Deployment of Sustainable Fueling/Charging Systems at California Highway Safety Roadside Rest Areas

December
2016

A Research Report from the National Center for Sustainable Transportation

Hengbing Zhao, Institute of Transportation Studies, University of California, Davis

Andrew Burke, Institute of Transportation Studies, University of California, Davis

National Center for Sustainable Transportation

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Acknowledgments

This study was funded by a grant from the National Center for Sustainable Transportation (NCST), supported by USDOT and Caltrans through the University Transportation Centers program. The authors would like to thank the NCST, USDOT, and Caltrans for their support of university-based research in transportation, and especially for the funding provided in support of this project. The authors are much more grateful to the experts of the Project Panel for their constructive comments.

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EXECUTIVE SUMMARY

The transportation and electricity sectors are major sources of U.S. greenhouse gas (GHG) emissions because fossil fuels are the dominant energy source for the transportation sector and for electricity generation**.** Both sectors are facing the challenge of shifting to a more sustainable future. In the transportation sector, plug-in electric vehicles (PEV) and hydrogen fuel cell electric vehicles (FCEV) will play a key role in meeting California's 2050 GHG goals. There is a need to deploy hydrogen fueling and Direct Current (DC) fast charging stations in suburban areas and along interstate and state highways. These stations are needed so FCEV and PEV drivers can be confident that fueling/charging will be available when they travel between communities or make long intercity trips. The electric utility sector is increasing the fraction of electricity generated from renewable sources such as wind and solar. The efficient use of renewable energy resources relies on the ability to store energy when/where it is produced and distribute it when/where it is needed. Building vehicle fueling/charging stations and installing grid-level energy storage facilities to deal with the fueling and grid challenges will be expensive and require long-term and smart infrastructure investment.

This research studied the feasibility of the deployment of renewable hydrogen fueling for FCEVs and DC fast charging stations for PEVs at Highway Safety Roadside Rest Areas (SRRAs) and the integration of the stations with the electricity grid, including solar electric generation, to lower the infrastructure cost and to accelerate the usage of renewable energy in the California transportation sector. Three hydrogen fueling/DC fast charging system configurations were studied: two integrated stations with energy storage using compressed hydrogen or batteries as the energy storage medium located on a single site, and a distributed system configuration deployed on different sites. In this study, the integrated fueling/charging systems use 1 MW solar PV panels as the major electrical power source. Major components are sized according to the solar PV power generation and vehicle fueling/charging demands. For comparison, the present distributed systems utilize grid electricity and separately site hydrogen fueling and DC fast charging stations with energy storage. The fueling/charging stations function as both vehicle fueling/charging stations and as distributed grid energy storage to benefit both the transportation and utility sectors. This makes the fueling/charging stations more sustainable. Technical and economic models of the major components and systems were developed to quantify costs and to analyze different fueling/charging station configurations and investing strategies. The initial capital cost, annual energy cost, total annualized cost, annual maintenance cost, and levelized fuel cost for the three fueling/charging stations were calculated using two sets of Time-of-Use (TOU) electricity rate schedules from Southern California Edison – general business schedule, TOU-8, and EV charging schedule, TOU-EV-4.

The primary conclusions from the analysis are that compared to the distributed stations, the integrated stations are more energy efficient and more economically attractive in terms of hydrogen fuel cost than the distributed stations. The cost of PEV charging in the sustainable integrated stations was close to that of the distributed stations using grid electricity and the general business electric schedule for current technologies. The cost of the hydrogen in the integrated stations was weakly dependent on the electricity cost schedule and varied between $11.22/kg and $12.31/kg in 2016 (current time), and between $5.88/kg and $6.47/kg in 2020 – 2025 (future time). EV charging from the integrated stations was projected to cost between $0.26/kWh and $0.28/kWh in 2016, and between $0.14/kWh and $0.15/kWh in 2020 – 2025. The estimated vehicle fueling costs at the distributed station varied significantly with the schedule for electricity cost. Using the TOU-8 schedule, the hydrogen costs were $20.75/kg in 2016 and $13.53/kg in 2025. For the TOU-EV-4 schedule, the hydrogen costs were $16.32/kg in 2016 and $9.43/kg in 2025. The EV charging costs in the distributed stations were $0.19/kWh in 2016 and $0.14/kWh in 2025 for the EV charging rate schedule, significantly reduced from $0.28/kWh and $0.22/kWh for the general business electricity rate schedule. The distributed station requires less capital investments, but the energy costs are more sensitive to the electricity rate schedule. If an incentive/subsidy is considered for installing fueling/charging stations at SRRAs, the capital and energy costs will be lower for all three station configurations. The maintenance cost of the charging stations is directly related to their initial capital costs, with the integrated stations having an annual maintenance cost of about $100k and the distributed station having a maintenance cost of $60k.

In this analysis, we assessed the sustainable integrated fueling/charging stations based on 100% of utilization of the local PV electricity for hydrogen fueling/DC fast charging. The hydrogen fuelings and EV chargings were evenly divided based on their energy consumption. However, in the early stage of FCEV and PEV adoption, a relatively low utilization of fueling/charging stations is likely. In that case, the integrated stations could function as distributed power generation and energy storage for the grid. As the market for FCEVs and EVs develops, the integrated stations have the potential to serve the larger numbers of FCEVs and PEVs by using grid electricity during off-peak hours. Additional research is needed to explore the role of the utilization rate of the integrated stations on fuel costs and their economic attractiveness particularly as the component technologies improve and their costs are reduced in the future.

Project Purpose

The transportation and electricity sectors are major sources of U.S. greenhouse gas (GHG) emissions because fossil fuels are the dominant energy source for the transportation sector and for electricity generation**.** Both sectors are facing the challenge of shifting to a more sustainable future. In the transportation sector, plug-in electric vehicles (PEV) and hydrogen fuel cell electric vehicles (FCEV) will play a key role in meeting California's 2050 GHG goals. There is a need to deploy hydrogen fueling and Direct Current (DC) fast charging stations in suburban areas and along interstate and state highways. These stations are needed so FCEV and PEV drivers can be confident that fueling/charging will be available when they travel between communities or make long intercity trips. The electric utility sector is increasing the fraction of total electricity generated from renewable sources such as wind and solar. The efficient use of renewable energy resources relies on the ability to store energy when/where it is produced and distribute it when/where it is needed. Building vehicle fueling/charging stations and installing grid-level energy storage facilities to deal with the fueling and grid challenges will be expensive and require long-term and smart infrastructure investment.

The objectives of this research were to study the feasibility of the deployment of renewable hydrogen fueling/DC fast charging stations at California Safety Roadside Rest Areas (SRRAs), not at service areas with commercial activity, and the integration of the stations with the electricity grid, including solar electric generation, to lower the infrastructure cost and to accelerate the usage of renewable energy in the California transportation sector. Hydrogen generated from electrolysis from local solar energy is used as an energy carrier. The fueling/charging stations function as both vehicle fueling/charging stations and as distributed grid energy storage to benefit both the transportation and utility sectors. This make the fueling/charging stations more sustainable.

In this report, the status of present EV charging and hydrogen fueling technologies are reviewed. Next, two integrated EV charging/hydrogen fueling system concepts for SRRAs are presented and analyzed. Distributed EV charging and hydrogen fueling are compared with the integrated approach based on the capital cost of major components and system operating cost. Government policies and regulations were also considered.

Present Status of PEV/FCEV Charging/Fueling Infrastructure in California

Technologies for PEV Charging and FCEV Fueling

PEV Charging

The Electric Vehicle Supply Equipment (EVSE), or Electric Vehicle Charging Station, has two basic types: Alternating Current (AC) charging and DC fast charging. The difference is where the

AC/DC conversion and the charging control takes place. This is illustrated in Figure 1. All charging systems take AC power from the grid and convert it to DC power at a suitable voltage for charging the battery. AC Level 1 and Level 2 charging utilize low power and are implemented by a charger onboard the vehicle, and AC Level 1 and Level 2 charging stations merely deliver AC power up to 20 kW to the vehicle. DC fast charging requires high power and relatively expensive power electronics. For fast charging, the AC/DC conversion and the power conditioning and control are exercised in a charger unit sited off the vehicle in the charging station, which can supply charging power of 135 kW or higher.

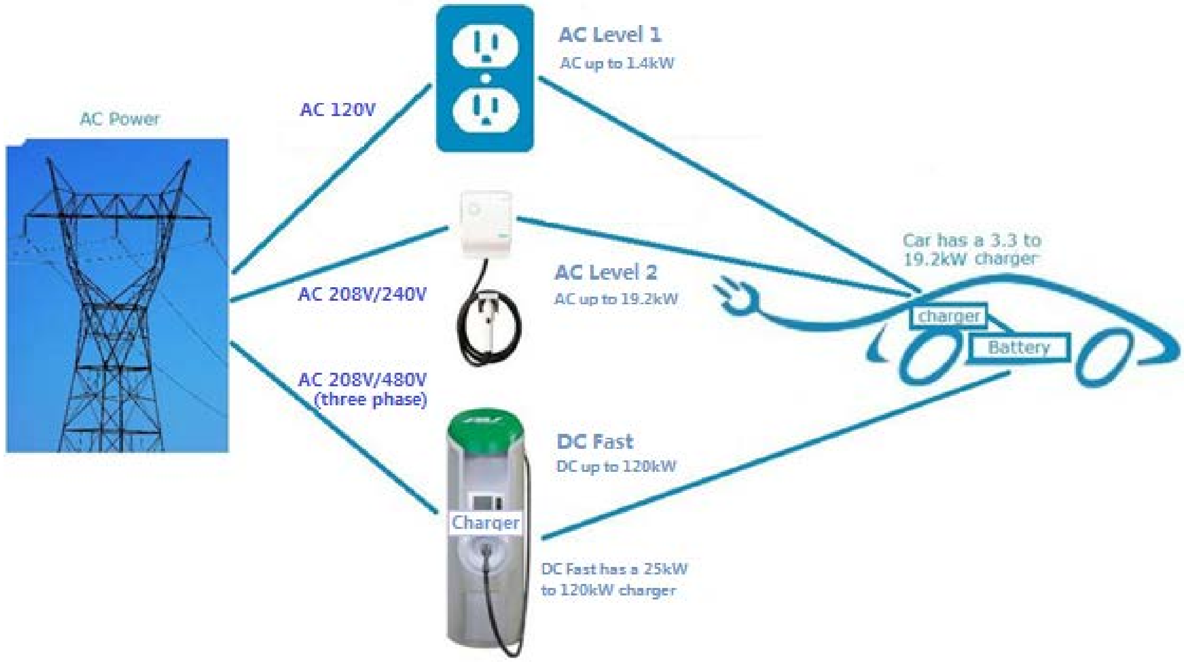


Figure 1: AC and DC charging paths (modified diagram from [1])

For DC fast charging, there are three connector standards in various stages of adoption - CHAdeMO, Tesla Supercharger, and SAE J1772 Combo or CCS (combined coupler standard). CHAdeMO, the Japanese Electric Vehicle Standard, is the most established and the only commercially available DC fast charger connector used today. It has been implemented by several large automakers and several dozen charger manufacturers. The Tesla Supercharger connector system is used only on Tesla vehicles, but Tesla is working on an adaptor to make their charging setup compatible with the CHAdeMO and SAE systems. The latest fast charger connection system is the SAE J1772 Combo, adopted by Chevy Spark EV and Bolt and the BMW i3. These three DC fast charging system interfaces are not physically compatible–the majority of current DC fast charger stations use either a CHAdeMo or SAE Combo connector, which provide 50 kW of charging with a charger price between $19,000 and $40,000. The Tesla charger stations provide up to 135 kW of charging per station but have been designed by Tesla for use only with their EVs. These competing DC fast charging standards make PEV charging inconvenient. PEV drivers can't just go to the closest fast charging station and have to find the one compatible with their car. Dual-standard adapters which enable DC fast charging from an incompatible charging station or DC fast charging stations with dual-format connectors will help to reduce the inconvenience caused by incompatible charging standards.

Hydrogen Production and FCEV Fueling

Hydrogen can be produced from a variety of sources, including fossil fuels (by steam methane reforming or partial oxidation of natural gas and coal), and renewable sources such as solar and wind via electrolysis of water. However, only hydrogen produced from clean, renewable energy sources is renewable. California Senate Bill 1505 (2006) requires that "on a statewide basis, no less than 33.3 percent of the hydrogen produced for, or dispensed by, fueling stations that receive state funds be made from eligible renewable energy resources" [2]. Currently, 95% of the hydrogen available in the United States (US) is produced from steam methane reforming of natural gas, a process that involves heating the natural gas up to 1000 °C in the presence of steam and catalysts to produce a mixture of hydrogen (H_2) and carbon dioxide (CO_2). High-purity hydrogen is then separated for industrial applications. At the present time, the production of hydrogen via steam reforming is the most economic approach; however, the steam reforming of natural gas results in relatively large emissions of GHG. Hydrogen production from steam reforming of natural gas produces approximately 10 kg CO_2 per kg H_2 produced [3].

