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Solar powered residential hydrogen fueling station

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SOLAR POWERED RESIDENTIAL HYDROGEN FUELING STATION

by

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PUBLICATION THESIS OPTION

This thesis consists of following papers that have been published as follows, and the papers were formatted in the style used by the university.

The first paper presented in pages 3 – 16 entitled “SOLAR POWERED RESIDENTIAL HYDROGEN FUELING STATION” has been accepted to be published in the proceedings of the International Journal of Hydrogen Energy.

The second paper presented in pages 17 – 33 entitled “SOLAR ENERGY POWERED RESIDENTIAL FILLING STATION FOR FUEL CELL PLUG-IN HYBRID ELECTRIC VEHICLE” has been presented at 2011 Fuel Cell and Hydrogen Energy Association, Washington DC.

ABSTRACT

Interest towards the hydrogen fuel technology is increasing but its potential benefits will not be felt until hydrogen vehicles and the fueling infrastructure captures a substantial market share. Though there has been a rapid progress in the hydrogen fuel cell technology, a major challenge to the commercialization of fuel cell vehicles is the lack of hydrogen fueling infrastructure. The development of a commercial hydrogen fueling station is a challenge due to its high initial cost and safety concerns. Residential fueling stations provide an innovative solution to this issue since they also produce electricity and heat for the residential buildings in addition to low volume fueling methods. Residential fueling is attractive since it provides a convenient and secure method to refuel for the consumers. Application of solar energy to power residential buildings as a methodology to achieve energy savings has been discussed.

The thesis consists of two papers describing the residential hydrogen fueling station design. The first paper presents the conceptual design of a residential hydrogen fueling station for a single family at Wallingford, Connecticut. The concept utilizes solar photovoltaic panels to power electrolyzer for generating hydrogen, and cater to 95% of home’s electricity needs. The second paper discusses the integration of solar energy with a residential building to power a Fuel Cell Plug-in Hybrid Electric Vehicle (FC-PHEV) at E^3 Commons, Rolla.

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1. INTRODUCTION

The development of hydrogen fueling infrastructure is a key to the development of a sustainable global hydrogen economy. Through the Hydrogen Program, The U.S. Department of Energy (DOE) is jointly working with International Energy Agency (IEA) and International Partnership of Hydrogen Economy (IPHE), to develop a feasible vision for future fueling infrastructure investments and development activities [1]. The Program is also keen on establishing the required fueling infrastructure for fuel-cell powered passenger vehicles by 2015. Proton Energy Systems in a partnership with SunHydro, is actively involved in building hydrogen fueling stations in NorthEastern U.S including Connecticut, Maine and Rhode Island [2].

The first paper identifies the hydrogen technologies for a residential hydrogen fueling infrastructure at Wallingford, Connecticut. The concept design incorporates hydrogen technologies that are commercially available and possible to implement for practical, real-world use from February 2011. This paper explains the conceptual design of a residential hydrogen fueling station located at Wallingford, Connecticut, hydrogen production using solar energy and a safe and convenient refueling of hydrogen. The advantage of incorporating residential hydrogen fueling includes an easy means to filling hydrogen and also reduces dependence on the commercial hydrogen fueling stations. Different hydrogen production methods including electrolysis, steam methane reformation, high pressure compressor and storage options were evaluated. The integration of renewable energy with the on-site, high pressure hydrogen generator is discussed. The residential hydrogen station technical design specifications including the sizing of solar photovoltaic (PV) panels, electrolyzer, storage tanks, dispensers, and other safety equipment is described.

The second paper discusses the E^3 Commons at Missouri S&T as the demonstration site for the solar residential hydrogen fueling station. E^3=C" i.e. Energy, Environment and Education equals Civilization has been established by Missouri S&T and Missouri Transportation Institute. This facility consists of a residential unit housing EcoCAR team members, a hydrogen fueling station, an EcoCAR garage and a transit depot. On-site hydrogen is produced by a Proton Electrolyte Membrane fuel cell which is then compressed at 5,000 psi. The compressed hydrogen is stored in three storage tanks, or dispensed using a SAE J2600 compliant nozzle. Solar energy is harnessed to generate power for residential building, electrolyzer and electric charging station.

Hydrogen Safety is an integral part which has to be factored into the residential hydrogen fueling station design. Hence, safety analysis is performed to address the precautionary measures to be considered before and after the installation of hydrogen devices. Fundamental failure mode analysis has also been performed. The application of hydrogen detection and ventilation devices has been described. To contrast the benefits of hydrogen fueled vehicles over gasoline counterparts, an environmental analysis has also been performed and the required energy efficiency improvement has been calculated.

