EVTC

Electric Vehicle Transportation Center

Hydrogen Fueling Stations Infrastructure

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Acronyms and Abbreviations

CaFCP	California Fuel Cell Partnership
DOE	US Department of Energy
EC	Early Commercial Station
EVTC	Electric Vehicle Transportation Center
FCEV	Fuel Cell Electric Vehicle
H2A	Hydrogen Analysis model
HSCC	Hydrogen Station Cost Calculation
LS	Larger Stations
MS	More Stations
NREL	National Renewable Energy Laboratory
PSA	Pressure Swing Adsorption
SMR	Steam Methane Reformer
SOTA	State-of-the-art
STREET	Spatially & Temporally Resolved Energy & Environment Tool
UCD	University of California, Davis

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1. INTRODUCTION

Fuel Cell Electric Vehicles (FCEVs) can provide customers with the benefits of low to zero greenhouse gas emissions, high performance, and comfort without compromising range and refill time. With three major automakers (Honda, Hyundai, and Toyota) planning to introduce consumer FCEVs by the end of 2015, FCEVs will play an increasingly important role in the electric vehicle arena. Building hydrogen fueling infrastructure has been identified as a major obstacle in FCEV commercialization.[1] This report is part of an ongoing effort within an Electric Vehicle Transportation Center (EVTC) project: "Fuel Cell Vehicle Technologies, Infrastructure and Requirements." This report is based on a survey of recent literature on several key aspects of a hydrogen infrastructure: types of hydrogen fueling stations, station costs, station rollout strategy, and codes and standards. The majority of hydrogen infrastructure studies focus on California's pioneering model of deploying and testing small fleets of FCEVs and demonstrational hydrogen fueling stations. Valuable lessons can be learned from California's experiences and used by other states to plan and prepare for the challenges and opportunities that hydrogen transportation might bring.

2. HYDROGEN FUELING STATIONS

Hydrogen fueling stations are one of the most important building blocks of the FCEV transportation infrastructure. In contrast to conventional gas stations where gasoline is delivered by tanker trucks, hydrogen fuel can be either delivered by trucks, by hydrogen pipelines, or produced onsite at the fueling stations. Despite the many variations on the station design, most stations required the following hardware:

- Hydrogen production equipment (for on-site hydrogen production types of stations only)
- Purification system: to purify hydrogen to meet the purity standards for fuel cell vehicles
- Storage vessels: to store hydrogen in gaseous or liquid form
- Compressor: minimize storage volume and prepare the gas for pumping into high pressure (35 MPa-70MPa) vehicle storage tanks
- Safety equipment (e.g. pressure relief valves, vent stack, hydrogen sensors, fencing)
- Mechanical equipment (e.g. underground piping, valves)
- Electrical equipment (e.g. control panels, high-voltage connections, meters)

Hydrogen fueling stations can be in many various types that mainly differ in hydrogen forming methods and hydrogen delivery methods. Some currently employed stations types and their capacities are shown in Table 1.

2.1. ONSITE STEAM METHANE REFORMING

Hydrogen fueling stations equipped with a steam methane reformer (SMR) is capable of converting other fuels (natural gas, biogas, etc.) to hydrogen. This method works by exposing e.g. methane to catalyst at a high temperature to produce a mixture of hydrogen and carbon monoxide called syngas. The syngas further react with the catalyst to form more hydrogen and carbon dioxide. The carbon dioxide is then removed by a pressure swing adsorption (PSA) system. The reforming reaction for hydrogen production can be simplified as: [2]

$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$

The configuration in this type of hydrogen station requires a water tank, a reformer containing a series of reactors, a purification system PSA, buffers and hydrogen compressor, filters, air dryers and compressors, and hydrogen dispensing pumps (Figure-A1).[3] The approximate hydrogen fueling capacity of this type station is 100-1000 kg/day depending on the size of the reformer and the number of dispensing pumps.[4]

2.2. ONSITE ELECTROLYSIS OF WATER

In this method, electricity from grid or intermittent electricity is used produce hydrogen from water. An electric current is passed through water with presence of an electrolyte membrane and catalysts to split water into hydrogen and oxygen. The hydrogen is compressed or stored for fueling FCEVs. Most commercial electrolyzers today are capable of electricity to hydrogen efficiencies above 75%, with many reaching 80-85%, while 90% has been demonstrated in laboratories. A typical electrolyzer station will require a water tank, deionizer, electrolyzer, purifier, buffers, compressors, air dryer, filters, and dispensers (Figure-A2).[3] The capacity of this type of station is relatively small (30-100 kg/day).

2.3. LIQUID OR GASEOUS HYDROGEN DELIVERY

Hydrogen is produced at a central point such as a hydrogen generating plant. It can be neither delivered to fueling stations in a gaseous form via “tube trailers” or in liquid form via “Dewar” tanker trucks (Figure-A3). The liquid hydrogen is liquefied by supercooling the gas to a cryogenic temperature of -253 °C. When delivered as a liquid form, the fuel can be either stored in a liquid form or can be gasified at ambient temperature with vaporization stacks at the station, and then compressed and stored for dispensing (Figure-A4).[4] Since the hydrogen is not produced onsite, the required elements are buffers, dispensing pumps, compressor, dryer, and air filters.

2.4. PIPELINE DELIVERY

Hydrogen pipelines are used to transport hydrogen from the point of production to the point of demand. They are typically built to deliver hydrogen between gasoline refineries and chemical plants. The hydrogen fueling stations can take advantage of the existing 700 miles pipeline in the United States.[4] Hydrogen is drawing from the pipeline at its service pressure, purified, and compressed and stored at the stations for dispensing. In the future, a designated hydrogen fueling pipeline may be built to roll out a more mature hydrogen fueling network. In addition, some studies indicate possibilities of blending a certain percentage of hydrogen with natural gas in the natural gas pipelines and then re-separating out hydrogen for fueling stations. A relatively low percentage (e.g., 10%) blends is suggested to minimize the pipeline safety issues, but further study is still needed.[5] The equipment needed in a fueling station are buffers, dispensing pumps, compressor, dryer, and air filters (Figure-A5).[3]

2.5. MOBILE REFUELING

Mobile refuelers deliver hydrogen storage tanks to a fueling site where they are stationed temporarily (Figure-A6).[3] This method is commonly used temporarily for fueling stations that are under construction or for short term events.

Table-1. Types of hydrogen fueling stations and their capacities.

Station Type	Onsite Production	Approx. Capacity (kg/day)
Steam methane reformer-based production	Yes	100-1000
Electrolyzer-based production	Yes	30-100
Mobile refueler	No	10-60
Pipeline gas delivery	No	100-1000
Delivered liquid or gaseous hydrogen	No	20-1000

2.6. COMPARISON OF DIFFERENT TYPES OF FUELING STATIONS

The cost and location will affect the technical solution chosen for hydrogen fueling stations. The cost analysis is presented in the Section 4. According to HyWays, an European hydrogen energy roadmap, the suitability of different fueling station types are described:[6]

- Stations in remote areas with a constant and small demand are best suited for onsite production.
- Stations in rural areas with higher demand, e.g. along highways, may be suitable for liquid hydrogen delivery.
- Large stations at the city borders may be suitable for liquid hydrogen delivery or pipeline gaseous hydrogen delivery.