Another pathway to produce hydrogen without using fossil fuels is the electrolysis of water. Abundant renewable power resources such as solar and wind are now being utilized to generate electricity. The electricity is then used to split water into hydrogen and oxygen via electrolysis. The production of hydrogen from the electrolysis of water using solar electricity has near zero life-cycle GHG emissions, but is currently more expensive than steam reforming.

With the deployment of FCEVs, production of hydrogen will need to increase to meet the growing FCEV market. This hydrogen can be produced in large centralized hydrogen production facilities with distribution to fueling stations via compressed tube trucks, liquid tankers, or pipelines, or in small distributed hydrogen production facilities on-site or located close to the point of use. Large centralized hydrogen production facilities take advantage of economies of scale but require large investment, which will not make business sense until large numbers of FCEVs have been sold. Hence, distributed hydrogen production via natural gas reforming or water electrolyzing is viewed as an attractive option for supplying hydrogen, particularly in the early stage of hydrogen FCEV adoption.

Present Charging/Fueling Infrastructure in California

California had about 3,500 public PEV charging stations (more than 11,000 outlets) in 2016, including workplace chargers [4]. The number of PEVs that a charging station can serve varies significantly. A well-designed Level 2 charging station at retail stores provides 7 to 11 charges per day, while a charging station at parking lots where vehicles can be parked for long periods of time like airports provides less than 2 charges per week [5]. Most of current chargers are

Level 2 chargers providing charging power of between 3 kW and 6.6 kW, and a relatively small number of DC fast chargers providing up to 50 kW. Tesla has provided fast chargers for their EV owners that provide up to 135 kW. Most of the charging stations are located in urban areas near shopping centers, restaurants, and hotels, and not along intercity highways, where DC fast chargers would be most useful.

Figure 2 shows the installed and planned DC fast chargers in California. Most of these DC fast chargers are positioned along the coast between San Diego, Los Angeles, and San Francisco, near shopping malls. Only a few of the Tesla superchargers have been installed along interstate and state highways. Each of the Tesla fast charger stations has 4-8 charger towers and each tower can provide charging power up to 120-135 kW. Since 500 kW to 1 MW peak charging power is needed, separate electric service to the charging stations would be necessary. Facility- and time-related demand charges associated with peak charging during on-peak times can have a significant impact on a business' monthly electric utility bill if a business rate schedule is selected. Other DC fast charging stations have only 1-2 chargers with relatively lower power demand, and are usually hosted in shopping centers and powered on the original business electrical supply.

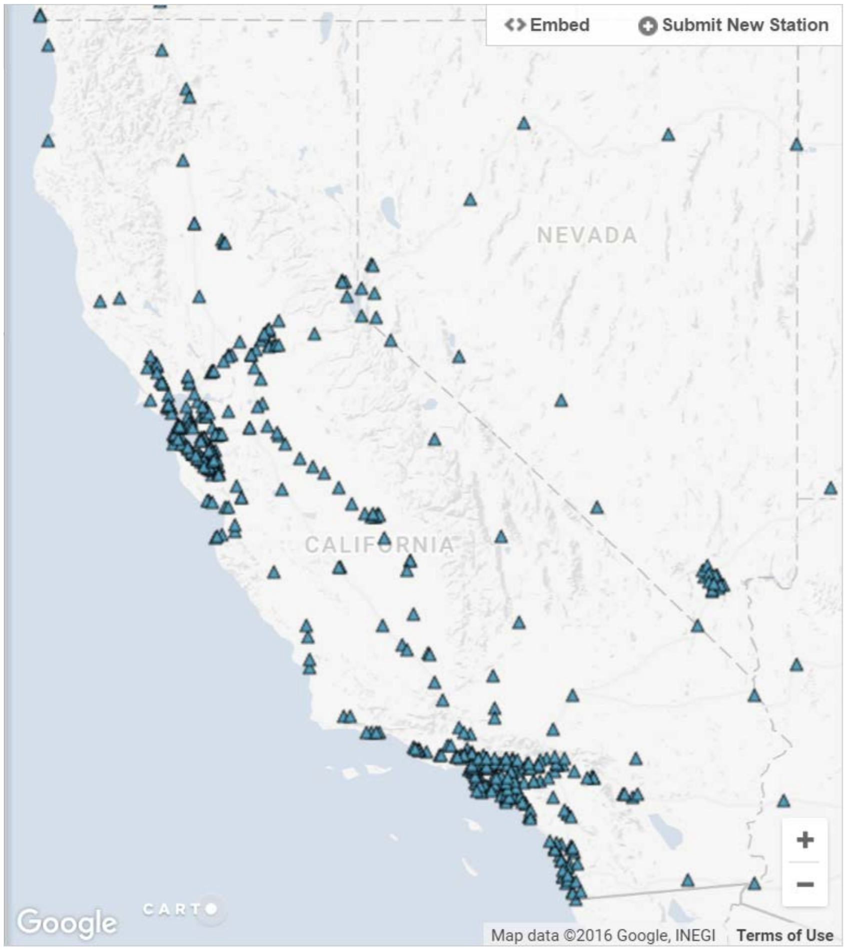


Figure 2: Installed DC fast charging in California by December 2016 [6]

California is leading the nation in installing FCEV hydrogen fueling stations. Currently, California has more than 20 hydrogen fueling stations available, as shown in Figure 3, enabling FCEV drivers to travel between and around Los Angeles, Orange County, Santa Barbara, Sacramento, the San Francisco Bay Area, and Lake Tahoe. According to a California Air Resources Board (CARB) analysis (Figure 4), there will be about 50 hydrogen fueling stations open by the end of 2017, which will be able to supply hydrogen for approximately 15,000 FCEVs, more than enough for the expected commercial fleet. In the case of current hydrogen fueling stations (Figure 5), most of the hydrogen fuel is produced via steam methane reforming in centralized facilities and delivered to the stations as compressed hydrogen or liquid hydrogen. About 25% of those planned stations will produce hydrogen on-site via electrolysis of water. Currently over 33% of hydrogen used as a transportation fuel in California is produced from renewable resources.

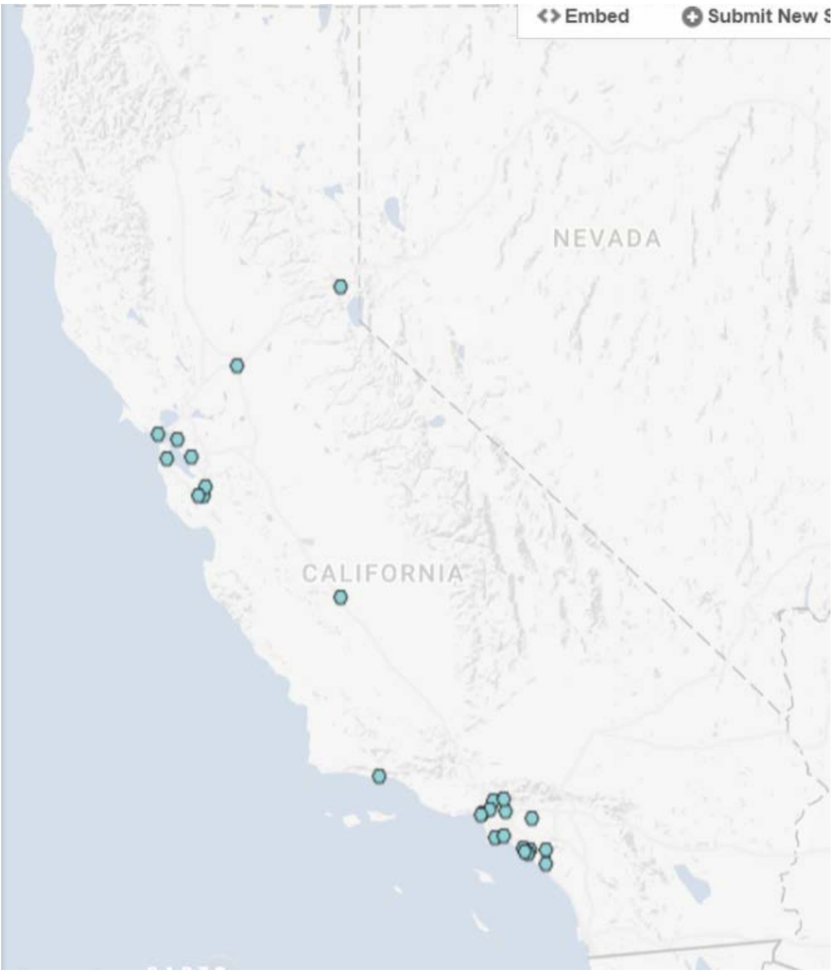


Figure 3: Hydrogen fueling stations in California [7]

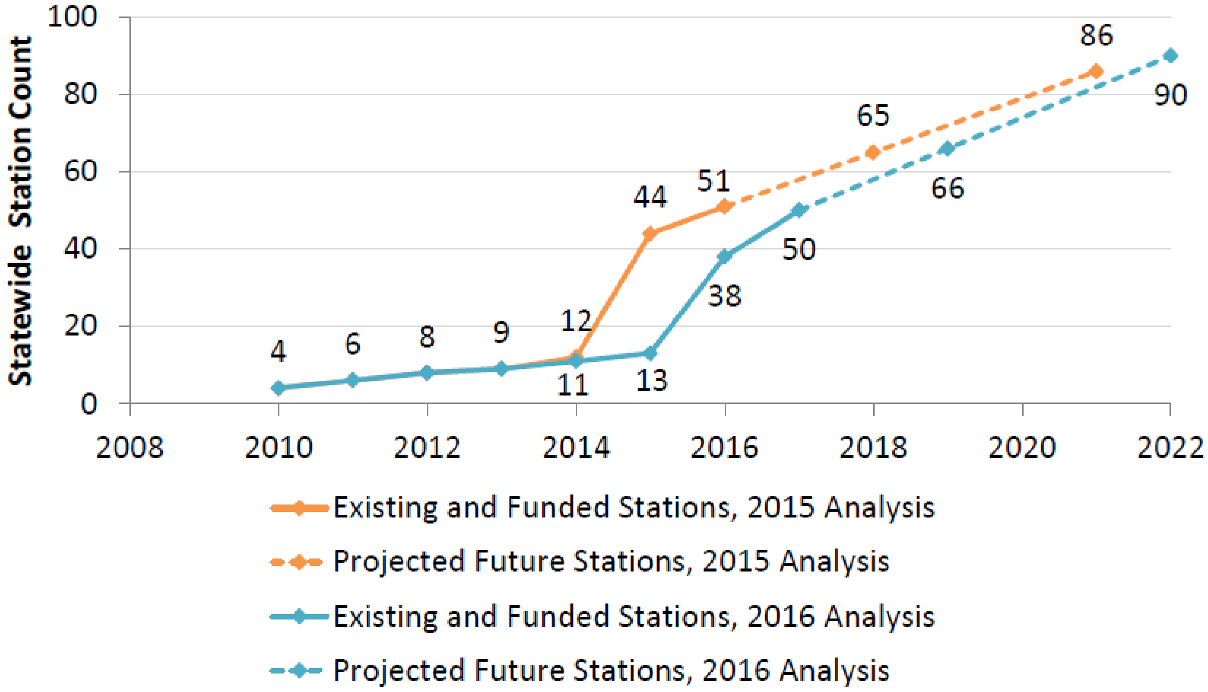


Figure 4: Estimated hydrogen fueling stations in California [8]