PAPER

I. SOLAR POWERED RESIDENTIAL HYDROGEN FUELING STATION

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Abstract

This paper presents a conceptual design of a solar powered hydrogen fueling station for a single family home in Wallingford, Connecticut, USA. Sixty high-efficiency monocrystalline silicon photovoltaic (PV) solar panels (Total capacity: 18.9 kW) account for approximately 94.7% of the hydrogen home's power consumption. The fueling station consists of a 165 bar high pressure electrolyzer for on-site production of 2.24 kg/day of hydrogen, three-bank cascade configuration storage tanks (4.26 kg of H_2 at 350 bar) and a SAE J2600 compliant hydrogen nozzle. The system produces 0.8 kg/day of hydrogen for a fuel cell vehicle with an average commute of 56 km/day (Fuel mileage: 71 km/kg H_2). Safety codes and standards applicable at the facility are described, and a well-to-wheel analysis is performed to contrast the carbon dioxide emissions of conventional gasoline and fuel cell vehicles. The energy efficiency obtained by incorporating a solar-hydrogen system for residential applications is also computed.

Keywords: Residential hydrogen fueling; photovoltaic; electrolyzer; safety; well-to-wheel; energy efficiency

1. INTRODUCTION

Hydrogen as a sustainable transportation fuel, has gained considerable importance in the past few decades due to reduction in fossil fuel supply and a significant increase in greenhouse gas emissions. The development of residential hydrogen infrastructure is one of the main challenges to promote fuel cell technology among the global community [1]. Hydrogen technologies possess higher efficiency and reliability than conventional systems, therefore having the potential to reduce these issues [2]. With the introduction of residential fueling stations, the customers will have an easy access to fill hydrogen vehicles at their residence which will in-turn reduce the burden on the commercial hydrogen fueling stations.

The conceptual design of a residential hydrogen fueling station located in Wallingford, Connecticut is discussed in this paper. An alternate design was also developed for Burbank, California to illustrate the home hydrogen refueling system being utilized in a completely different climate than the northeastern United States. The Los Angeles region provides an ideal atmosphere for a hydrogen home due to its existing hydrogen infrastructure and a higher public awareness and acceptance of hydrogen technology. Socio-economic conditions of the Burbank area also make it a prime location for incorporating renewable energy systems into a home. In the 2011 Hydrogen Student Design Contest, ten designs of residential hydrogen fueling systems are available online [3]. The Wallingford design employs solar photovoltaic (PV) panels to produce renewable hydrogen through electrolysis. This assists in the reduction of carbon emissions and the dependence on conventional grid. The assessment of safety analysis is paramount to mitigate the potential risks associated with the hydrogen system. The analysis accounts for acceptable design and positioning of system components according to accepted convention and applicable codes and standards [4, 5]. Fundamental failure modes such as hydrogen leaks, hydrogen overfill and over pressure have been mitigated by appropriate process control devices and pressure relief systems [6]. An environmental analysis using GREET, compares the emissions of carbon dioxide and other gaseous products from hydrogen fuel cell and conventional gasoline

2. HYDROGEN HOME

The concept of hydrogen home has been designed for increased feasibility in challenging climatic conditions with a possibility of greater returns, in comparison to those locations having more annual solar exposure. A new-construction single family residence located in Wallingford, Connecticut is considered for the design. Wallingford is a small New England town of 44,881 residents [7], located between New Haven and Hartford, Connecticut. Proton Energy Systems and the Hydrogen Highway have been instrumental in the development of hydrogen infrastructure in Connecticut, resulting in higher public acceptance for hydrogen fueling station [8]. The hydrogen home comprises of two levels: first level includes two bedrooms, two bathrooms, a closet, kitchen, dining room and living room, and second level houses one bedroom. The residential design has strong architectural heritage with steep sloped roofs, incorporating sustainable system throughout the building. The floor plan is compliant with American with Disabilities Act (ADA) [9] for improved accessibility to its residents by providing easy accessible appliances, open floor plan and wide doorways.