HyWays also presents three scenarios of hydrogen infrastructure build up, shown in Figure-1.[6] The scenario's variables are the buildup rate of fueling stations and the percentage of liquid hydrogen demand at the pump. In the first scenario, assuming that 20% of the hydrogen demanded will be in liquid form (when the vehicle hydrogen storage method is liquid hydrogen), the liquid hydrogen delivery method will have the highest share in the early stage. In the later phases, pipeline delivery may become more relevant once a significant market penetration of FCEVs has been achieved. In remote areas, onsite production of hydrogen remains the most suitable choice, but the high cost of the onsite production prevents this method from taking a higher share. In the second scenario where 0% liquid hydrogen is demanded at the pump, gaseous trailer might be favorable at the beginning and liquid delivery and pipeline will increase their shares as demand increases. This scenario is more likely to happen because most early generation hydrogen vehicles will adopt high pressure hydrogen tank storage method rather than onboard liquid hydrogen storage. In the third scenario, the fueling station network is built up in a moderate way. Larger and better utilized stations enter in earlier stages. Therefore liquid hydrogen delivery might play an important role in the early stage, despite that 0% liquid hydrogen is demanded at the pump. In all three scenarios, pipeline delivery will become increasingly important as demand raises. The centralized hydrogen production will remain predominant (>90%) compared to onsite production.

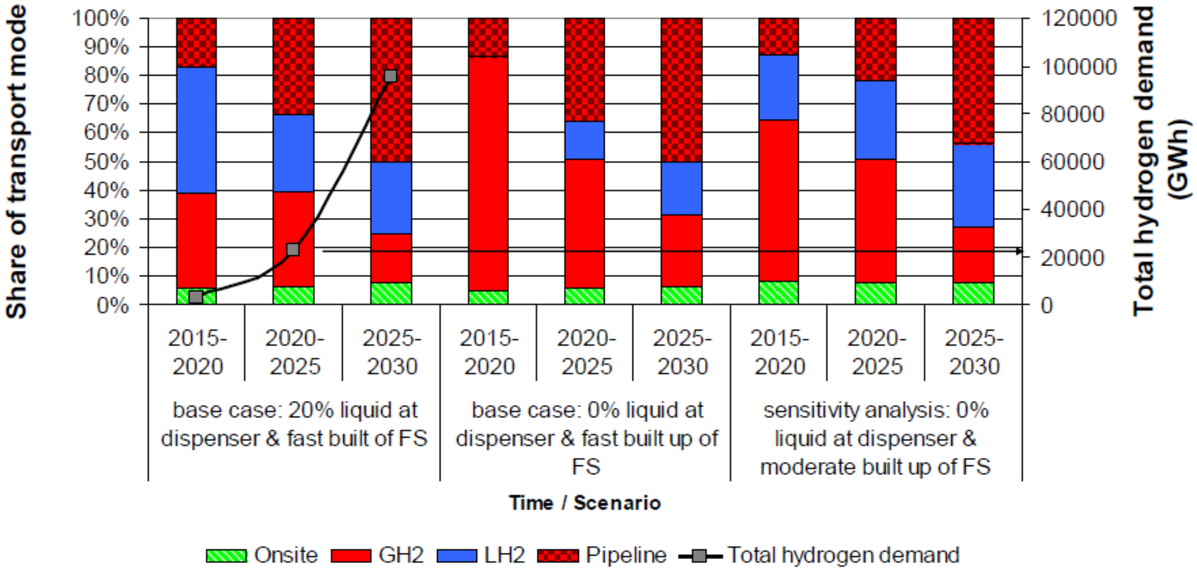

Figure-1. Shares of hydrogen fueling station types based on time and scenarios.

2.7. FUELING STATIONS WITH 35 MPA AND 70 MPA DISPENSERS

The current and near-future FCEVs will most likely be equipped with onboard compressed hydrogen storage tanks at 35 or 70 MPa (350 or 700 bar). Most fueling stations will need to install dispensers to accommodate both pressures. The 70 MPa dispensers post higher challenge than the lower pressure counterpart. Take a public station in Irvine, California as an example. Hydrogen is delivered in a liquid form and stored in three storage tubes at 54 MPa. When a 35 MPa FCEV refuels, hydrogen directly flows from the 54 MPa tank to the vehicle's tank from the lowest pressure tank first. If the pressure of the first tanks falls to the same pressure as the vehicle tank, the second storage tank kicks in, and then the third.[7] However, when filling a 70 MPa vehicle, two additional steps are required. The 54 MPa hydrogen needs to be first further compressed to 80 MPa. The extra compression and high pressure require the fuel to be cooled substantially in order to avoid overheating the vehicle tanks during filling. Therefore, the high pressure hydrogen has to pass through a cooling block before entering the vehicle. The cooling block is cooled by an onsite refrigeration unit. If the pre-cooler temperature rises above a set threshold due to a combination of ambient temperature and hydrogen throughout, the filling will stop until the temperature drops back to the pre-determined level, causing a filling delay. When designing hydrogen stations, extra attention needs to be paid to the 70 MPa dispensers and the cooling equipment in order to ensure smooth fueling experience.

3. CODES AND STANDARDS

Codes dictate when and where requirements apply, and standards direct how to meet those requirements. Fuel cell vehicle stakeholders such as government agencies, standards development organizations, and industries are responsible for leading the effort to develop key codes and standards. As fuel cell fueling stations represent a series of emerging technologies, new standards and codes associated are still under development or revision. For instance, contaminants such as carbon monoxide and hydrogen sulfide are impurities in the hydrogen fuel that are produced by reforming techniques from methane or biogas. They are most harmful to proton exchange membrane fuel cells (PEMFC) as they will poison the platinum catalyst. International Organization for Standardization (ISO) has set a purity of 99.97 % H_2 as a standard for PEMFCs with a maximum allowance of 0.2 ppm for carbon monoxide and 4 ppb for hydrogen sulfide (ISO 14687-2:2012). Since new technologies have been continuously developed to reduce the platinum catalyst loading in the fuel cell, the fuel standard may need to be revised to accommodate these changes. This research effort is conducted by Los Alamos National Laboratory (LANL) and ASTM International supported by the US Department of Energy (DOE) Hydrogen and Fuel Cells Program.[8]

For all hydrogen station types described in above section, the compression, storage, and dispensing of hydrogen gas should follow certain codes and standards. For example, some pioneer hydrogen fueling stations in the State of California followed the Society of Automotive Engineers (SAE) standard J2601: “Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles” for their hydrogen fuel dispensers [4, 9, 10] This standard applies to light duty vehicles fueling for vehicles with storage capacity from 1 to 10 kg H_2 for 70 MPa and 1 to 7.5 kg for 35 MPa. The criteria include maximum fuel temperature at the dispenser nozzle, the maximum fuel flow rate, the maximum rate of pressure increase and other performance criteria based on the cooling capability of the station’s dispenser.[11]

The National Renewable Energy Laboratory (NREL) published a list of codes and standards applicable for U.S. hydrogen infrastructure projects. They categorize the codes and standards in sixteen aspects: annual inspections, balance of plant, canopy tops, compressed hydrogen gas storage, compression systems and equipment, design, dispensing, fire safety, liquid hydrogen storage, dispensing/operations/maintenance safety, on-site hydrogen production, operation approvals, setbacks and footprints, outdoor gaseous systems, transportation, and vaporizers.[12] The website fuelcellstandards.com contains a database of over 300 world-wide hydrogen and fuel cell standards and is also a good source to locate codes and standards relevant to hydrogen fueling stations.[13] In addition, the California Fuel Cell Partnership (CaFCP) and California Department of Food and Agriculture are developing test methods for evaluating metering equipment and dispensers for the purpose of selling hydrogen as a vehicle fuel in California. This standard will very likely to be adopted by more states as hydrogen fueling stations roll out.[14]

