safe through judicious safety protocol, much as gasoline refueling safety is routine and transparent for drivers today.

The usage at the UCI Hydrogen Station has increased each year as manufacturers introduced new vehicles and expanded their current fleets, with operation at 90% of design capacity in 2011. Not surprisingly, the bulk of fuel (82%) is dispensed between 7:00 am and 5:00 pm. Weekday usage is roughly double that of weekend refueling. Weekend refueling is concentrated around midday with usage tapering in the morning and afternoon, whereas the station is utilized nearly constantly between 7:00 am and 5:00 pm on weekdays.

Though the average station throughput has not reached full design capacity, peak usage in the waking hours often exceeds design constraints resulting in partial customer fills. Surprisingly, despite frequent overloading (150 days in 2011), the station has operated robustly (i.e. in service for 362 out of 365 days in 2011).

When the UCI Hydrogen Station opened in 2007, 90% of refuelings were performed with vehicles from just two automakers. In 2011, five automakers contributed significantly to station throughput, demonstrating the broadening and maturation of fuel cell vehicle products. The increased number of automakers signifies a growing industry realization of the fuel cell vehicle (FCV) market potential, despite the ebb and flow of political and social alternative vehicle opinions.

The UCI Hydrogen Station, dispensing an average of 22.4 kg per day, supports a local fleet of roughly 32 vehicles. This equates to 0.7 kg/car/day. Given similar usage, the Irvine/Newport Beach hydrogen station cluster under development which includes a 100 kg/day capacity station in Newport Beach, a 100 kg/day station in Fountain Valley, an upgraded UCI station capable of 180 kg/day, a second Irvine station capable of 180 kg/day, and a Laguna Niguel station rated at 240 kg/day, will be able to serve an on-road fleet of roughly 1000 FCVs.

Base load electrical power consumption at the UCI Hydrogen Station is a substantial cost and greenhouse gas factor when throughput is low. Electricity used to maintain cooling block temperature when idle, provide lighting, and power control equipment is a fixed penalty that is best mitigated by increasing throughput. The actual electricity consumed to pressurize hydrogen from 1.3 MPa (liquid vapor pressure) to 35 MPa or 70 MPa ranges from 2.5 to 2.7 kWhr/kg.

Hydrogen generation, distribution, and dispensing costs for UCI's small (25 kg/day), liquid supplied hydrogen station

are significantly higher on a cost-per-mile basis than equivalent gasoline fuel. In 2011, hydrogen cost, not including station management, land, or insurance was \$14.95 per kg. Assuming FCV efficiency is 2.2 times higher than a standard vehicle (e.g. Honda FCX Clarity compared to Honda Accord per U.S. Department of Energy), then the UCI Hydrogen Station cost equated to gasoline priced at \$6.79 per gallon. Next generation distribution and dispensing technology combined with greater station throughput aims to achieve parity with gasoline on a per mile basis. Given the domestic sourcing of hydrogen and the geo-economics and finite resources associated with petroleum, the future cost of hydrogen per mile is envisioned to be less than that of gasoline with an increasing margin of difference.

Hydrogen station performance standards prescribed in SAE J2601 help to better describe actual station capacity through the understanding that refueling does not occur methodically over each 24 h period. Caution must be used to ensure that the SAE J2601 standards for 1 h and daily capacity are fully understood when comparing station designs. A model for the UCI Hydrogen Station shows the capability to dispense 28 kg in 1 h under ideal conditions. However, the station would then take nearly 24 h to recover before more fuel could be dispensed. Similarly, the model predicts a daily capacity of 35 kg per SAE J2601 specifications, but that capacity could not be repeated for consecutive days.

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