The design specified for 18.9 kW DC power from sixty SUNPOWER™ 315 PV panels [10] in a series-parallel configuration is utilized for residential applications and hydrogen generation. The hydrogen home comprises of two PV solar arrays. Array 1 containing 18 solar panels is located over the master bedroom at an orientation of 65° and is directed 19° off the East-west axis for capturing maximum solar energy in the mornings. Array 2 consists of 42 solar panels located over first level, oriented at an angle of 65° and is directed due south for maximum output of solar energy during the afternoons and evenings. The slope of the back roof was designed to be the same as the optimal angle for solar collection to provide stability to withstand harsh winter weather conditions thus reducing heat losses. Clips are installed to prevent large sheets of ice from displacing the solar array. The angle of the solar panels is adjusted by varying the settings on the mounting system for different seasons. Considering the average daylight in Connecticut to be 4.74 hours/day, the energy utilization is 32.7 MWh/yr. The concept hydrogen home at Wallingford spans an area of 292.4 m^2.

The concept conforms to Wallingford's zoning regulations [11] and safety codes for the hydrogen fueling system [4, 5]. The Hydrogen Home, shown in Figure 1 is also compliant with 2003 International Residential Code, 2005 National Fire Protection Association (NFPA) 70, and International Fire Code 2003 [12]. The lighting system inside the garage is strategically placed to maintain the set-off distances, thus eliminating all ignition sources near the hydrogen devices. The electrolyzer and dispenser are installed in an insulated area located in the garage. Detectors are installed at the highest portion of the roof to identify any hydrogen leaks. The dispenser and storage tanks are surrounded with concrete barriers to protect against accidental collision with the equipment. Failure modes for solar PV panels are considered and their installation directly over the hydrogen equipment is avoided [13]. The home comprises of a ground source heating and cooling system to maintain a constant and comfortable temperature. The electrolyzer is protected from the freezing temperatures by a heat loop, keeping it at a temperature range of 10 – 12.5° C (50 – 55° F) throughout the year.

Concrete-insulation sandwich panels and fire break walls are incorporated for increased thermal performance. The foam insulation separates the thermal mass of the interior and exterior concrete layers, thus providing a thermal break from the exterior to the interior. This provides a temperature controlled environment throughout the year. It also reduces the transmittance of sound waves, making the interior more comfortable for its occupants [14, 15]. The insulation increases the resistance to fire or explosion, resist vibrations, shockwaves and sound detonation qualities of the home.

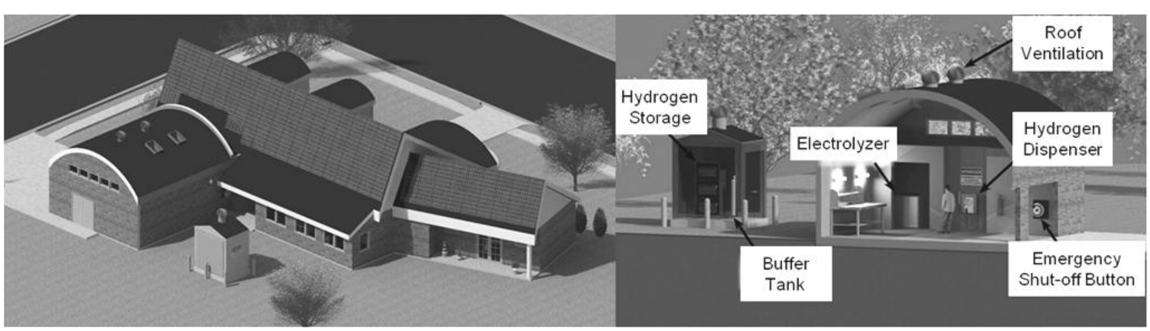

Figure 1 - Hydrogen home

3. HYDROGEN SYSTEM COMPONENTS

The Piping and Instrumentation diagram, shown in Figure 2, outlines the major components of a residential hydrogen fueling station. Hydrogen is produced on-site by a 165 bar HOGEN® HP 40 high-pressure electrolyzer and is accumulated in three storage tanks ST_1, ST_2 and ST_3. The electrolyzer is set to turn 'On' when the pressure inside the storage tanks falls below 138 bar and 'Off' when the pressure reaches 165 bar. Check valves CV_1 and CV_2 ensure that the hydrogen does not flow back into the electrolyzer and storage tanks respectively. Pressure transducers PT_1 and PT_2 keep a track of the pressure inside the storage tanks and on-board vehicle storage tank. The nozzle used for dispensing hydrogen into the vehicle is compliant with SAE J2600 standards [16]. The residential hydrogen fueling system is designed for a hydrogen fuel cell vehicle with a commute of 56 km/day and fuel mileage of approximately 71 km/kg of hydrogen. The cascading results and amount of hydrogen transferred to the vehicle is calculated based on its daily hydrogen demand of 0.8 kg.