4. COST ESTIMATES FOR THE FUELING STATIONS

The cost analysis of hydrogen fueling stations is a complex issue due to a number of reasons. Unlike gasoline, hydrogen can be generated from multiple feedstocks such as natural gas, ethanol, biomass, water, using multiple sources of energy such as fossil fuel, nuclear power, solar energy, and wind energy, etc. Hydrogen can be either produced at centralized locations and delivered to fueling stations, or generated on-site. Therefore, depending on the locations of the fueling stations (distances from a centralized hydrogen production plant) and accessibility or emphasis on the renewable energy, the cost for the stations may vary significantly. Moreover, factors such as government incentives, increased scale of FCEVs fleets, increased utilization efficiencies, and economies of scale associated with high capacity stations all play important roles in the final cost of the fueling stations. Several efforts conducted by different entities have developed several models to estimate the cost: (1) the Hydrogen Analysis (H2A) model developed by the US Department of Energy's Fuel Cell Technologies Office, (2) models developed by University of California, Davis (UCD), (3) Hydrogen Station Cost Calculation (HSCC) developed by the National Renewable Energy Laboratory (NREL), and (4) recent hydrogen station installation estimates in California.

The H2A model was developed with input and deliberation from industrial stakeholders such as American Electric Power, BOC Gases, British Petroleum, Chevron, ExxonMobil, etc. H2A case studies include both onsite production types and delivery types of hydrogen fueling stations. The current cases refer to technology status in 2010 and assume deployment five year later in 2015 with mass production.[15] UCD studies were conducted by collecting inputs from multiple stakeholders such as California Fuel Cell Partnership (CaFCP), Chevron, DOE, General Motors, Honda Motor Company, Shell Hydrogen, Toyota Motor Company, etc. It also takes consideration of different types of fueling stations into the cost estimates. [16] In contrast, results from the HSCC do not distinguish between stations of different production or delivery types. Their cost estimates apply to various types of hydrogen stations that are likely to be installed over the next 5 to 10 years.[17] The recent hydrogen stations installed in California offer invaluable real-world data of the hydrogen fueling station costs, which is used to evaluate the model predictions.

Table-2 depicts the cost estimates of four types of fueling stations from H2A prediction of 2015 and UCD prediction for 2012-2014. Cost per capacity ($/kg/day) is widely used as a measurement for the economics of hydrogen fueling stations. The Total capital is equal to the Cost per capacity multiplied by the Station capacity. UCD values are generally higher than the H2A values. It is due to that the UCD study takes into account of a baseline cost for site preparation, permitting, engineering, utility installation, and buildings, assuming all new stations being built from the ground up. In both models, a clear trend of cost per capacity reduction is shown for all station types (Figure-2). This can be attributed to economies of scale. The stations utilizing onsite hydrogen production have higher costs than the ones using delivered hydrogen due to the added complexity of the station design.

Table-2. Cost estimates for hydrogen fueling stations based on the H2A and UCD models

	GH2 Delivery		LH2 Delivery		Onsite SMR		Onsite Electrolysis	
Station Capacity (kg/day)	Cost per Capacity ($/kg/day)	Total Capital ($M)	Cost per Capacity ($/kg/day)	Total Capital ($M)	Cost per Capacity ($/kg/day)	Total Capital ($M)	Cost per Capacity ($/kg/day)	Total Capital ($M)
H2A model for 2015								
100	13900	1.39	9025	0.903	11230	1.12	10610	1.06
400	5100	2.04	4305	1.72	5182	2.07	5242	2.10
1000	4097	4.10	3435	3.44	4013	4.01	4394	4.39
UCD model for 2012-2014								
100	22200	2.22	25800	2.58	31800	3.18	32200	3.22
400	7025	2.81	7025	2.81	12025	4.81	13125	5.25
1000	n/a	n/a	3210	3.21	7760	7.76	9260	9.26

GH2 = gaseous hydrogen, LH2 = liquid hydrogen, SMR = steam methane reforming

The real-world hydrogen station cost estimates are good benchmarks to verify the validity of models. Table-3 shows the cost estimates of early demonstration stations in 2009 and recently funded stations in 2014. The correlation of the cost per capacity and station capacity is plotted in Figure-3. The H2A and UCD modeled values of hydrogen stations with liquid delivered type are also shown in the figure. The stations with smaller capacities and onsite hydrogen production are more expensive in terms of cost per capacity than the larger stations with delivered hydrogen, which agrees with both models. The 2014 stations cost less than the 2009 ones due to larger size, and lowered technology costs. The cost of 2014 stations with liquid hydrogen delivery method fit well with the UCD model, suggesting that the UCD model captures a more realistic trend of hydrogen station cost.