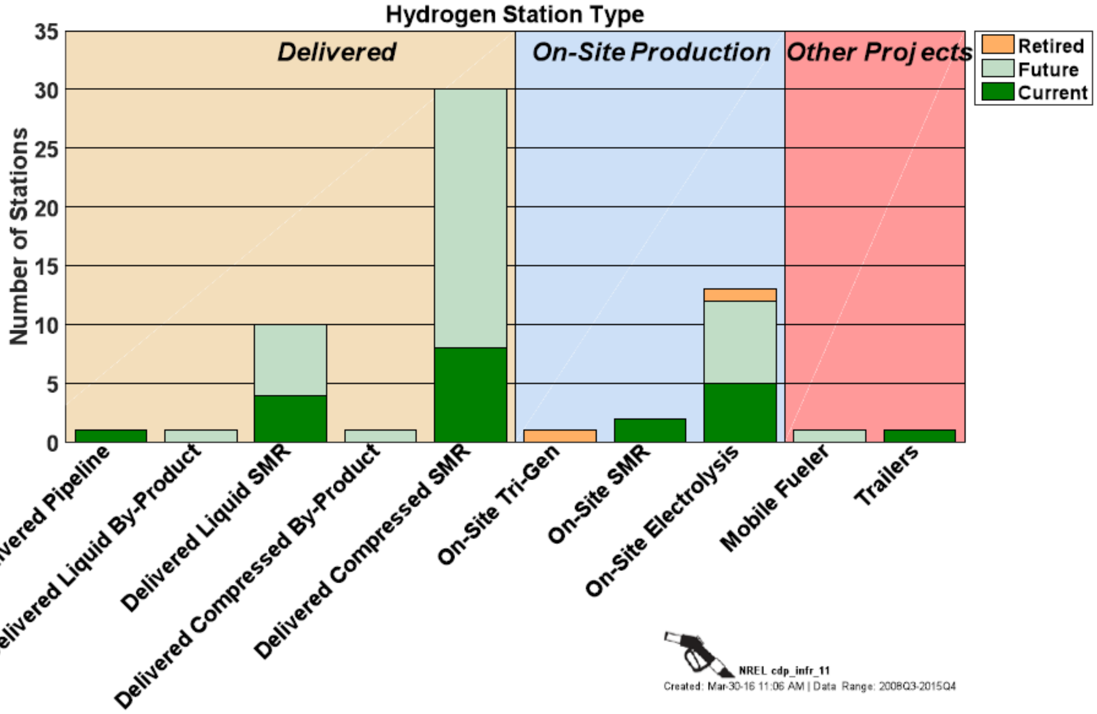


Figure 5: Current hydrogen fueling station technologies [9]

Charging Infrastructure for 1.5 Million Zero Emission Vehicles by 2025

Current deployment of charging and hydrogen fueling stations for EVs in urban areas is essential for the successful marketing of PEVs and FCEVs. Now that PEVs with more than 200 miles of range on a charge like the Tesla Model S and the Chevrolet Bolt are on the market, long-distance, intercity travel with those vehicles will become more frequent. DC fast charging of the batteries at SRRAs and other locations along the interstate and state highways can provide more flexibility for EV drivers. In addition, a number of auto companies are beginning to lease and sell hydrogen FCEVs, such as the Hyundai Tucson available in 2014, the Toyota Mirai in 2015, and by the end of 2016, the Honda Clarity. These FCEVs have ranges of over 300 miles, with the Clarity achieving an EPA estimated range of 366 miles. It would be convenient to refuel those vehicles with hydrogen along the state highways on long trips. If California is to place 1.5 million zero emission vehicles (ZEVs) by 2025, sales of EVs and FCEVs will have to average about 150,000 per year from 2017-2025, and many DC fast charging stations and hydrogen fueling stations will be needed [10, 11]. But if sustainable transportation infrastructure is also to be developed, most transportation fuels (electricity and hydrogen) for ZEVs must be produced from clean, non-fossil, renewable energy sources, such as solar and wind.

Concept and System Design of Integrated Charging/Fueling System

Integrated Charging/Fueling System Concept

Sustainable transportation systems should be designed and operated in a way that will generate minimal GHG emissions and criteria pollutants, be accessible to potential users, make efficient use of land and natural resources, and be cost effective and easy to be expanded. Currently, most of the hydrogen fueling stations and the DC fast charging stations are designed and installed without considering integration with renewable power sources or to reduce their high initial investment cost. A hydrogen fueling station can cost as much as $2 million. DC fast chargers cost about $60,000 for a 50 kW unit, but the installation cost of a DC fast charging station can be up to $200,000 depending on available electrical capacity and the distance from the charger to the electrical service. Most of the current DC fast charging stations require 50 kW to 120 kW from the grid.

The key issues in combining hydrogen fueling and DC fast charging in an infrastructure facility are the high capital costs and relatively low utilization during early stages of the PEV and FCEV market. The block diagrams in Figure 6 show how hydrogen fueling and DC fast charging stations are installed at different locations and connected to renewable power sources and energy storage facilities. The fueling/charging stations, the renewable power sources, and the energy storage are located at different sites and connected to the utility grid. This is not the most cost effective approach to providing charging of PEVs and fueling of FCEVs that use the same roadways.

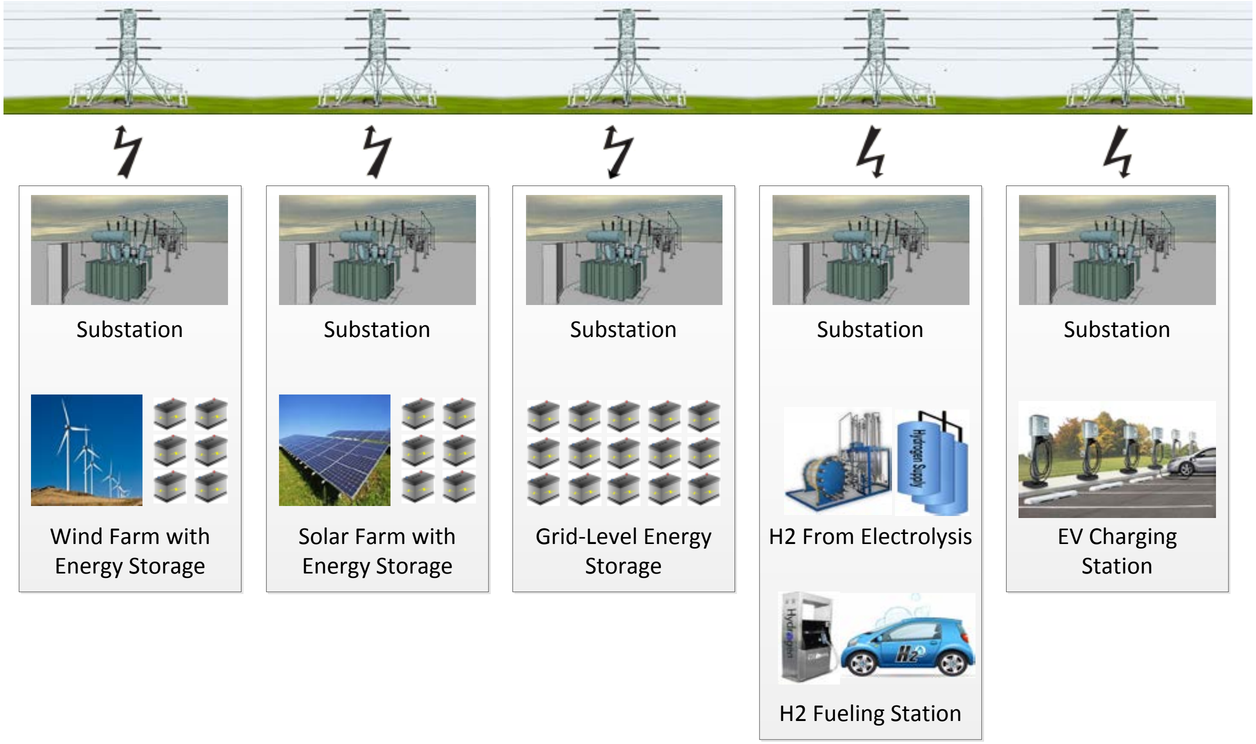


Figure 6: Present renewable fueling/charging stations, renewable power sources, and energy storage on different sites

In this project, the integration of the hydrogen fueling station, DC fast charging station, renewable electricity generation, and energy storage on a single site is studied (i.e., at SRRAs). This approach will lower the infrastructure costs associated with building multiple, separate sites for vehicle fueling/charging stations, renewable electricity generation, and energy storage. This also reduces the operating costs and the need for upgrading the transmission/distribution on the grid. The proposed integrated hydrogen fueling/DC fast charging systems use compressed hydrogen and batteries for energy storage as shown in Figure 7 and Figure 8, respectively. For the integrated system with hydrogen storage, renewable electricity from solar photovoltaic (PV) panels or wind turbines is used to charge EVs directly. Hydrogen for fueling hydrogen FCEVs is produced from electrolysis of water using excess renewable electricity. The hydrogen is used to refuel FCEVs as needed or stored for later use. Some of the hydrogen may be later converted back to electricity for charging EVs or used to provide peak power to the grid. The hydrogen works as energy storage at the fueling stations and/or as distributed energy storage on the load side of the transmission system. For the integrated system using battery storage, renewable electricity is directly used to charge PEVs and/or power an electrolyzer to produce hydrogen for FCEVs. Excess renewable electricity is stored in the batteries for later use, such as PEV charging, hydrogen production, or being fed back into the grid.

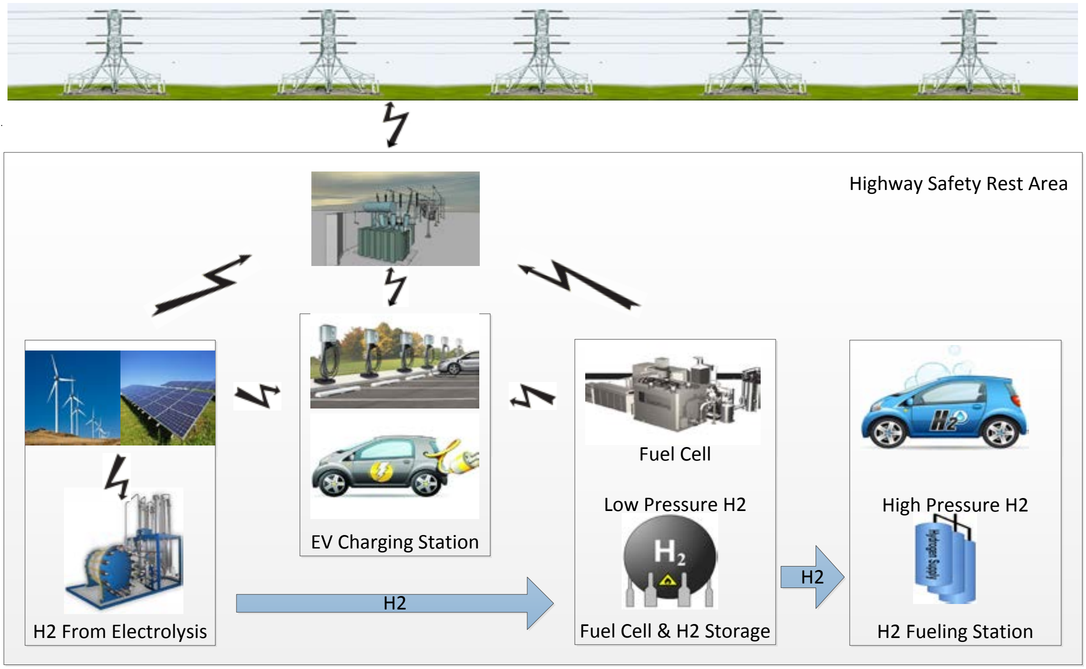


Figure 7: Integrated H_2 fueling/DC fast charging station using hydrogen for energy storage at a SRRA

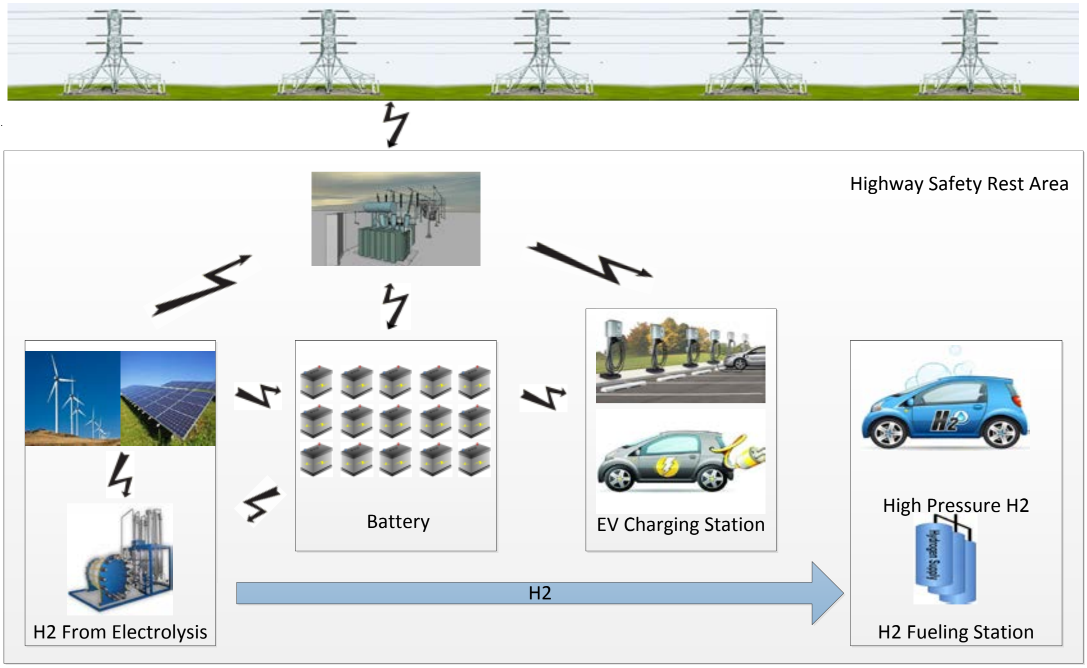


Figure 8: Integrated H_2 fueling/DC fast charging station using batteries as energy medium at a SRRA

The integrated hydrogen fueling/EV charging system can be cost effective and sustainable due to relatively high efficient energy utilization of local renewables, and also provide reliable energy storage for the grid, thus improving the availability of electricity. The combination of fueling stations and energy storage can reduce the need for future transmission grid construction upgrades, as well as augment the performance of existing transmission and distribution assets. Using transportation fuels (hydrogen and electricity) as distributed energy storage at fueling/charging facilities can reduce grid line-congestion and power loss, the peak loads on the electrical grid system, and extend the useful life of existing infrastructure. Both the utility operator and the fueling/charging station owner will benefit from the system integration. In summary, the integration design and operation of the hydrogen fueling station, DC fast charging station, renewable power sources, and energy storage at the SRRAs will generate less GHG emissions, be accessible to PEV and FCEV owners, make efficient use of land and natural resources, and could be cost effective and be capable of expanding as the market for PEVs and FCEVs develops.