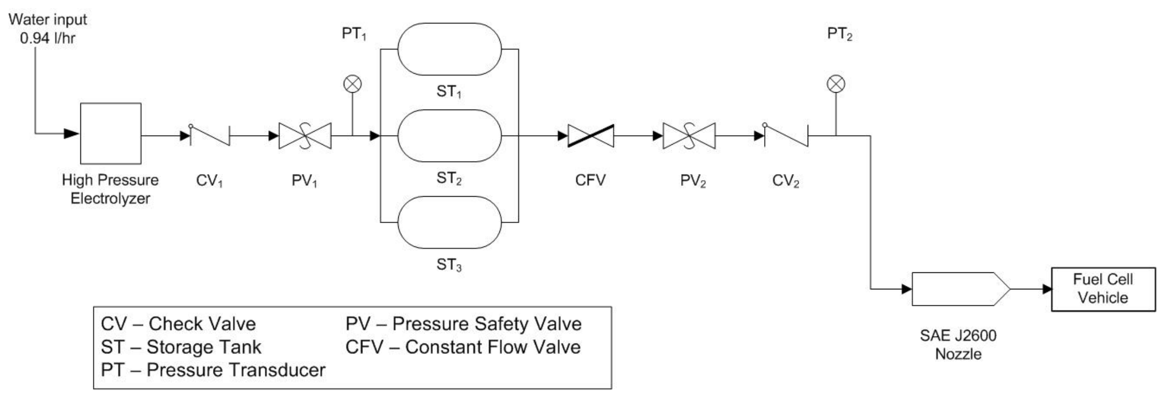

Figure 2 – Major components of a residential hydrogen fueling station

The various hydrogen production methods include utilization of steam methane reformer, reversible PEM fuel cell and electrolyzer. The high pressure electrolyzer can produce up to 2.24 kg of hydrogen per day at 165 bar [17]. It has a low energy consumption, high efficiency and high output pressure. The usage of high pressure electrolyzer eliminates the requirement of a compressor resulting in major energy savings.

The hydrogen storage tanks from Dynetek Industries Ltd are employed at the site and are capable of storing up to 4.26 kg of hydrogen at 350 bar. Each tank has an internal volume capacity of 176 liters of water. The tanks are certified to ISO11439, NGV2, CSA B51 Part2, FMVVSS304, and other standards [18]. The light weight composite storage tanks are configured to allow cascading to complete fueling in the required time.

Since the concept employs a high pressure electrolyzer with an output of 2,400 psi, a hydrogen compressor is not required to achieve the daily fill requirement. The vehicle is designed to follow a non communication fill protocol at 350 bar or 700 bar, and has an on-board storage vehicle capacity of 4.2 kg. For cascading analysis, the daily vehicle route is set to 236.5 km. Figure 3 shows the total amount of hydrogen inside the onboard vehicle storage system at the end of the fueling process through cascading is 1.86 kg (773 sccf). This satisfies the daily requirements of 0.8 kg of hydrogen. From Table 1 it can be seen that the fueling time for vehicle is 10 minutes.