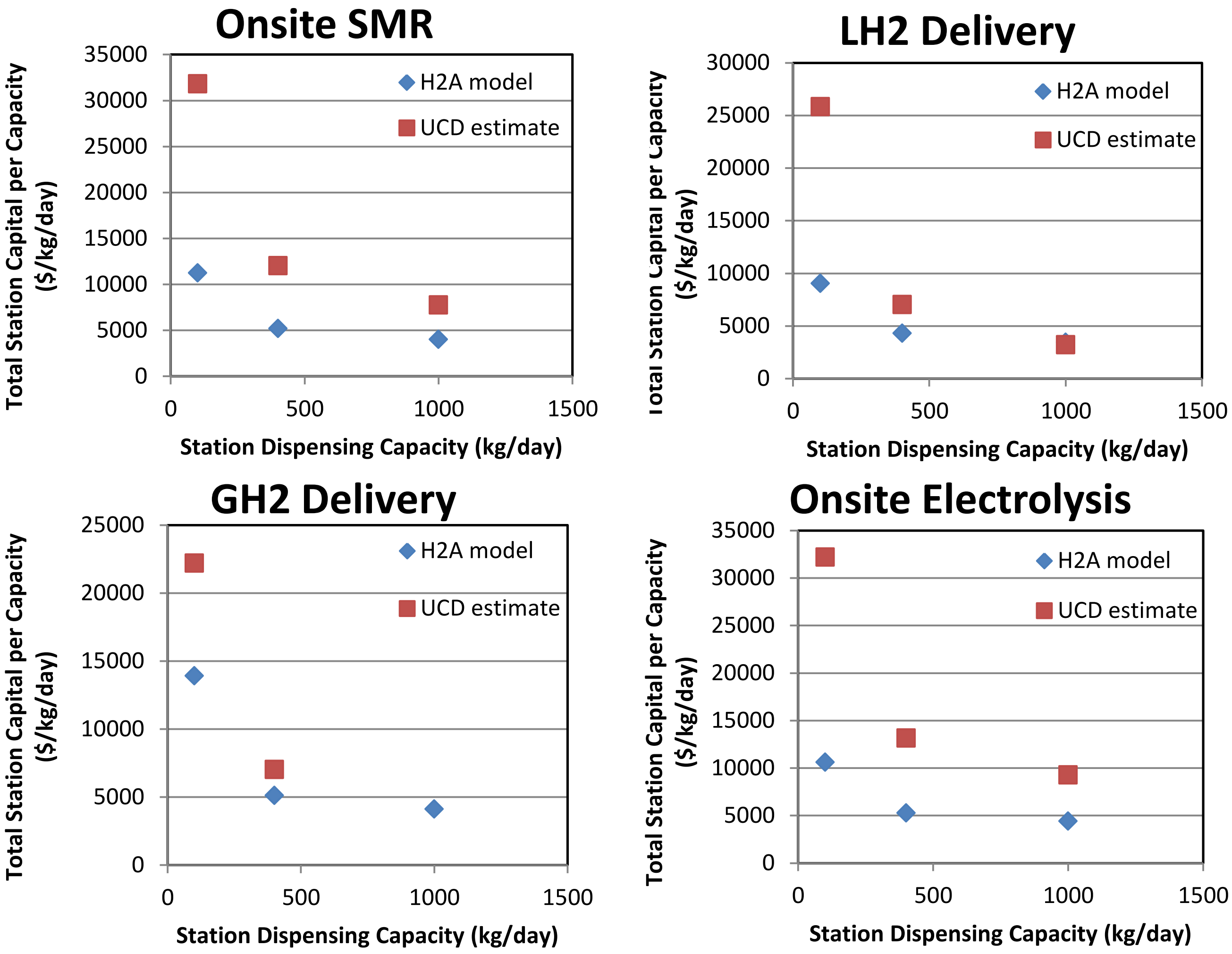

Figure-2. The cost for four types of stations predicted by H2A and UCD models.

Table-3. Cost estimates of early demonstration and recently funded hydrogen fueling stations in California.

Hydrogen Stations	Station Capacity (kg/day)	Cost per Capacity ($/kg/day)	Total Capital ($M)
Hydrogen stations 2009			
onsite electrolysis (Emeryville)	60	92667	5.56
Electrolysis (CSULA)	60	73333	4.40
Onstei SMR	100	40300	4.03
LH2 Delivery (Askland)	180	33111	5.96
Onsite SMR (UCLA)	140	30857	4.32
GH2 Truck (Harbor city)	100	24700	2.47
LH2 Delivery (SFO)	120	20083	2.41
Hydrogen stations planned for 2014			
GH2 truck (APCI, 2Stns)	180	12702	2.29
LH2 truck (Linde, 3 Stns.)	350	7209	2.52
LH2 truck (Air Lquide, 1 Stn.)	200	12170	2.43
Onsite Electrolysis (H2 Frontier, 1 Stn.)	105	43956	4.62

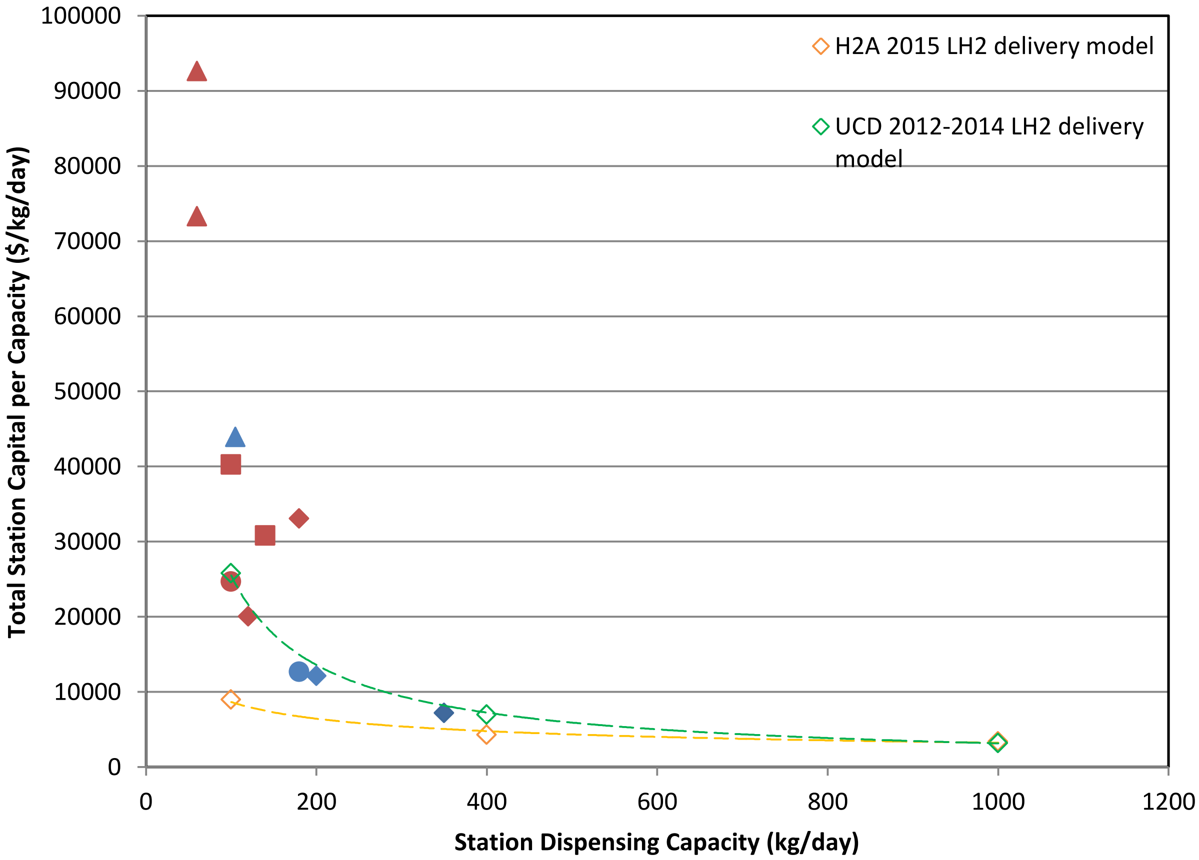

Figure-3. Comparisons of model predicted hydrogen station cost with the cost of real-world stations in California. Legend: Circle=gaseous H2 delivery; Diamond=liquid H2 delivery; Square=onsite SMR; Triangle=onsite electrolysis. The red legends represent the stations built in 2009, and the blue ones represent station planned for 2014.

The HSCC model does not distinguish between station types. Its classification system takes into account the degree of station market readiness, capacity, and volume of stations produced.[17] It classifies hydrogen fueling station into four categories:

(1) State-of-the-art Stations (SOTA): the stations would include the most recent generation of major components, and be installed and operated within the 2011-2012 timeframe.
(2) Early Commercial Station (EC): the stations are financially viable with little government support. They are sized to support growing demand in a promising market region and to ensure adequate return on investment. The station design enables cost reductions because it is replicable.
(3) More Stations (MS): Same EC deployed in larger numbers.
(4) Larger Stations (LS): identical to EC, but designed for higher volume output, with 2000 kg/day as an upper limit. MS and LS are installed later than EC stations.

Table-4 shows the cost estimates of the four classes of stations based on HSCC model. This model also simulates station costs in the state of California over time from 2009 to 2030. This result as well as its comparison to other models is shown in Figure-4.[17] It predicts that the station cost will rapidly drop as EC begin to install in a 2014-2018 timeframe. With a nominal capacity of 450 kg/day, an average capital investment of \$2.8 million per station is estimated. And the cost will continue to decline at a slower rate and reach \$3200 per kg/day at 2025, which aligns with the low UCD prediction of liquid H2 delivery stations.

Table-4. Cost estimates for hydrogen fueling stations based on the HSCC model.