Integrated charging/fueling systems can be deployed in many locations. SRRAs are ideal locations for deploying the systems because these areas are already in place on the routes PEV and FCEV drivers use when they travel between communities or make long distance trips. SRRAs are often close to electric grids according to California transmission lines and substations maps and have area available for installing solar panels if expanding the charging/fueling systems is needed. The US Department of Transportation (DOT) is increasingly exploring the use of highway right-of-way to accommodate renewable energy technologies [12]. Development of renewable charging/fueling stations at SRRAs also fits with the current DOT’s goal of finding sustainable ways to address the Nation’s transportation needs.

Integrated Charging/Fueling System Design

Three fueling/charging system configurations were studied in this project. The two integrated system configurations are the integrated charging/fueling stations with hydrogen (CASE-A) or with battery energy storage (CASE-B), located at a single site, as shown in Figures 9(a) and 9(b), respectively. For comparison, the present distributed systems (CASE-C) utilize grid electricity and separately site hydrogen fueling and DC fast charging stations with energy storage, as shown in Figure 9(c). For all system configurations, major components are sized according to the solar PV power generation and vehicle fueling/charging demands.

The fueling/charging systems can be sized according to peak fueling/charging demand and available land at the SRRA sites. Correctly sizing the system can have a big impact on the economic analysis. In this study, the fueling/charging systems (CASE-A and CASE-B) use 1 MW solar PV panels as the major electrical power source. The land required for installing a 1 MW solar PV system depends on PV module efficiency, solar insolation, and land utilization. Considering environmental constrains such as storm water, visuals, etc. at the SRRA site, a land utilization factor of 0.3 in parking areas and ample land around SRRA sites, a 1 MW unit requires about 4 acres of land in California. Typically, SRRAs are located on sites of about 15 acres and may be able to accommodate solar PV installation. Additional land along the highways may be available for installing solar PV panels if needed. A 1 MW solar PV panel can generate an annual average electricity of 5 MWh/day in California, which is sufficient for charging 50 PEVs per day with electricity consumption of 50 kWh per PEV, and 15 FCEVs per day with hydrogen consumption of 4 kg H_2 per FCEV.

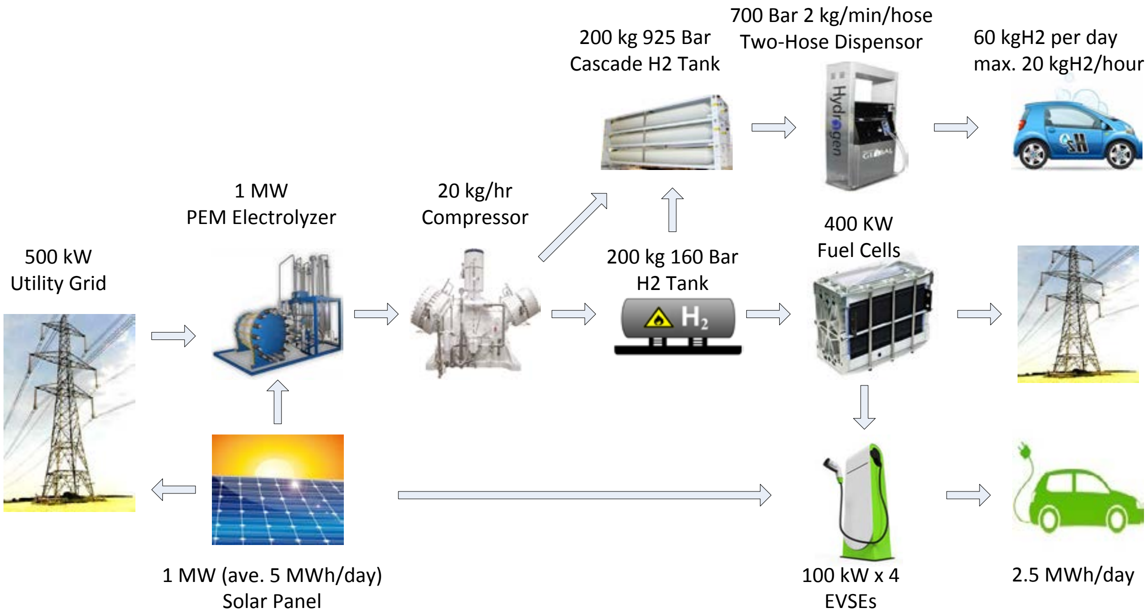


Figure 9(a): Integrated H_2 fueling/DC fast charging station with hydrogen storage (CASE-A)

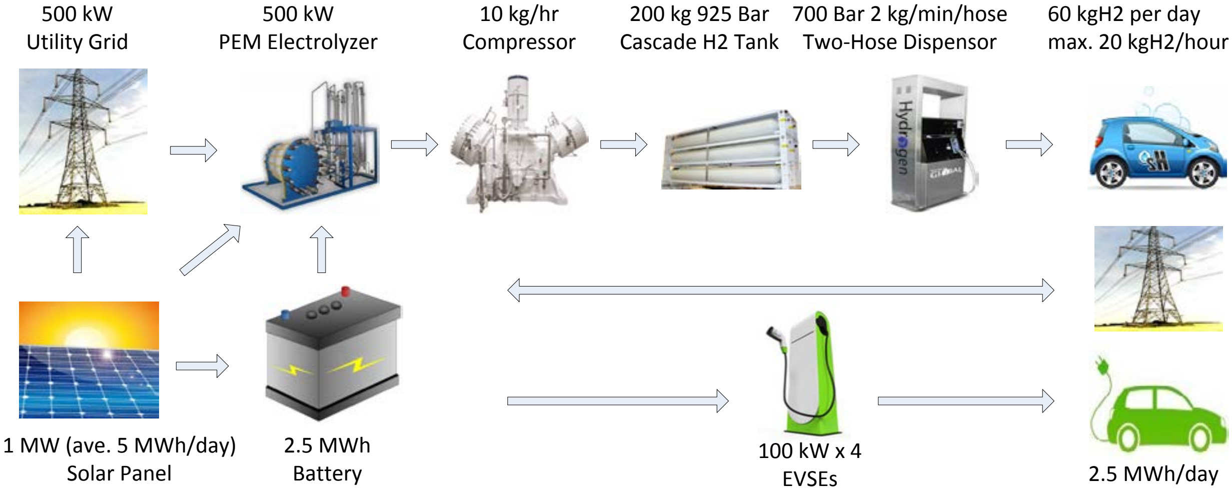


Figure 9(b): Integrated H_2 fueling/DC fast charging station with battery storage (CASE-B)

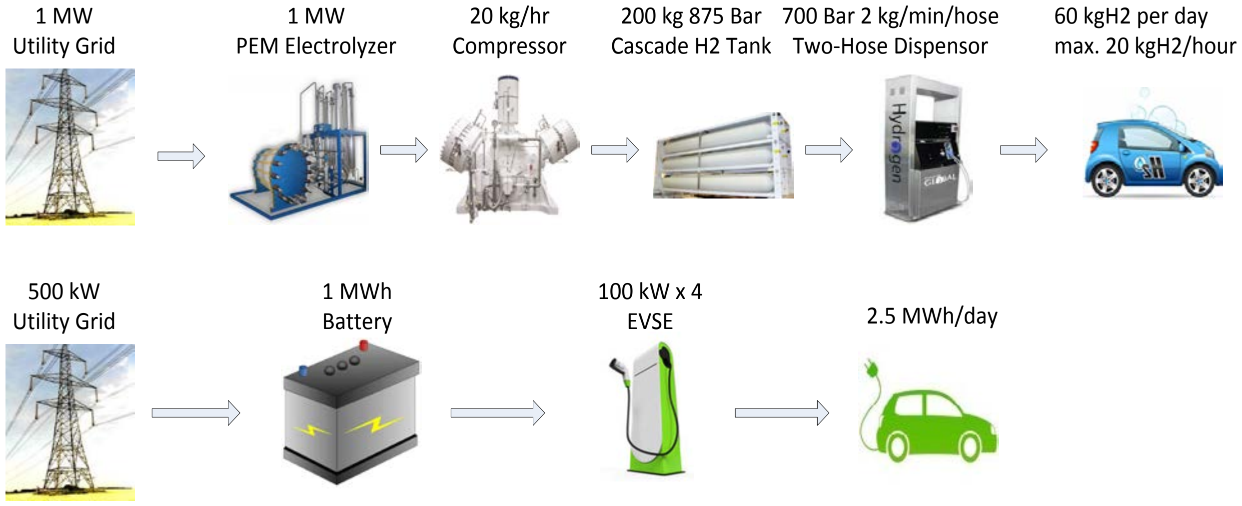


Figure 9(c): Distributed H_2 fueling/DC fast charging station (CASE-C)
Figures 9(a)-(c): Three H_2 fueling/EV charging station configurations

The solar PV electricity is used by the electrolyzer to produce hydrogen from water. Polymer electrolyte membrane (PEM) and alkaline are the main types of low temperature electrolyzers commercially available. PEM electrolysis enables safe differential pressure operation, which in turn allows the electrolysis unit to be operated in a load-following mode with 100% turndown capability, which is very attractive for renewable energy applications. PEM electrolysis also has higher efficiency over a wide range of current densities. Therefore, the PEM electrolyzer is utilized in this study.

In the integrated station with hydrogen storage (CASE-A), solar PV power can be partially consumed by PEV charging or completely converted into hydrogen. Hence, a 1 MW PEM electrolyzer was selected to match the peak solar PV output power. Since a 1 MW PEM electrolyzer produces about 20 kg H_2 per hour, a 20 kg H_2/hr two-stage piston compressor that can compress hydrogen up to 875 bar is employed to discharge the hydrogen into the low pressure hydrogen tank or the high pressure cascade hydrogen tank via manifold control in the design of CASE-A. For the integrated system with batteries (CASE-B), a large portion of solar PV power is consumed by PEV charging or stored in the battery. Hence, both the electrolyzer and compressor in CASE-B are downsized to half of the capacity of that in CASE-A. For the distributed configuration (CASE-C), a 1 MW electrolyzer and a 20 kg H_2/hr compressor are employed to maintain high pressures of hydrogen for getting a full vehicle tank fill under the peak hydrogen demand, which is 5 FCEV fuelings per hour with each fueling requiring 4 kg hydrogen.

Regarding energy storage, CASE-A employs a 200 kg low pressure tank for hydrogen storage to manage the solar PV power supply and vehicle fueling/charging demand. Low pressure hydrogen can be further compressed to high pressure for FCEV fueling or converted back to electricity via a fuel cell for PEV charging. All three fueling/charging configurations – CASE-A, CASE-B, and CASE-C – have high pressure, wire wrapped cylinder cascade storage with a capacity of 200 kg hydrogen for FCEV fueling. CASE-B employs a 2.5 MWh battery as energy storage to balance PV electricity output and vehicle fueling/charging demand, as well as a shift in electricity demand during peak periods. The PEV charging part of CASE-C employs a 1 MWh battery to smooth PEV charging spikes and reduce their peak demand charges during the day.