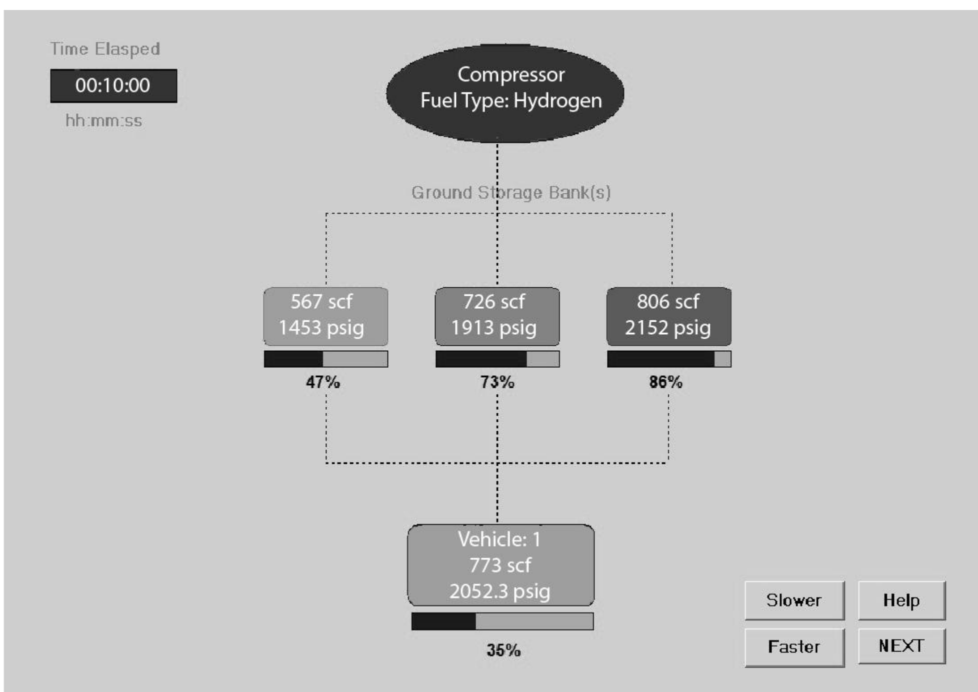

Figure 3 – Cascade simulation

Table 1 – Compressor/storage refueling station analysis

Fuel Type: Hydrogen		*Vehicle*	*Bank 1*	*Bank 2*	*Bank 3*
00:00:00	**Start Filling Vehicle 1**	**Compressor > Bank**	**Bank 1 > Vehicle**		
	Pressure (psig)	502	2,400	2,400	2,400
	Capacity (liter)	5,975	25,117	25,117	25,117
00:02:17	**Vehicle switched to Bank 2**	**Compressor > Bank**	**Bank 2 > Vehicle**		
	Pressure (psig)	1,353	1,453	1,913	2,400
	Capacity (liter)	15,036	16,056	25,117	25,117
00:03:26	**Vehicle switched to Bank 3**	**Compressor > Bank**	**Bank 3 > Vehicle**		
	Pressure (psig)	1,813	1,453	1,913	2,400
	Capacity (liter)	19,595	16,056	20,558	25,117
00:03:26	**Vehicle switched to Bank 3**	**Compressor > Bank**	**Bank 3 > Vehicle**		
	Pressure (psig)	1,813	1,453	1,913	2,400
	Capacity (liter)	19,595	16,056	20,558	25,117
00:04:00	**Vehicle switched to Bank 0**	**Compressor > Bank**	**Bank > Vehicle**		
	Pressure (psig)	2,052	1,453	1,913	2,152
	Capacity (liter)	21,889	16,056	20,558	22,823
10:00:00	**End Filling Vehicle 1**	**Compressor > Bank**			
	Pressure (psig)	2,052	1,453	1,913	2,152
	Capacity (liter)	21,889	16,056	20,558	22,823

Gas Technology Institute (GTI) has designed a hydrogen priority panel which is used to prioritize filling of the three storage tanks and sequence the hydrogen flow to the dispenser. During hydrogen dispensing, the system is designed to operate within the maximum allowable ramp rate (MARR). According to the SAE TIR J2601 Appendix A compliant protocols, the hydrogen dispensing equipment uses the SAE J2600 compliant connections and a SAE J2600 certified nozzle [16]. The detachable hose connects the hydrogen priority panel to the nozzle. The outlet of the priority panel consists of solenoid valve and pressure transducer which controls the fueling between the vehicle onboard storage system and storage tanks. The fueling operation can be performed once the vehicle reaches equilibrium in 20 minutes with the ambient temperature inside the garage [19]. Hydrogen dispenser of 350 bar is not included in the conceptual design since the fueling requirement is lesser than actual amount of hydrogen that can be transferred.

Table 2 lists the specifications of the major components of the hydrogen fueling station and the solar PV panels employed at the facility.

Table 2 – Specifications of major components

Component	Description
Electrolyzer	Manufacturer – Proton Energy Systems, Model – HOGEN HP 40, Net production rate – 2.28 kg/day, Delivery pressure – 165 bar, Water
Storage Tanks	Manufacturer – Dynetek Industries Limited, Model – ZM180, Capacity – 4.26 kg H_2, Storage pressure – 350 bar
Dispenser	Non communication @ 350 bar & 700 bar, SAE J2600 compliant nozzle
Solar PV Panels	Manufacturer – SUNPOWER, Peak Watts/Panel – 315 W, Peak Watts/m^2 – 193 W, Rated voltage – 54.7 V

4. SAFETY ANALYSIS

A consistent track record of safety and reliability is of utmost importance in the design and implementation of a residential hydrogen fueling station. Some of the safety devices included in the concept are hydrogen detectors, emergency shut-off button, fire extinguishers, remote emergency stop and pressure relief valves. The power is disconnected to prevent ignition from electrical sources in case of any hydrogen leak. The hydrogen system is designed and installed according to the applicable safety regulations. Some of the regulations include: NFPA 55, NFPA 52, SAE J2600, SAE TIR J2601, US Department of Transportation regulations and International Fire Code (IFC) [16].