Station Attribute	SOTA	EC	MS	LS
Introduction timeframe	2011-2012	2014-2016	after 2016	after 2016
Total Capacity (kg/day)	160	450	600	1500
Utilization (%)	57	74	76	80
Capital cost per capacity ($/kg/day)	16570	6220	5150	3370
Total capacity ($M)	2.65	2.8	3.09	5.05

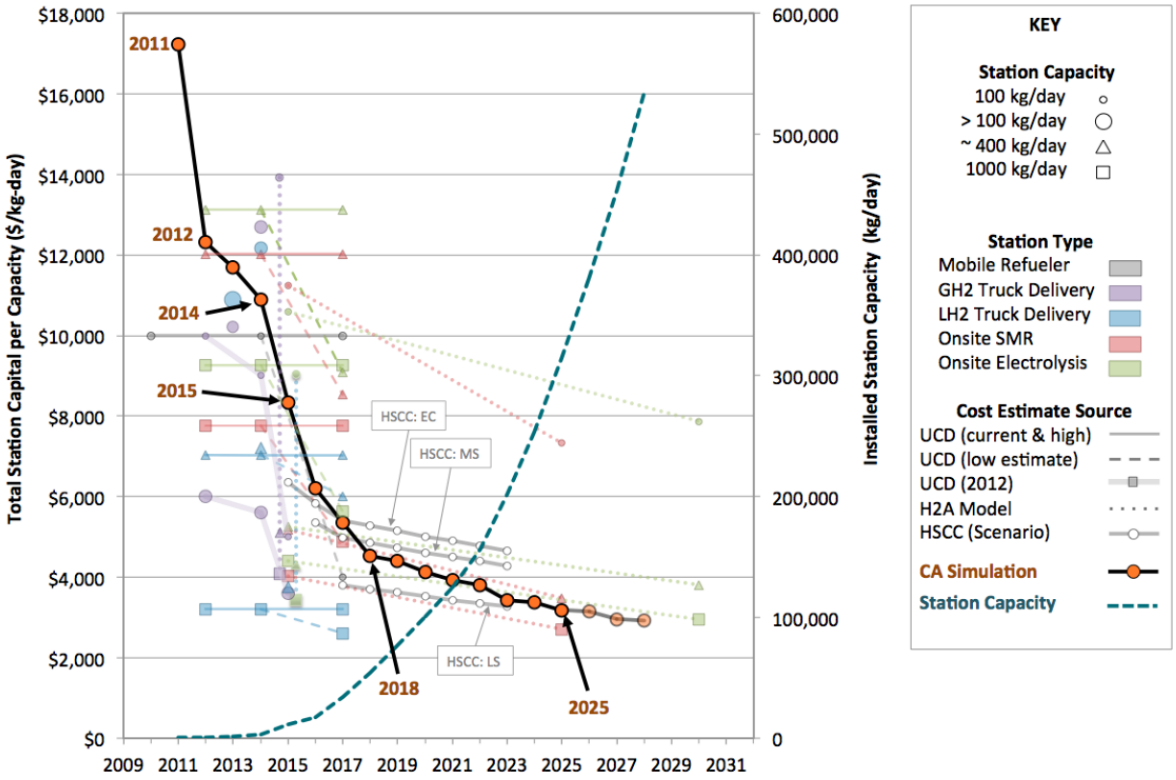

Figure-4. Cost estimate of hydrogen fueling stations in California between 2009 and 2030.

The station cost reduction will play a crucial role in the successful introduction of FCEVs. Above mentioned models and real-world examples demonstrate the importance of more and larger stations. In addition, a feedback from a "Hydrogen Infrastructure Market Readiness" workshop hosted by NREL in concludes the following strategies for the reduction of station costs:[18]

(1) Expand and enhance supply chains for production of high-performance, lower-cost parts.
(2) Reduce cost of hydrogen compression
(3) Develop high-pressure hydrogen delivery and storage components.
(4) Develop standard station designs.
(5) Harmonize/standardize dispensing equipment specifications.
(6) Develop "type approvals" for use in permitting.
(7) Improve information and training available to safety and code officials.
(8) Develop mechanisms for planning station rollouts and sharing early market information.

5. HYDROGEN FUELING STATIONS ROLLOUT STRATEGY

California has been a leading advocate for fuel cell transportation technologies. In 2012-2013 the State redoubled efforts to expand hydrogen fueling station deployments in preparation for anticipated introduction of commercial fuel cell vehicles by major auto makers starting in 2015-2017. CaFCP propose a set of evaluation criteria to steer the station build-out:[1]

(1) Does it add capacity in one of the early market communities in the timeframes needed?
(2) Does it support automakers plans for customer locations?
(3) Does the station have a stated plan for customer service enhancements (hours of operation, on-site attendant, signage, etc.)?
(4) Does it help bridge a distance between several other existing stations?
(5) Does it include new hydrogen production or storage technology identified by CEC, CARB or DOE as a need or transitional technology?
(6) Does it provide renewable hydrogen?
(7) Does it provide fuel for non-vehicle applications (combined heat/power, forklifts, etc)?
(8) Does it provide opportunities for local business or local jobs?

The hydrogen fueling station rollout strategy has evolved over time. One of the earliest policy initiatives was aimed at creating a “hydrogen highway” with hydrogen stations every 20 miles along highways in California. This plan would have created many underutilized stations as many would be located in rural areas and would not benefit the early FCEV adopters. A second policy proposed placements of hydrogen stations according to population density within major metropolitan areas in the state. It failed to consider that different cities or areas may adopt the technology at a different rate. Currently, “clustering” strategies are considered a more realistic approach for early stations siting with efficient use of stations at low cost. Clustering focuses on introduction of both hydrogen vehicles and refueling stations in a limited number of geographic areas such as smaller cities (e.g. Santa Monica, Irvine) within a larger region (e.g. the Los Angeles Basin). By concentrating early stations in a cluster area, a certain level of consumer convenience can be achieved with minimum number of strategically planed stations. Connector stations can be added to facilitate travel between clusters to create a hydrogen transportation network.

A good example of a “cluster” rollout strategy is a study conducted by the Institute of Transportation Studies at UCD.[19] They researched 12 clusters in the Los Angeles Basin areas that are likely to have most early FCEV adopters. The approximate boundaries of the clusters are shown in Figure-5. They utilized the population density and traffic flow information within the clusters to analyze consumer convenience of early station networks. In this study, the total hydrogen demand is estimated based on an average of 0.7 kg hydrogen per day (a mid-size FCEV wit fuel economy of 60 miles per kg, driven 15,000 miles per year). The utilization efficiency was assumed to be 70% of maximum capacity. Therefore, all scenarios have a total hydrogen station capacity of at least 1 kg per day for each FCEV. They also conducted workshop and interviews for different stakeholders and concluded several underlying factors to consider when planning the number, location, size and type of stations:

(1) It is important to locate the stations near early adopters to render a short travel time from drivers’ homes to the stations.
(2) A minimum of 2 stations is needed per cluster to ensure reliability.
(3) The stations should offer easy, quick, and familiar, or even a new “high-tech” setting to increase customer acceptance
(4) Station capital cost and operating costs.
(5) Technology readiness greatly determines the size and type of stations.
(6) California requires that state-funded hydrogen stations derive 33% of the hydrogen from renewable sources. It may cause some trade-off between economics and sustainability.

UCD’s model predicts transition paths starting with 8 stations in 4 clusters in 2009 to 2011, and developing to 20 stations in 6 cluster in 2012 to 2014, and eventually 42 stations in all 12 clusters in 2015 to 2017 (Table-5). The number of connection stations also increases to connect clusters. The later-introduced stations also increase in capacities from the initial 100 kg/day to 1000 kg/day. The hydrogen cost and average travel time decreases due to the economics of scale and increased density of stations.