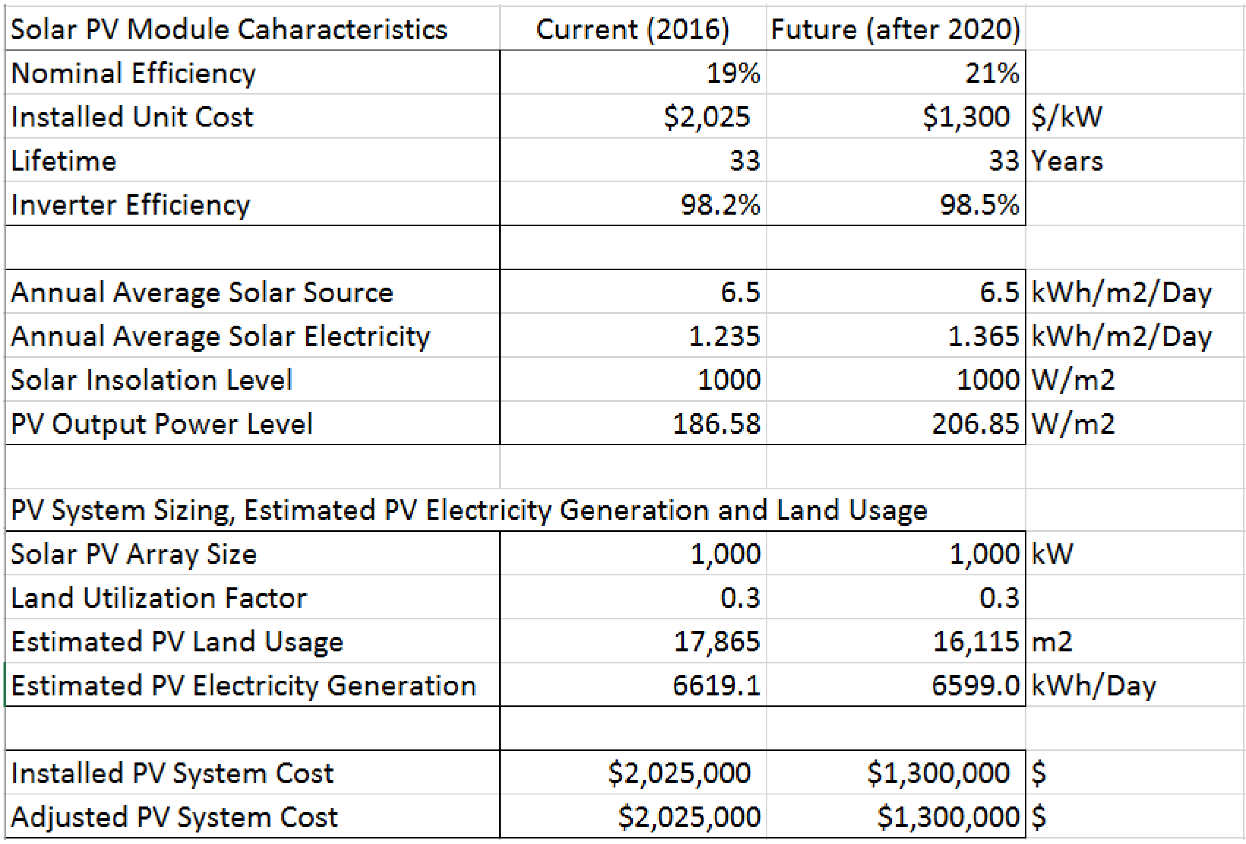
A 2-hose hydrogen dispenser with a cooling unit is selected for hydrogen dispensing. The hydrogen delivery rate is 2 kg H_2/minute/hose and maximum 20 kg H_2 per hour. Each fueling/charging configuration has four DC Fast chargers and each charger can provide charging power up to 100 kW. For the configuration of CASE-A, a 400 kW PEM fuel cell is employed to convert low pressure hydrogen back to electricity for PEV charging when solar PV electricity is insufficient or not available directly from the PV panel. The charging system requires quick startup and response of the fuel cell for PEV charging, which is different from conventional stationary fuel cell operation. An automotive/bus fuel cell is selected in the configuration CASE-A. The fuel cell can also convert excess hydrogen into electricity and send electricity back to the grid during peak hours for recovering some of the infrastructure costs at consumer level.

Characteristics and Costs of Major Components

Two technology development time horizons are considered: current for year 2016 and future for years 2020 – 2025. Current time represents present technology available in the market with relatively low performance and small production volume. Future time projects further development of the technologies with high performance and mass production reducing costs.

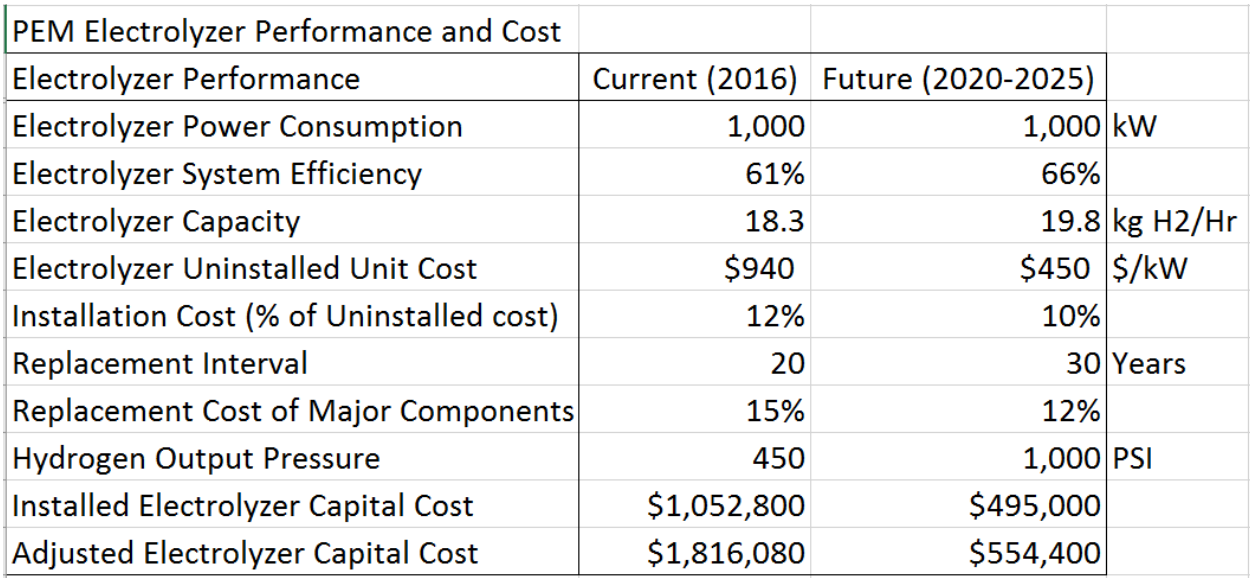
Performance and cost of current and future PEM electrolysis technology is obtained from US Department of Energy (US DOE) reports [13-15]. Characteristics, cost, and lifetime related to hydrogen compression, dispensing and cooling are extracted from the US DOE Hydrogen Analysis (H2A) models and reports [15-23]. The cost and lifetime of underground Hydrogen storages is taken from the DOE Fiscal Year (FY) 2015 Annual Progress Report. The cost for solar PV electricity generating technology is obtained from the 2016 Distributed Generation Renewable Energy Estimate of Costs [24]. The electrical characteristics of solar modules are based on currently available advanced solar PV technologies. Efficiency, cost, and lifetime of battery storage are obtained from recent reports related to PEV batteries and grid energy storage [25, 26]. The cost of fuel cells is obtained from scaling an 80 kW automotive fuel cell system [27]. The cost of DC fast chargers is estimated based on statistical data of current DC fast charger installed cost [11, 28]. Detailed cost and characteristics of the solar PV system, PEM electrolyzer, hydrogen compression, storage, and dispensing, fuel cells, batteries, and DC Fast chargers are summarized in Table 1 – Table 6, respectively. Adjusted cost of major components is determined according to their lifetime over the designed 30-year lifetime of the station.

Table 1: Characteristics and cost of solar PV system



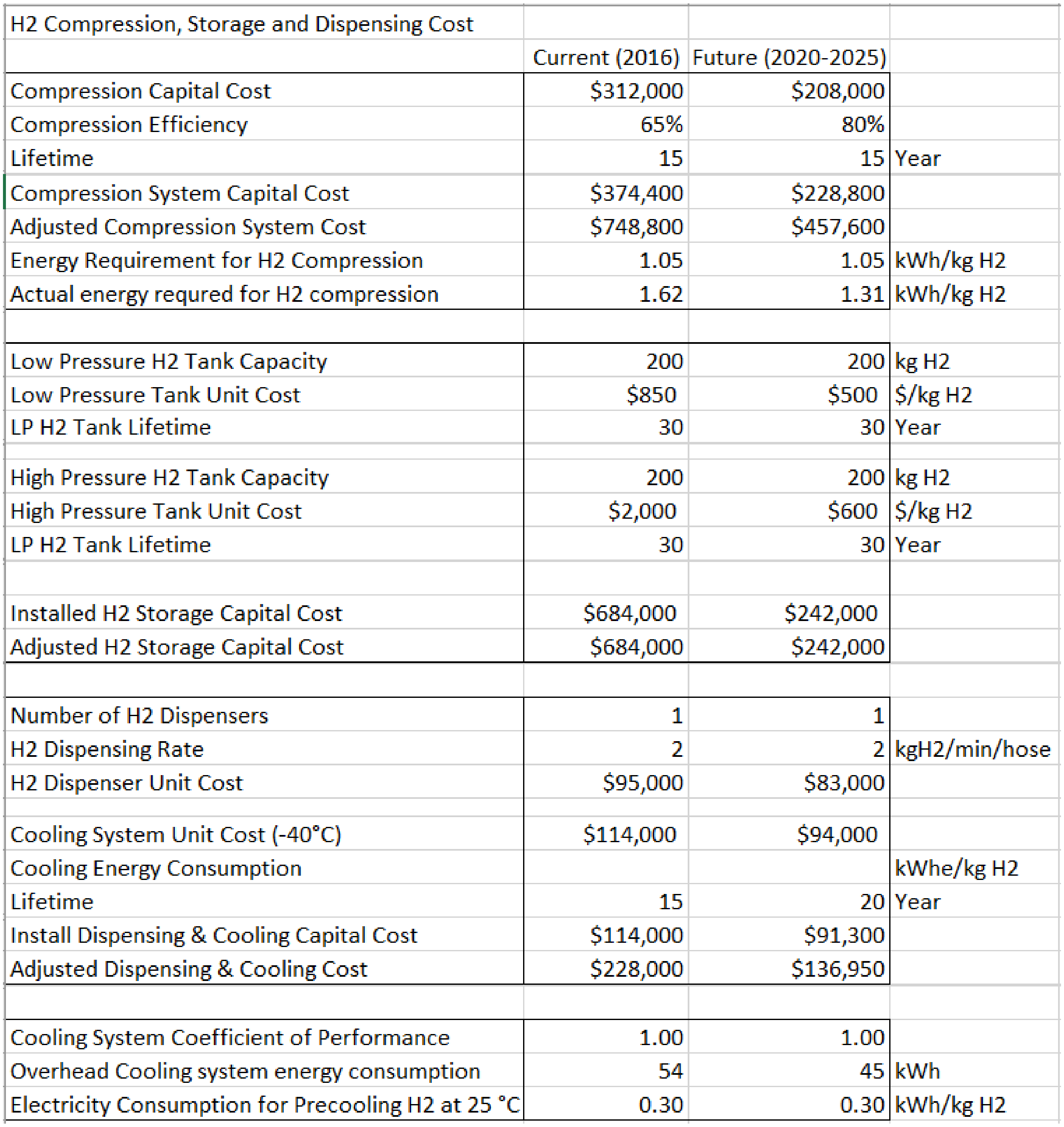
Solar PV Module Caharacteristics	Current (2016)	Future (after 2020)	
Nominal Efficiency	19%	21%	
Installed Unit Cost	$2,025	$1,300	$/kW
Lifetime	33	33	Years
Inverter Efficiency	98.2%	98.5%	
Annual Average Solar Source	6.5	6.5	kWh/m2/Day
Annual Average Solar Electricity	1.235	1.365	kWh/m2/Day
Solar Insolation Level	1000	1000	W/m2
PV Output Power Level	186.58	206.85	W/m2
PV System Sizing, Estimated PV Electricity Generation and Land Usage			
Solar PV Array Size	1,000	1,000	kW
Land Utilization Factor	0.3	0.3	
Estimated PV Land Usage	17,865	16,115	m2
Estimated PV Electricity Generation	6619.1	6599.0	kWh/Day
Installed PV System Cost	$2,025,000	$1,300,000	$
Adjusted PV System Cost	$2,025,000	$1,300,000	$