Regular inspection and replacement of hydrogen equipment is required for optimal safety and performance of the hydrogen system. The significant failure modes taken into account are vehicle collision with storage tanks or fueling nozzle, leakage of hydrogen gas and hydrogen overfill which can result in either ultimate or partial system failure [6]. Risk mitigation methods involve hydrogen detection system and sensors to stop fueling in case of leak, allowing natural ventilation, posting of signs in areas with flammable compressed gas and prohibition of smoke or use of open flame within 7.62 m of the storage area [20]. Employment of trained personnel on equipment handling is also encouraged. Moreover, to reduce the likelihood of any accidents, all the potential hazards and safety measures should be depicted on the chart in and around the hydrogen fueling station.

5. WELL-TO-WHEEL ANALYSIS

Since the hydrogen home is powered using grid connected solar panel system, the total output by the solar panels and total demand of the house should be considered before performing an environmental analysis. The estimated demand of the Wallingford home is 95 kWh/day, assuming the average power consumption of the house is 21 kWh/day and consumption by the hydrogen fueling system is 74 kWh/day [17]. The average daily electrical output by PV panels is 90 kWh/day, hence 5 kWh/day is the power requirement from the grid.

Table 3 shows the well-to-wheel analysis comparing a gasoline and a hydrogen fuel-cell vehicle using GREET. The total carbon emissions produced by a hydrogen fuel cell vehicle – 34.8 g/km (56 g/mile) is far less than a gasoline vehicle – 272.2 g/km (438 g/mile).

Table 3 – Well-to-Wheel analysis

Gasoline Vehicle: Conventional Gasoline and Reformulated Gasoline			
	kJ/km or g/km		
Item	**Feedstock**	**Fuel**	**Vehicle Operation**
Total Energy	154	596	3,185
Fossil Fuels	131	455	2953
Coal	2.5	58.5	0
Natural Gas	93.2	146	0
Petroleum	34.8	252	2,953
CO_2 (w/ C in VOC & CO)	7.5	33	232
CH_4	0.28	0.04	0.01
N_2O	0.00	0.00	0.01
GHGs	15	34.2	234.2

FCV: grams of H_2			
	kJ/km or g/km		
Item	**Feedstock**	**Fuel**	**Vehicle Operation**
Total Energy	-974	2,012	1,377
Fossil Fuels	-131	270	185
Coal	-129	267	183
Natural Gas	0	0	0
Petroleum	-1.9	3.7	2.5
CO_2 (w/ C in VOC & CO)	34.8	0	0
CH_4	0.04	0.00	0.00
N_2O	0.00	0.00	0.00
GHGs	36	0	0

6. RESULTS AND CONCLUSIONS

On an average, carbon dioxide emissions resulting from the electricity generation in the United States is 574.5 g /kWh [21]. Sixty solar panels generate 90 kWh/day or approximately 94.7% of the electricity required by the home at Wallingford, Connecticut. Since CO_2 emissions during photovoltaic manufacturing is 43 g CO_2-eq/kWh [22] (PV panels type for SUNPOWER™ 315: Monocrystalline silicon [10]), annual CO_2 savings is estimated to be 16.5 metric tons.

The benchmarked energy utilization for a single family detached home is 138 kWh/m^2-yr [23]. The resulting target area of the home required to attain maximum energy utilization is 238 m^2. Hence, the required energy efficiency improvement for the Wallingford home is approximately 23%. Through a well-to-wheel analysis, the carbon dioxide emissions produced by a fuel cell vehicle is also computed which is approximately 13% of a conventional gasoline vehicle.