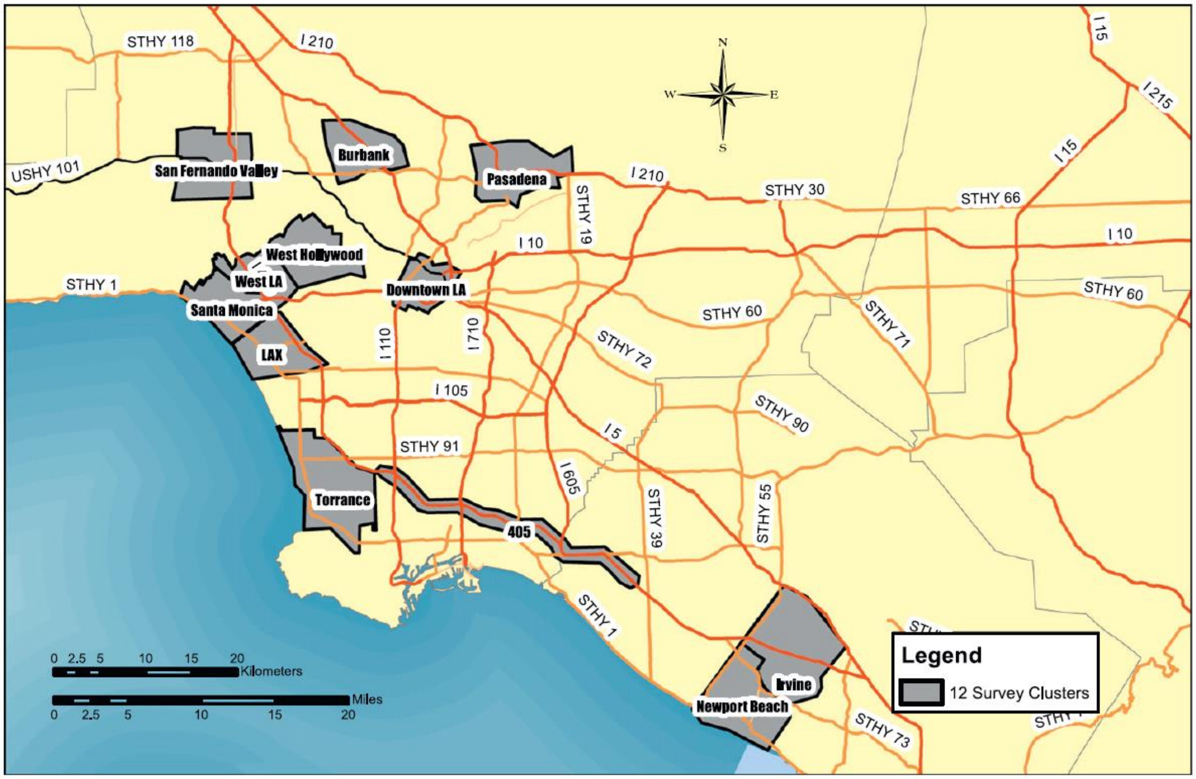

Figure-5. The shaded regions define 12 clusters identified by CaFCP for early FCEV adopters.

Table-5. Hydrogen fueling station rollout strategy by UCD.

	2009-2011 636 FCEVs	2012-2014 3442 FCEVs	2015-2017 25000 FCEVs
# Stations	8	20	42
# Clusters	4 (2 Sta./Cluster)	6 (3 Sta/Cluster)	12 (3 Sta./Cluster)
# Conn. Sta.	0	2	6
Station Mix	4 mobile refuelers 4 SMRs(100kg.day)	8 mobile refuelers 12 SMRs(250kg.day)	10 mobile refuelers 12 SMRs(100kg.day) 20 SMRs (1000 kg/day)
New Equip. Added	4 mobile refuelers 4 SMRs(100kg.day)	4 mobile refuelers 12 SMRs(250kg.day)	2 mobile refuelers 20 SMRs (1000 kg/day)
Capital Cost	\$20 M	\$21 M	\$98 M
H_2 cost	77 \$/kg	37 \$/kg	13 \$/kg
Travel Time	3.9 min	2.9 min	2.6 min

The number of FCEVs in California is anticipated to be over 50,000 by 2017. The CaFCP roadmap identifies 68 strategically placed stations required to be operational by the beginning of 2016 to accommodate the first wave of commercially available FCEVs. Forty five of the stations will be concentrated in five geographic clusters: Santa Monica/West Los Angeles, coastal

Southern Orange County, and Torrance with nearby coastal cities, Berkeley, and San Francisco South Bay. An additional 23 stations will be seeding other early markets as well as connecting these clusters into a regional hydrogen network.[20] As of July 2012, California has 19 hydrogen stations in operation or planned (either new construction or expansion of existing stations). The National Fuel Cell Research Center, a CaFCP member, analyzed the clusters with their Spatially & Temporally Resolved Energy & Environment Tool (STREET) model to determine the locations of the stations in the above mentioned five clusters. The optimal results of the 45 stations are displayed in Figure-6. The concentration is the hydrogen stations is equivalent to ~5-7% of existing gasoline stations within a cluster, providing a maximum of 6 minutes travel time between stations. The estimated incentive funding for all 68 stations are $65-67 millions. If the initial "clustering" build-out strategy of hydrogen infrastructure in California is successful, it may be adopted by other U.S. states to eventually build a nationwide hydrogen transportation network.