Table 2: Characteristics and cost of PEM electrolyzer



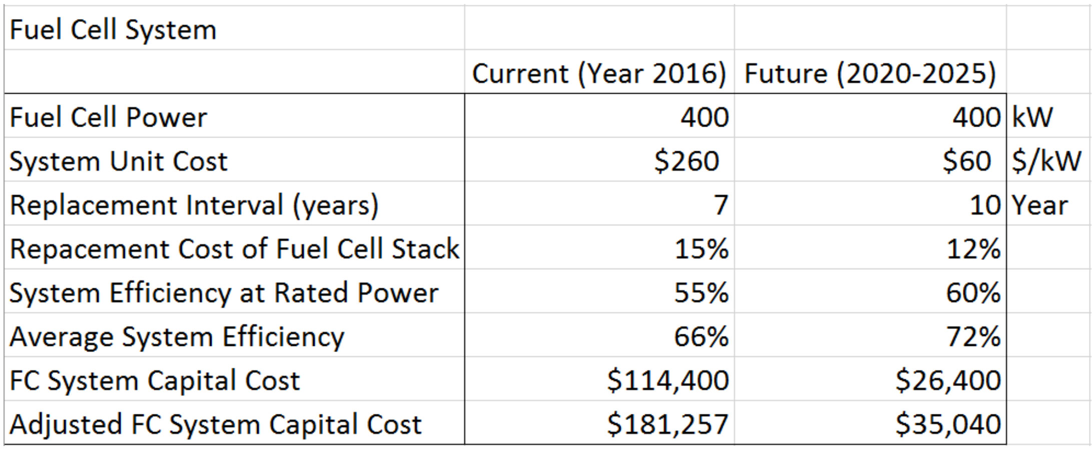
PEM Electrolyzer Performance and Cost			
Electrolyzer Performance	Current (2016)	Future (2020-2025)	
Electrolyzer Power Consumption	1,000	1,000	kW
Electrolyzer System Efficiency	61%	66%	
Electrolyzer Capacity	18.3	19.8	kg H2/Hr
Electrolyzer Uninstalled Unit Cost	$940	$450	$/kW
Installation Cost (% of Uninstalled cost)	12%	10%	
Replacement Interval	20	30	Years
Replacement Cost of Major Components	15%	12%	
Hydrogen Output Pressure	450	1,000	PSI
Installed Electrolyzer Capital Cost	$1,052,800	$495,000	
Adjusted Electrolyzer Capital Cost	$1,816,080	$554,400	

Table 3: Characteristics and cost of hydrogen compression, storage, dispensing, and cooling



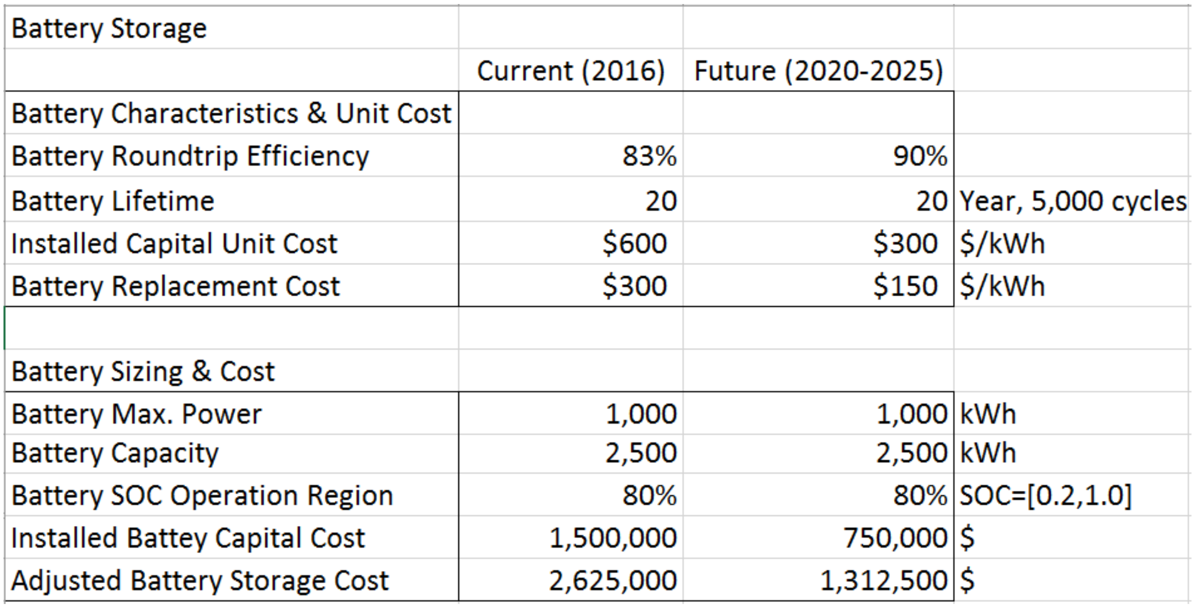
H2 Compression, Storage and Dispensing Cost			
	Current (2016)	Future (2020-2025)	
Compression Capital Cost	$312,000	$208,000	
Compression Efficiency	65%	80%	
Lifetime	15	15	Year
Compression System Capital Cost	$374,400	$228,800	
Adjusted Compression System Cost	$748,800	$457,600	
Energy Requirement for H2 Compression	1.05	1.05	kWh/kg H2
Actual energy requred for H2 compression	1.62	1.31	kWh/kg H2
Low Pressure H2 Tank Capacity	200	200	kg H2
Low Pressure Tank Unit Cost	$850	$500	$/kg H2
LP H2 Tank Lifetime	30	30	Year
High Pressure H2 Tank Capacity	200	200	kg H2
High Pressure Tank Unit Cost	$2,000	$600	$/kg H2
LP H2 Tank Lifetime	30	30	Year
Installed H2 Storage Capital Cost	$684,000	$242,000	
Adjusted H2 Storage Capital Cost	$684,000	$242,000	
Number of H2 Dispensers	1	1	
H2 Dispensing Rate	2	2	kgH2/min/hose
H2 Dispenser Unit Cost	$95,000	$83,000	
Cooling System Unit Cost (-40°C)	$114,000	$94,000	
Cooling Energy Consumption			kWhe/kg H2
Lifetime	15	20	Year
Install Dispensing & Cooling Capital Cost	$114,000	$91,300	
Adjusted Dispensing & Cooling Cost	$228,000	$136,950	
Cooling System Coefficient of Performance	1.00	1.00	
Overhead Cooling system energy consumption	54	45	kWh
Electricity Consumption for Precooling H2 at 25 °C	0.30	0.30	kWh/kg H2

Table 4: Characteristics and cost of fuel cells



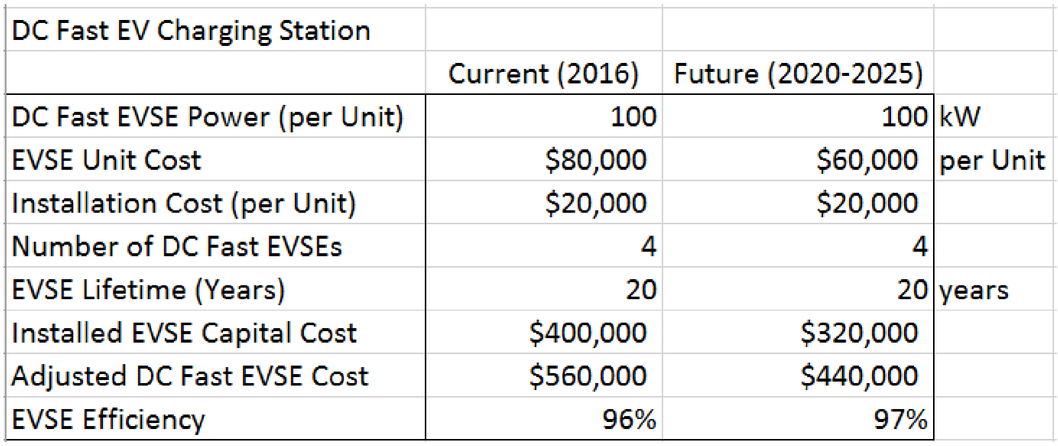
Fuel Cell System			
	Current (Year 2016)	Future (2020-2025)	
Fuel Cell Power	400	400	kW
System Unit Cost	$260	$60	$/kW
Replacement Interval (years)	7	10	Year
Repacement Cost of Fuel Cell Stack	15%	12%	
System Efficiency at Rated Power	55%	60%	
Average System Efficiency	66%	72%	
FC System Capital Cost	$114,400	$26,400	
Adjusted FC System Capital Cost	$181,257	$35,040	

Table 5: Characteristics and cost of batteries



Battery Storage			
	Current (2016)	Future (2020-2025)	
Battery Characteristics & Unit Cost			
Battery Roundtrip Efficiency	83%	90%	
Battery Lifetime	20	20	Year, 5,000 cycles
Installed Capital Unit Cost	$600	$300	$/kWh
Battery Replacement Cost	$300	$150	$/kWh
Battery Sizing & Cost			
Battery Max. Power	1,000	1,000	kWh
Battery Capacity	2,500	2,500	kWh
Battery SOC Operation Region	80%	80%	SOC=[0.2,1.0]
Installed Battey Capital Cost	1,500,000	750,000	$
Adjusted Battery Storage Cost	2,625,000	1,312,500	$

Table 6: Characteristics and cost of DC fast chargers



DC Fast EV Charging Station			
	Current (2016)	Future (2020-2025)	
DC Fast EVSE Power (per Unit)	100	100	kW
EVSE Unit Cost	$80,000	$60,000	per Unit
Installation Cost (per Unit)	$20,000	$20,000	
Number of DC Fast EVSEs	4	4	
EVSE Lifetime (Years)	20	20	years
Installed EVSE Capital Cost	$400,000	$320,000	
Adjusted DC Fast EVSE Cost	$560,000	$440,000	
EVSE Efficiency	96%	97%	

Economic Analysis of Integrated Charging/Fueling Stations

Approach

Cost modeling was performed to achieve realistic capital cost, fuel cost estimates, and long-term maintenance cost for the integrated hydrogen fueling/DC fast charging systems using renewable solar PV power sources. Two technology development time horizons – current and future are considered in the analysis. The economic analysis of the stations includes capital cost, system efficiency, operating energy cost, and maintenance cost. Each station shown in Figure 9(a)-(c) can provide charging for 50 EVs per day with electricity consumption of 50 kWh per EV charge, and 15 FCEV fueling services per day with each fueling consuming 4 kg hydrogen. Solar PV electricity is first used locally for PEV charging and hydrogen production. The excess PV electricity is fed into the grid and any electricity deficit will be provided by the grid.