7. ACKNOWLEDGEMENT

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II. SOLAR POWERED RESIDENTIAL FILLING STATION FOR FUEL CELL PLUG-IN HYBRID ELECTRIC VEHICLE

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Abstract

Application of solar energy to generate power has emerged as a trend in the utilization of renewable energy sources for various commercial and residential areas, in the wake of economic instability. Research and development has also significantly increased towards the implementation of fuel cell and other hydrogen applications. This paper discusses the integration of solar energy in a residential building and its usage to power a Fuel Cell Plug-in Hybrid Electric Vehicle (FC-PHEV) as a methodology to achieve energy savings. Development of hydrogen infrastructure, electric charging station and the safety measures undertaken at E^3 Commons, Rolla are described. The production and utilization of back-up power for auxiliary purposes at the site is also highlighted.

Keywords: *Solar; residential; fuel cell; hydrogen; FC-PHEV; electric charging; E^3 Commons; back-up*

1. INTRODUCTION

In the past few decades there has been a growing interest towards the applications of hydrogen fuel and a significant rise in the research and development towards hydrogen fuel cell technology. Considering the importance of the transportation sector, both ecologically and economically, hydrogen fuel cell vehicles have been a significant addition to create sustainability and balance. Hence the transition from the gasoline to hydrogen powered vehicles depends upon the infrastructure development of hydrogen filling station. Hydrogen infrastructure is currently an area which needs development to promote the global awareness of fuel cell vehicles [1]. Residential hydrogen fueling stations are being designed to harness this technology. On-site hydrogen production, storage and dispensing facilitate the technology to be more accessible, consequently increasing the acceptance rate. Combining different renewable energies with hydrogen fueling station is further advantageous in terms of net metering [2]. Industries and governments are making an extra effort by improving the codes and standards for safe operation of hydrogen infrastructure.

EcoCAR – The NeXt Challenge is a three-year North America's premier collegiate advanced vehicle technology competition which began in the fall of 2008. Four hundred schools participated in this challenge and Missouri S&T was one of the two teams chosen to engineer a hydrogen fuel cell vehicle. The challenge is sponsored by General Motors (GM), U.S. Department of Energy (DOE) and Argonne National Laboratory (ANL), as well as by Natural Resources Canada and other industrial leaders. This competition challenges the students from different universities to re-engineer a light duty GM vehicle, minimizing energy consumption, emissions and greenhouse gases while maintaining the vehicle's utility, safety and performance [3]. It gives an opportunity to the graduate and undergraduate students to improve their understanding of fuel cell and electric hybrid vehicles and the necessary research and development required. Into the third year of the competition, Missouri S&T EcoCAR team has designed, built, and integrated a hydrogen fuel cell as their advanced propulsion technology to create a Plug-in Hybrid Electric Vehicle [4].

The ("E^3=C" i.e. Energy, Environment and Education equals Civilization) E^3 Commons at Missouri S&T is selected as the demonstration site for this paper. Figure 1 shows the E^3 Commons facility which consists of an EcoCAR garage, transit depot, hydrogen fueling station and a residential size building. Missouri S&T in partnership with the Missouri Transportation Institute established this hydrogen test bed to develop, demonstrate, evaluate and promote the hydrogen technologies. The hydrogen fueling station consists of the electrolyzer, high pressure compressor, hydrogen storage tanks, stationary PEM fuel cell and a hydrogen dispenser. The detached two car garage is used as a center for the EcoCAR team's activities wherein the team works on the fabrication and assembly of the various powertrain components. The residential building houses the EcoCAR team offices and training area. The photovoltaic panels are installed on the transit depot to generate renewable power. The modeling and simulation lab located in the transit depot, provides the team with the latest simulation softwares required to model and assemble the powertrain components to obtain an optimal design [5].

Figure 1 – E^3 Commons

2. SOLAR POWERED RESIDENTIAL UNIT

Missouri S&T's renewable energy transit depot is a green building which is fabricated from four recycled shipping containers and is used as a residential unit for EcoCAR team. The overall design of the residential unit highlights the strategies for sustainable site development, water and energy savings, material and resource selection, and improvement in the indoor environmental quality [6].

Figure 2 shows the arrangement of solar photovoltaic panels on the shipping containers. The transit depot is a multi-functional building, serving as an office and training space to Missouri S&T EcoCAR team. The total area occupied by the four containers is 1,100 square feet.

Figure 2 – Residential building

Sixteen photovoltaic panels are used to generate 2.3 kW to power residential unit, battery charging station and other auxiliary systems. Table 1 lists the specifications of solar panels used for the power generation.