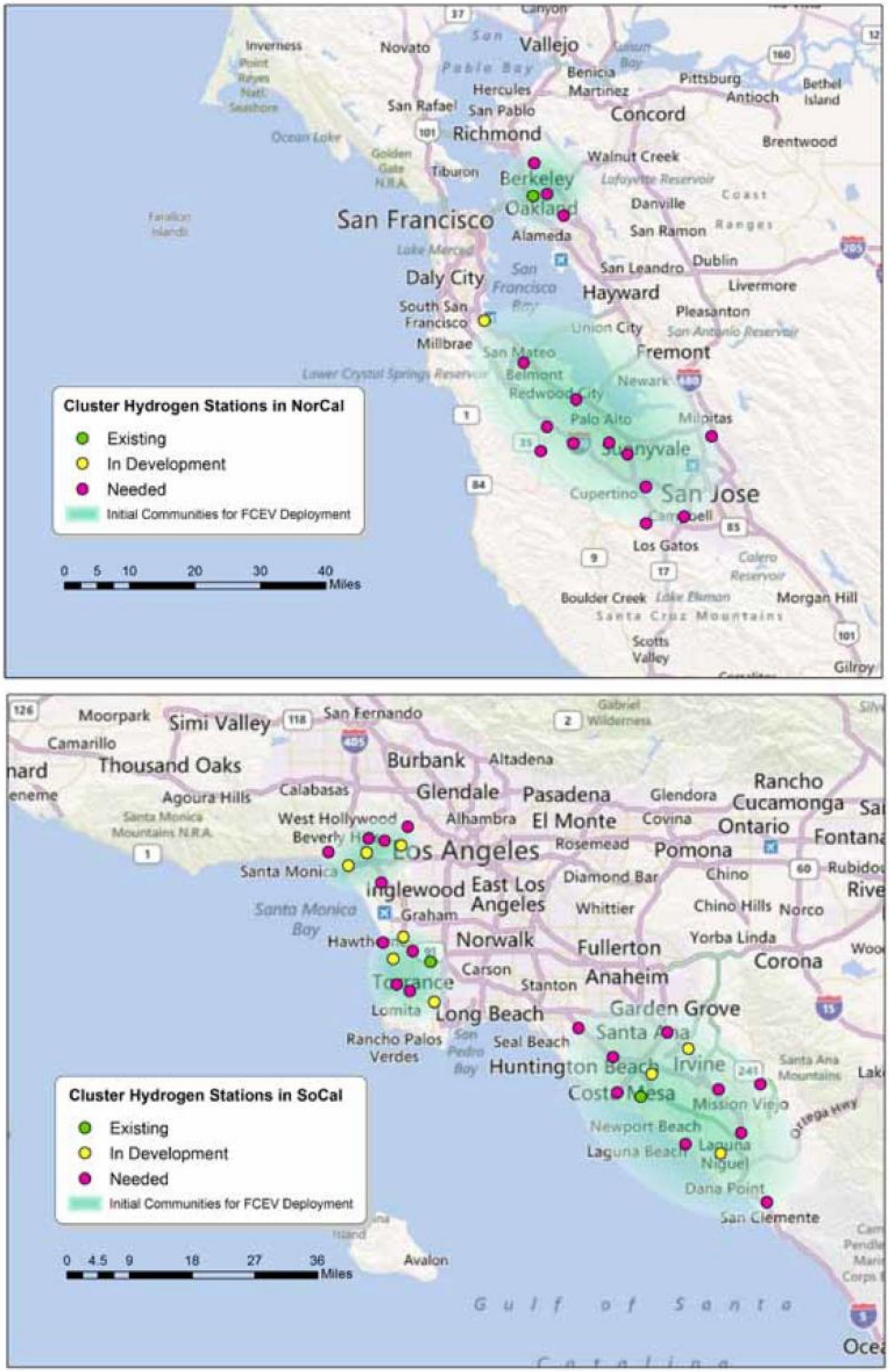

Figure-6. Cluster hydrogen fueling stations in northern and southern California.

6. CONCLUSIONS AND FUTURE WORK

The biggest obstacle to introducing FCEVs to the market is the lack of hydrogen fueling infrastructure. A hydrogen infrastructure rollout is a significant undertaking that requires careful planning, synergistic efforts among governments, academia, and industrial stakeholders.

Our research has thus far identified the most feasible types of hydrogen fueling stations: (1) stations relying on hydrogen produced in centralized locations and delivered via liquid hydrogen trucks, compressed hydrogen tube trailers, or pipelines; (2) stations with onsite hydrogen production from water electrolyzers or steam methane reformers. Hydrogen can be produced in centralized facilities at relatively low costs but with additional delivery costs. The onsite production of hydrogen at fueling stations (i.e., forecourt hydrogen) eliminates transportation and delivery costs, but the hydrogen production costs are likely to be higher due to small scales. Hydrogen can be produced in centralized facilities at relatively low costs, but the delivery costs may be higher than the onsite produced hydrogen. On the other hand, onsite produced hydrogen stations can eliminate delivery costs, but the hydrogen production costs are likely to be higher. The onsite hydrogen production stations are most suitable for remote areas with smaller consumer concentration while stations relying on hydrogen delivery are more suited for urban areas with high demand. Stations should equip with both 35 MPa and 70 MPa dispensers to cover both types of FCEVs. Smaller scale fueling stations (100-350kg/day) are likely to be installed to accommodate early markets. Larger stations with 1000+ kg/day capacity will be economically favored as more consumers adopt FCEV transportation. The costs of fueling stations will drop due to the lowering cost of components, standardization of station design, and economies of scale. The projected capital cost per capacity of fueling stations is $3200/kg/day by 2025. Government incentives and funding are critical in the early stages of building and operating hydrogen fueling stations in selected geographic “clusters.” The clusters with strategically placed fueling stations will serve as seeding elements to spur FCEV market growth. When planning to build a hydrogen fueling station, there are currently sixteen categories of codes and standards to follow. New codes and standards are still under development to accommodate the fast development of fuel cell and fueling station technologies.

California is a leading state in implementing hydrogen fueling infrastructures. Sixty-eight stations are anticipated by the beginning of 2016, forty-five of which will be concentrated in the

San Francisco and Los Angeles areas. The lessons learned during the station planning, building, and operation will be valuable for other states planning on constructing or expanding their hydrogen infrastructures.

In the next report, we will attempt to perform a case study on a fuel cell/battery hybrid bus recently acquired by NASA - Kennedy Space Center. We will evaluate FCEV technologies in the aspects of fuel cell system efficiency, range, durability, and lifespan given current catalyst, membrane and hydrogen storage system technology and identify obstacles for mass production. We will compare the “well to wheel” hydrogen production cost and greenhouse gas generation to fossil fuels and other alternative fuels. We will also collate data to project consumer costs of FCEVs.

7. APPENDIX

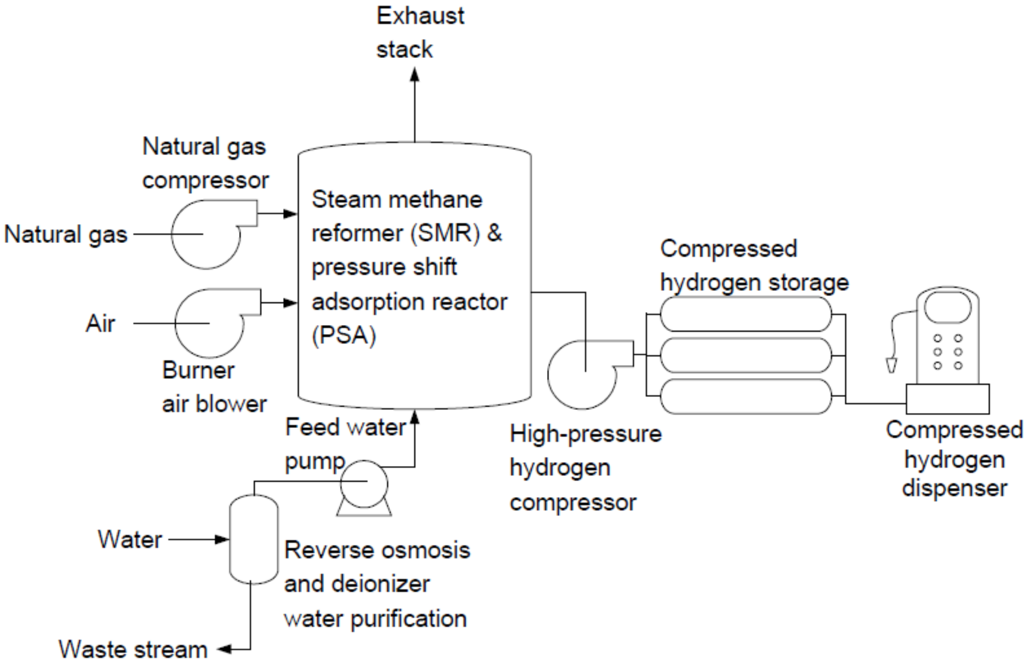

Figure-A1. A configuration of an onsite SMR station.