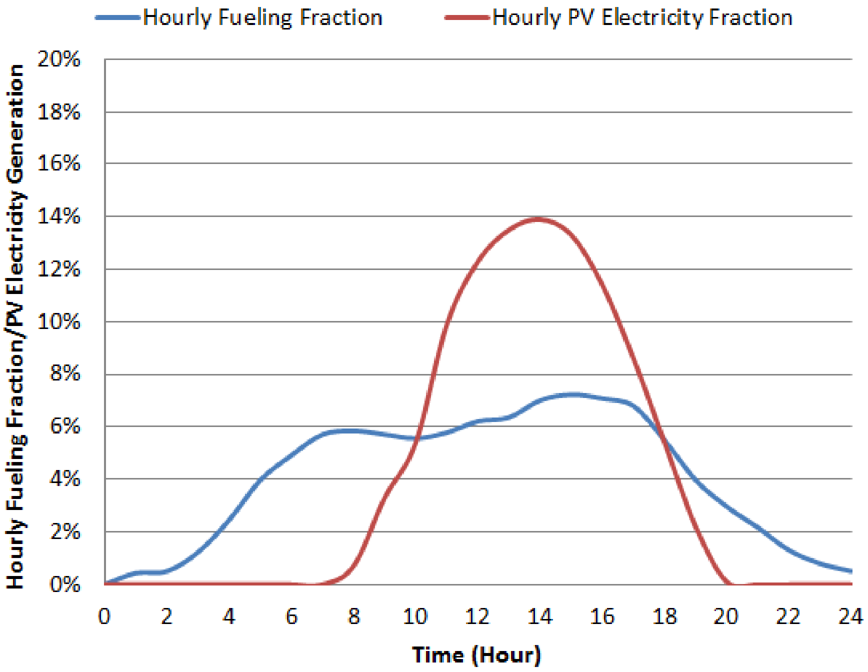
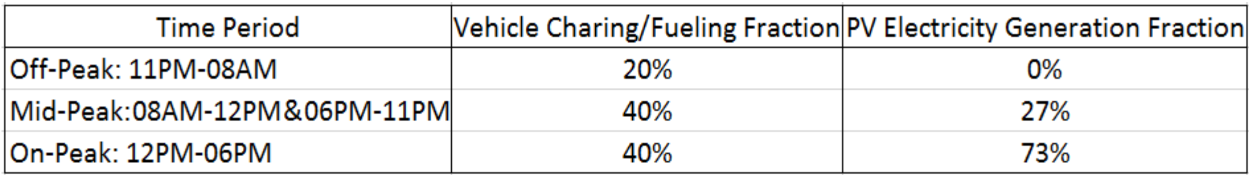


Figure 10: Hourly hydrogen/electricity delivery fraction and PV electricity generation fraction

The FCEV fueling and PEV charging load profiles of a public fueling/charging station vary according to station location, day of the week, and travel pattern. A Chevron gasoline station workday hourly fueling profile is employed to represent the FCEV fueling and PEV charging load profile [16]. An hourly electricity generation profile of a solar PV facility in the West Village at UC Davis is used to estimate the amount of electricity that the charging station's PV system would produce during different time periods of the day. Both hourly hydrogen/electricity delivery fraction and hourly PV electricity generation are shown in Figure 10. The mismatch of solar PV electricity generation and the vehicle fueling/charging demands requires energy management to store electrical energy in the batteries or in the form of hydrogen, and to import/export electricity from/to the grid. The energy losses on energy storage and the energy cost are calculated based on three time periods – on-peak, mid-peak, and off-peak, which roughly matches the different periods in major business electricity and EV charging rate and demand charge schedules of major utilities in California. Table 7 shows the fraction of vehicle fueling/charging load demand and PV electricity generation over the three time periods.

Table 7: Fraction of fueling/charging demand and PV electricity generation during different time periods



Time Period	Vehicle Charing/Fueling Fraction	PV Electricity Generation Fraction
Off-Peak: 11PM-08AM	20%	0%
Mid-Peak:08AM-12PM&06PM-11PM	40%	27%
On-Peak: 12PM-06PM	40%	73%

The levelized cost of hydrogen and electricity are calculated for all three hydrogen fueling/DC fast charging stations. It is assumed that all stations have an anticipated lifetime of 30 years. The initial capital cost is calculated and adjusted according to the lifetime of each component. The salvage value of the stations is estimated to cover the cost of dismantling the stations after 30 years. A 4% interest is applied to repay the capital investment, compounded annually. The annual operating and maintenance costs include the cost of the electricity required from the grid and maintenance cost. Maintenance cost can vary significantly with station size and configuration. Large solar PV systems and hydrogen tanks have annual maintenance cost less than 1% of the initial capital cost, while electroylzers and compressors have maintenance cost more than 4% of initial capital cost. Considering fueling/charging stations don't operate continuously around the clock, an annual maintenance cost of 2% of initial capital cost is included in the contracted maintenance cost. No attendant will be present at the stations, but the telephone number of a service that monitors multiple stations will be available for reporting trouble with the stations. The annual return to investors/owners is 5% of the capital repayment cost plus the energy cost. The levelized fuel cost is estimated on an annual time increment.

The adjusted initial capital cost (P_{c0}) is compounded into a present value (P_{c30}) and converted into an equivalent uniform series (S_c) of values over the lifetime of 30 years. Considering building sustainable fueling/charging infrastructure is a long-term investment with a social purpose, the initial capital cost was adjusted to account for the replacement of components with lifetimes less than 30 years.

$$P_{c30} = P_{c0}(1+4\%)^{30} \qquad (1)$$

Annual uniform series equivalent of total capital cost is calculated by

$$S_c = P_{c30}\left\{\frac{(1+4\%)^{30}-1}{4\%}\right\}^{-1} \qquad (2)$$

Total annualized cost S is the sum of annual uniform capital repayment S_c, annual return to private investors S_r, annual operation energy cost S_e, and annual maintenance cost S_m.

$$S = S_c + S_r + S_e + S_m \tag{3}$$

The levelized hydrogen fueling cost ($/kg H_2) and the EV charging cost ($/kWh) are the total annualized cost (S) divided by the annual energy delivery. For the integrated fueling/charging stations (CASE-A and CASE-B), the annualized cost is assumed to be equally divided between hydrogen dispensing and EV charging. In the distributed configuration (CASE-C), the annualized cost for the hydrogen station and the EV charging station is estimated separately.

$$levelized\ fuel\ cost = \frac{S_{H2}}{m_{H2}}\ or\ \frac{S_{ev}}{E_{ev}} \tag{4}$$

S_{H2} is the annualized hydrogen station cost; $S_{ev}\ is\ the$ annualized EV charging station cost; m_{H2} is annual hydrogen delivery; and e_{ev} is annual electricity used.

The system performance modeling and the economic calculations were done using an Excel spreadsheet using the inputs shown in Tables 1-6 and the relationships given in Equations 1-4. Results of the calculations are given in Tables 10-12. The spreadsheet makes it quick and easy to perform the calculations for different sets of inputs and grid electric cost schedules.

Inputs and Results

Electricity rate schedules change often and vary by the service voltage among different utilities. However, the actual charges per kilowatt of demand and per kilowatt-hour of usage for different utilities, which vary by time-of-day and season, are similar. Hence, the different utility rate schedules will not influence the comparisons of different station configurations. The integrated fueling/charging stations are mainly powered by solar PV power produced locally; hence, electric schedules have little effect on the fuel cost of the integrated stations. However, the change of electric rates can have a significant impact on the operating energy cost of the distributed fueling/charging stations, which are powered by grid electricity.

Two sets of Time-of-Use (TOU) electricity rate schedules from Southern California Edison [29] are used to calculated the levelized fuel cost for the three fueling/charging configurations. One is the business schedule, TOU-8 Secondary Voltage, for monthly power demand of 500 kW or greater, as shown in Table 8. Schedule TOU-8 charges customers at different rates depending on the time of the day and season of the year. A facility-related demand charge and a summer peak-time related demand charge are also applied. Since there is no electricity generation rate in schedule TOU-8, a flat generation rate is used in the analysis. Another is general service EV charging schedule, TOU-EV-4 (Table 9), which is applicable to users whose power demand is between 20 kW and 500 kW. Schedule TOU-EV-4 charges a low flat rate for electricity delivery service all year, but has high facility-related demand charges. For the electricity fed back into the grid, the utility company buyback rate varies with the time of the day and season of the year.

Table 8: Business Electricity Rate Schedule – TOU-8

Select Rate Structure	TOU-8			
TOU-EV-4	: For EV Charging - Demand Metered, up to 500 kW			
TOU-8	: For Business Time-Of-Use, 500 kW or over			
Energy Charge - $/kWh		Delivery Service	Generation	
Summer Season	On-Peak	$0.110	$0.090	12PM-06PM
(June 1 - September 30)	Mid-Peak	$0.090	$0.090	08AM-12PM & 06PM-11PM
	Off-Peak	$0.065	$0.090	Others
Winter Season	On-Peak	$0.092	$0.090	12PM-06PM
(Octomber 1 - May 31)	Mid-Peak	$0.092	$0.090	08AM-12PM & 06PM-11PM
	Off-Peak	$0.067	$0.090	Others
Customer Charge - $/meter/Month		$458.04		
Demand Charge -Facilities Related		$10.74	$/per monthly max KW per meter	
Demand Charge - Time-related	Summer	$15.23	per max on-peak kW in the sumer season only	
	Summer	$5.14	per max mid-peak kW in the summer season only	

Table 9: EV Charging Schedule – TOU-EV-4

Select Rate Structure	TOU-EV-4			
TOU-EV-4	: For EV Charging - Demand Metered, up to 500 kW			
TOU-8	: For Business Time-Of-Use, 500 kW or over			
Energy Charge - $/kWh		Delivery Service	Generation	
Summer Season	On-Peak	$0.024	$0.194	12PM-06PM
(June 1 - September 30)	Mid-Peak	$0.024	$0.057	08AM-12PM & 06PM-11PM
	Off-Peak	$0.024	$0.034	Others
Winter Season	On-Peak	$0.024	$0.046	12PM-06PM
(Octomber 1 - May 31)	Mid-Peak	$0.024	$0.043	08AM-12PM & 06PM-11PM
	Off-Peak	$0.024	$0.038	Others
Customer Charge - $/meter/Month		$223.75		
Demand Charge -Facilities Related		$15.44	$/kW of Billing Demand/Meter/Month	
Demand Charge - Time-related	Summer	$0.00	per max on-peak kW in the sumer season only	
	Summer	$0.00	per max mid-peak kW in the summer season only	

Table 10: Summary of fueling/charging station economic parameters of major components

		CASE-A			CASE-B			CASE-C	
SYSTEM & CAPITAL COST									
		Current	Future		Current	Future		Current	Future
System Lifetime (Year)	30			30			30		
Solar PV Array Size (kW)	1,000	$2,025,000	$1,300,000	1000	$2,025,000	$1,300,000	1000		
Grid Power Capacity (kW)	500			500			1000		
Electrolyzer Power Consumption (kW)	1,000	$1,052,800	$495,000	500	$526,400	$247,500	1000	$1,052,800	$495,000
High Pressure H2 Tank Capacity (kg)	200	$480,000	$132,000	200	$480,000	$132,000	200	$480,000	$132,000
Low Pressure H2 Tank Capacity (kg)	200	$204,000	$110,000	0			0		
Number of H2 Dispensors	1	$114,000	$242,000	1	$114,000	$132,000	1	$114,000	$132,000
Fuel Cell Power (kW)	400	$114,400	$26,400	0	$0	$0	0	$0	$0
Battery Capacity (kWh)	0	$0	$0	2500	$1,500,000	$750,000	1000	$600,000	$300,000
Number of EVSEs	4	$400,000	$320,000	4	$400,000	$320,000	4	$400,000	$320,000
H2 Compressor		$374,400	$228,800		$187,200	$114,400		$374,400	$228,800

As noted previously, each system provides for charging 50 EVs per day with electricity consumption of 50 kWh per EV charge, and 15 FCEV H_2 fuelings per day with each fueling consuming 4 kg hydrogen. This corresponds to a daily electricity and hydrogen delivery of approximately 2.5 MWh/day and 60 kg H_2/day, which is close to 100% of the station's capacity based on its solar PV electricity generation. The three station configurations were modeled using a fixed interest rate of 4% and an investment return rate of 5%. No hydrogen fuel/EV charging tax or other incentives are included in the analysis. Table 10 summarizes the economic parameters for the major components of the three station configurations.

Economic analysis using business electricity schedule TOU-8

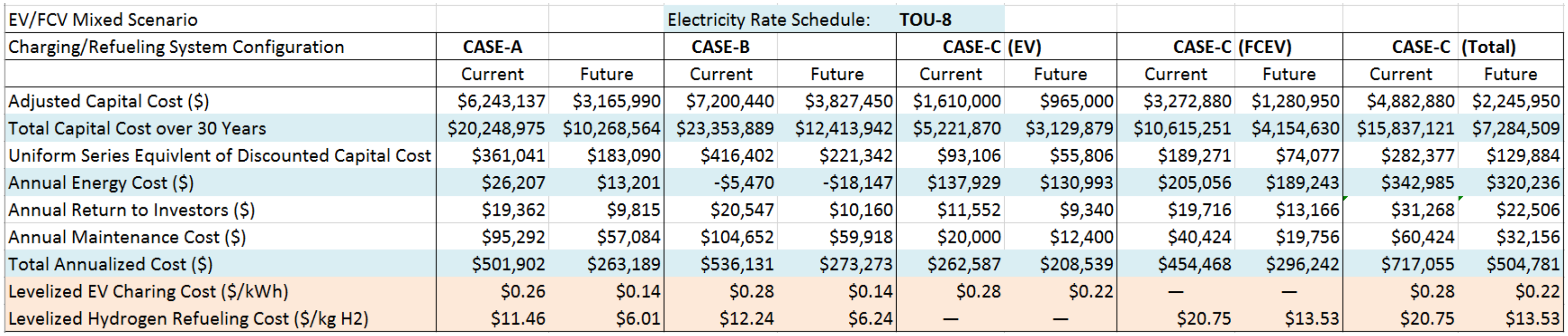
Table 11 shows the adjusted initial capital cost, annual energy cost, total annualized cost, annual maintenance cost, and levelized fuel cost for the three fueling/charging stations. For the distributed station (CASE-C), the costs for hydrogen fueling and EV charging are estimated separately in the column "CASE-C (FCEV)" and "CASE-C (EV)", and combined together in the column of "CASE-C (Total)". The integrated stations using hydrogen (CASE-A) or battery (CASE-B) for energy storage require initial capital costs between \$6.2 million and \$7.2 million, which is 28-47% higher than that of the distributed station (CASE-C). The annual energy cost for the three station configurations varies significantly, with the integrated station (CASE-B) receiving an annual energy credit of \$5,470 and the distributed station (CASE-C) having an annual energy cost of \$343k. The contracted maintenance cost is related to the initial capital cost, with the integrated station having an annual maintenance cost of \$95k - \$105k and the distributed station having an annual maintenance cost of \$60k. The total annualized costs for the two integrated stations are between \$502k - \$536k, and that for the distributed station is \$717k.