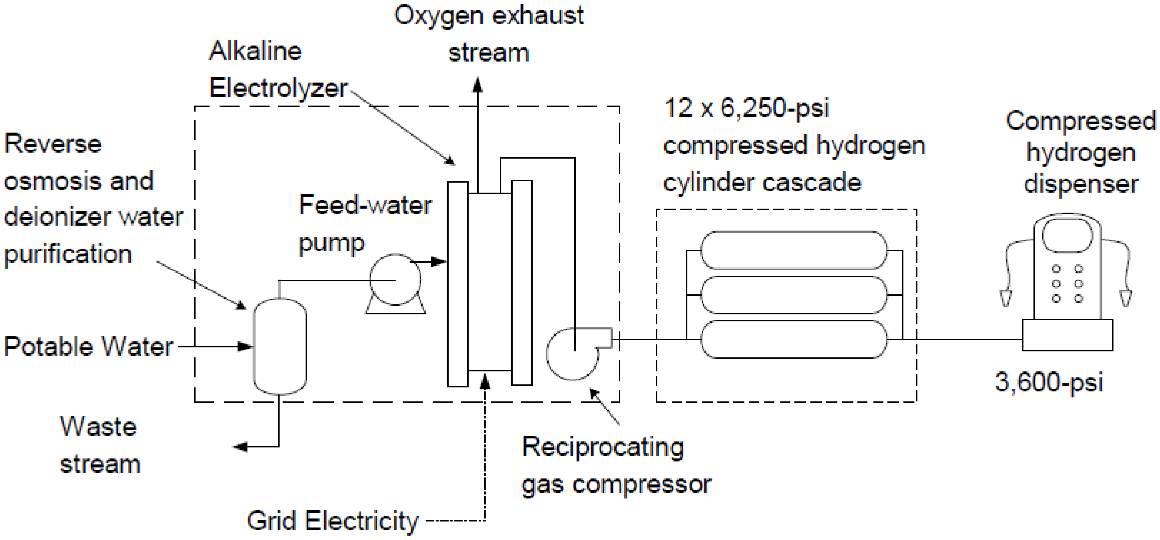

Figure-A2. A configuration of an onsite electrolysis station.

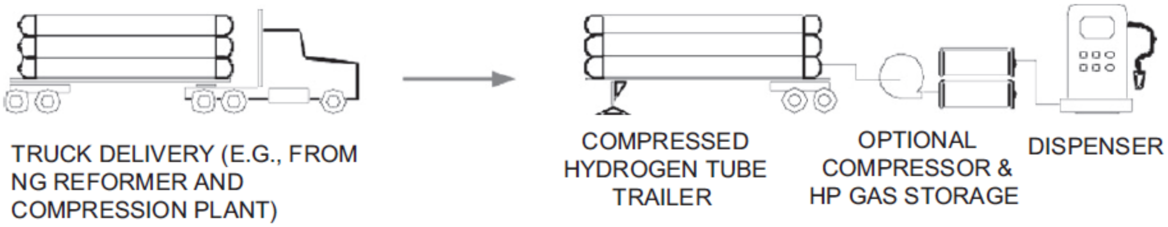

Figure-A3. A configuration of a hydrogen station with gaseous hydrogen delivery.

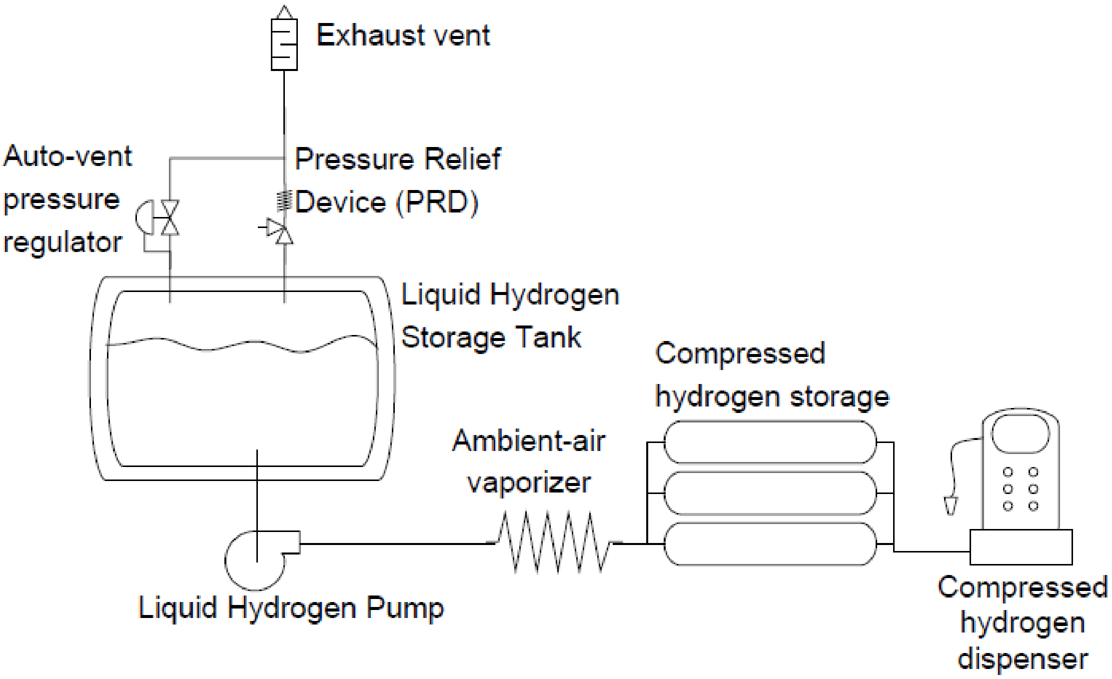

Figure-A4. A configuration of a hydrogen station with liquid hydrogen delivery.

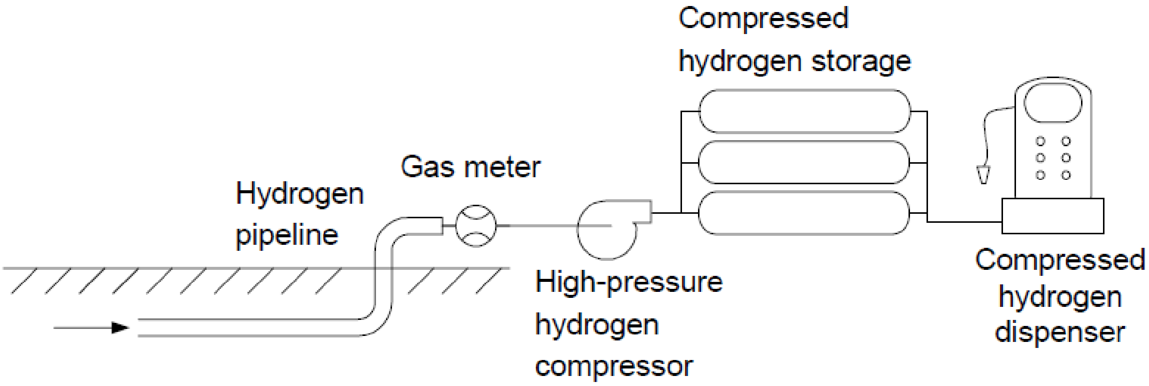

Figure-A5. A configuration of a hydrogen station with pipeline delivery.

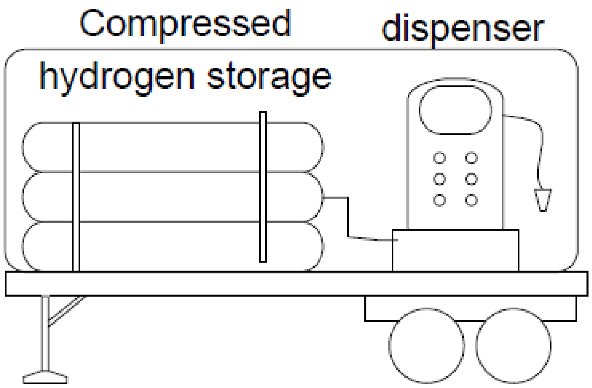

Figure-A6. A configuration of a hydrogen mobile refueler.

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