The hydrogen costs for the three station configurations ranged from \$11.46/kg to \$20.75/kg for current technology. The integrated systems using either hydrogen storage or batteries can deliver hydrogen at 55%-59% of the price of the distributed station. With the improvement of technology and cost reduction due to mass production, the hydrogen cost would be reduced by half for the integrated stations, reaching approximately \$6/kg. The current EV charging electricity costs for all three stations are between \$0.26/kWh and \$0.28/kWh. Future technology can reduce the EV charging cost by half to \$0.14/kWh for the integrated stations. For CASE-C, the electricity is purchased from the grid and the charging cost remains high at about \$0.22/kWh.

Economic analysis using EV charging schedule TOU-EV-4

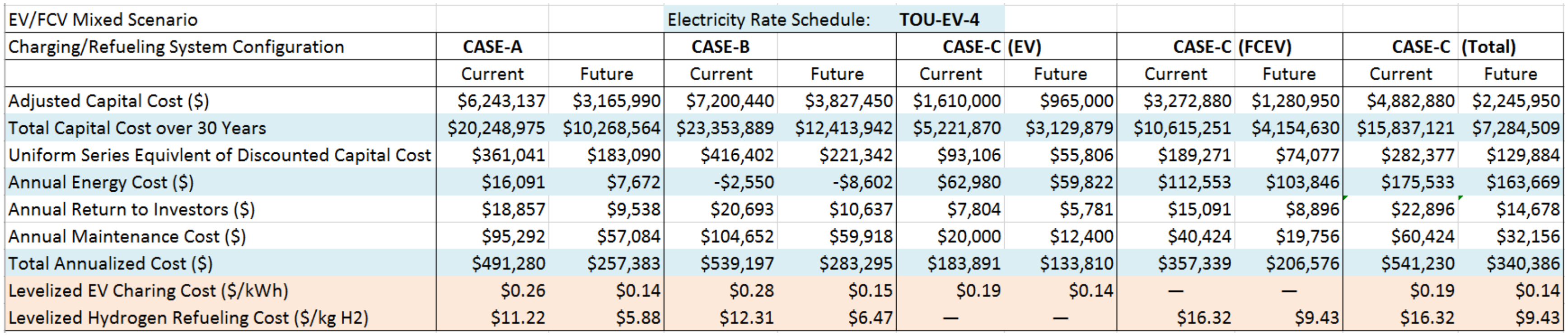
The economic analysis was also done using an EV charging schedule. The results (Table 12) show that similar total annualized costs and levelized energy costs were obtained for the integrated stations using both the Southern California Edison's TOU-8 and TOU-EV-4 schedules because of the relatively low energy consumption from the grid. The low flat electricity rate of

Table 11: Results of the economic analysis using schedule TOU-8



EV/FCV Mixed Scenario			Electricity Rate Schedule:		TOU-8					
Charging/Refueling System Configuration	CASE-A		CASE-B		CASE-C	(EV)	CASE-C	(FCEV)	CASE-C	(Total)
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Adjusted Capital Cost ($)	$6,243,137	$3,165,990	$7,200,440	$3,827,450	$1,610,000	$965,000	$3,272,880	$1,280,950	$4,882,880	$2,245,950
Total Capital Cost over 30 Years	$20,248,975	$10,268,564	$23,353,889	$12,413,942	$5,221,870	$3,129,879	$10,615,251	$4,154,630	$15,837,121	$7,284,509
Uniform Series Equivlent of Discounted Capital Cost	$361,041	$183,090	$416,402	$221,342	$93,106	$55,806	$189,271	$74,077	$282,377	$129,884
Annual Energy Cost ($)	$26,207	$13,201	-$5,470	-$18,147	$137,929	$130,993	$205,056	$189,243	$342,985	$320,236
Annual Return to Investors ($)	$19,362	$9,815	$20,547	$10,160	$11,552	$9,340	$19,716	$13,166	$31,268	$22,506
Annual Maintenance Cost ($)	$95,292	$57,084	$104,652	$59,918	$20,000	$12,400	$40,424	$19,756	$60,424	$32,156
Total Annualized Cost ($)	$501,902	$263,189	$536,131	$273,273	$262,587	$208,539	$454,468	$296,242	$717,055	$504,781
Levelized EV Charing Cost ($/kWh)	$0.26	$0.14	$0.28	$0.14	$0.28	$0.22	—	—	$0.28	$0.22
Levelized Hydrogen Refueling Cost ($/kg H2)	$11.46	$6.01	$12.24	$6.24	—	—	$20.75	$13.53	$20.75	$13.53

Table 12: Result of economic analysis using schedule TOU-EV-4



EV/FCV Mixed Scenario			Electricity Rate Schedule:		TOU-EV-4					
Charging/Refueling System Configuration	CASE-A		CASE-B		CASE-C	(EV)	CASE-C	(FCEV)	CASE-C	(Total)
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Adjusted Capital Cost ($)	$6,243,137	$3,165,990	$7,200,440	$3,827,450	$1,610,000	$965,000	$3,272,880	$1,280,950	$4,882,880	$2,245,950
Total Capital Cost over 30 Years	$20,248,975	$10,268,564	$23,353,889	$12,413,942	$5,221,870	$3,129,879	$10,615,251	$4,154,630	$15,837,121	$7,284,509
Uniform Series Equivlent of Discounted Capital Cost	$361,041	$183,090	$416,402	$221,342	$93,106	$55,806	$189,271	$74,077	$282,377	$129,884
Annual Energy Cost ($)	$16,091	$7,672	-$2,550	-$8,602	$62,980	$59,822	$112,553	$103,846	$175,533	$163,669
Annual Return to Investors ($)	$18,857	$9,538	$20,693	$10,637	$7,804	$5,781	$15,091	$8,896	$22,896	$14,678
Annual Maintenance Cost ($)	$95,292	$57,084	$104,652	$59,918	$20,000	$12,400	$40,424	$19,756	$60,424	$32,156
Total Annualized Cost ($)	$491,280	$257,383	$539,197	$283,295	$183,891	$133,810	$357,339	$206,576	$541,230	$340,386
Levelized EV Charing Cost ($/kWh)	$0.26	$0.14	$0.28	$0.15	$0.19	$0.14	—	—	$0.19	$0.14
Levelized Hydrogen Refueling Cost ($/kg H2)	$11.22	$5.88	$12.31	$6.47	—	—	$16.32	$9.43	$16.32	$9.43

schedule TOU-EV-4 significantly reduced the annual energy cost of the distributed charging station. The levelized hydrogen delivery and EV charging energy costs for the distributed stations at the present time are $16.32/kg and $0.19/kWh, respectively, which are 21% and 32% lower compared to the results using schedule TOU-8. In the future, the EV charging costs projected are about $.14/kWh for all three station configurations. The hydrogen costs for the integrated stations are about two-thirds those of the distributed stations for both present and future technologies, being about $11 and $6, respectively. In the distributed hydrogen station, the high capital cost plays a dominant role in deciding hydrogen cost, and the low electricity rate has less influence on it.

Comparing the two integrated hydrogen fueling/DC fast charging stations, the station with hydrogen storage is more economically attractive for both electricity rate schedules, while the station with battery storage is more energy efficient. Among all three station configurations, the distributed station requires the lowest capital cost and maintenance cost, but is most grid energy intensive. The distributed station is not economically attractive using business schedule TOU-8. The EV charging schedule TOU-EV-4 makes distributed EV charging economically attractive, but is less attractive for fueling FCEVs. In addition, the distributed system uses electricity from the grid, which is not sustainable energy for the most part.

Summary and Conclusions

In this project, the costs of deploying sustainable infrastructure (solar panels) at SRRAs to produce and supply hydrogen to FCEVs and to provide DC fast charging to battery EVs were analyzed. Three hydrogen fueling/DC fast charging system configurations were studied– two integrated systems using hydrogen or batteries for energy storage, and a distributed system for fueling FCEVs and charging EVs. Aspects of hydrogen fueling and DC fast charging stations that are costly in capital investments were identified and their impact on the maintenance and operating costs of the combined fueling/charging station configurations determined.

Integrated hydrogen fueling/DC fast charging systems with different energy storage media were designed, and technical and economic models of components and systems for solar PV electricity generation, battery electricity storage, hydrogen production, compression, storage and dispensing, fuel cells, and EV chargers were developed to quantify costs and permit analysis of different fueling/charging station configurations and investing strategies. The characteristics and costs of the major components of the fueling/charging stations were collected for **current** and **future** technologies. Economic analyses of capital investment, operating energy demand, annualized cost, energy costs, and contracted maintenance cost were performed for different station configuration options. The impact of two different electricity rate schedules on hydrogen fueling and DC fast charging energy costs were estimated.

The primary conclusions from this analysis are that compared to the distributed stations, the integrated stations are more energy efficient and more economically attractive in terms of hydrogen fuel cost than the distributed stations. The cost of PEV charging in the sustainable integrated stations was close to that of the distributed stations using the business electric schedule for current technologies. The cost of the hydrogen in the integrated stations was weakly dependent on the electricity cost schedule and varied between $11.22/kg and $12.31/kg in 2016 (current time), and between $5.88/kg and $6.47/kg in 2020 – 2025 (future time). EV charging from the integrated stations was projected to cost between $0.26/kWh and $0.28/kWh in 2016, and between $0.14/kWh and $0.15/kWh in 2020 – 2025. The estimated vehicle fueling costs at the distributed station varied significantly with the schedule for electricity cost. Using Southern California Edison's TOU-8 schedule, the hydrogen costs were $20.75/kg in 2016 and $13.53/kg in 2025. For the TOU-EV-4 schedule, the hydrogen costs were $16.32/kg in 2016 and $9.43/kg in 2025. The EV charging costs in the distributed stations were $0.19/kWh in 2016 and $0.14/kWh in 2025 for the EV charging rate schedule, significantly reduced from $0.28/kWh and $0.22/kWh for the general business electricity rate schedule. The distributed station requires less capital investments, but the energy costs are more sensitive to the electricity rate schedule. If an incentive/subsidy is considered for installing fueling/charging stations at SRRAs, the capital and energy costs will be lower for all three station configurations. The maintenance cost of the charging stations is directly related to their initial capital costs, with the integrated stations having an annual maintenance cost of about $100k and the distributed station having a maintenance cost of $60k.

As the owner of the SRRAs, the California Department of Transportation (Caltrans) is exploring the use of highway right-of-way to accommodate renewable energy technologies [30]. Development of integrated hydrogen fueling/DC fast charging stations at and/or near SRRAs is compatible with the present Caltrans goal of building a sustainable transportation system. However, current federal law relating to the use of and access to interstate rights-of-way prohibits commercial activities at SRRAs. A renewable fueling/charging station may be treated as a renewable energy facility that meets the terms and conditions outlined in the FHWA-approved Utility Accommodation Plan, like the nation's first solar highway project – Baldock Solar Station on Interstate 5 in Oregon. If the fueling/charging stations are free of charge, then they are not considered commercial. The Federal Highway Administration is seeking public comments on reinterpretation of certain provisions of the law in consideration of new technologies and the interest of the States to provide sustainable fueling of zero emission vehicles.

In this analysis, we assessed the sustainable integrated fueling/charging stations based on 100% of utilization of local PV electricity for hydrogen fueling/DC fast charging. The hydrogen fuelings and EV chargings were evenly divided based on their energy consumption. However, in the early stage of FCEV and PEV adoption, a relatively low utilization of fueling/charging stations is likely. In that case, the integrated stations could function as distributed power generation and energy storage for the grid. As the market for FCEVs and EVs develops, the integrated stations have the potential to serve the larger numbers of FCEVs and PEVs by using grid electricity during off-peak hours. Additional research is needed to explore the role of the utilization rate of the integrated stations on fuel costs and their economic attractiveness particularly as the component technologies improve and their costs are reduced in the future.

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