Table 1 – Specification of solar panels [7]

Component	**Photovoltaic Solar Laminate**
Manufacturer	UNI-SOLAR
Model	PVL-144
Rated Power	144 W
Quantity	16
Total Power Generated	2.3 kW

3. CHARGING STATION

The vehicle charging unit provided by Aerovironment is used to charge the PHEV located outside the garage. The charging unit uses an industry-approved SAE J1772 connector. The EVSE-RS charging model, shown in Figure 3, is designed to be compatible with EVs and PHEVs from all major automakers [8].

Figure 3 – AeroVironment charging station

4. ECOCAR GARAGE

The EcoCAR garage serves as a hydrogen research and development area to support the Missouri S&T EcoCAR team in building FC-PHEV. This garage is utilized to work on the fabrication and assembly of the powertrain components. The Missouri S&T EcoCAR garage is a 12.2 m x 7.6 m garage, and is classified as a Class 1 Division 2, Group B hazardous location. It consists of a 5 kW DC power source for 7.5 kW DC load EV testing and 8000 lb two post hydraulic vehicle lift. The garage shown in Figure 4 is inclusive of heating and ventilation unit, safety alarms, security cameras and compressed air systems [9].

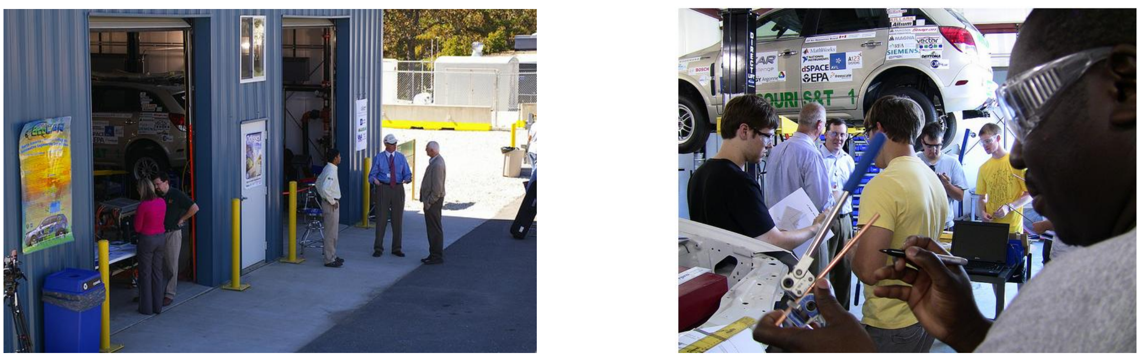

Figure 4 – Missouri S&T EcoCAR garage

4.1 FC-PHEV DEVELOPMENT

The standard production vehicle has to be transformed into hydrogen Fuel Cell Plug-in Hybrid Electric Vehicle. The major powertrain components of FC-PHEV are 95 kW Chevrolet Equinox Fuel cell and the 110 kW peak load Electric Traction System, provided by General Motors. It also includes an Electrical Storage System (ESS) comprising of five prismatic 16.1 kWh lithium-ion battery modules donated by A123 Systems. The ESS is a split pack with the front pack containing 3 modules and the rear pack containing 2 modules. The ESS weighs 150 kg and operates within a voltage range of 312.5 V – 450 V. The battery modules store the energy from regenerative braking and thus provide additional power to the electric motor. The Hydrogen Storage System (HSS) located between the two sets of ESS modules stores 4 kg of hydrogen fuel by pressurizing the gas at 700 bar and 15°C. The total mass of the HSS inclusive of three hydrogen cylinders (Outer diameter: 391.5 mm; Length: 737.5 mm) is 191 kg. The cylinders are made up of carbon composites with inside layer of steel [10].

4.2 EcoCAR GARAGE COMPONENTS

The garage is equipped with lighting, heating, hydrogen detection and ventilation. It is supplied with 3 phase 480 VAC, 240 VAC and 120 VAC power. The design for lighting and the electrical layout has been provided by Killark, a leading manufacturer of electrical construction products for standard, harsh and hazardous environments. The equipment required for the integration of powertrain components into the vehicle are vehicle lift, battery charging stations, air compressor, laptops and others. The electrical equipment in the garage conforms to Article 501 of NFPA 70, National Electrical Code and Class 1 Division 2, Group B [11].

4.2.1 Lighting. The recommended light levels for "medium contrast or small size" tasks based on the standards for illumination set by the Illuminating Engineering Society of North America (IESNA) is 538 lux (50 fc). Metal halide lamps are being employed since they have a higher color rendering index than high pressure sodium lamps and provide more light per fixture than LED or fluorescent lamps. In order to prevent interference with garage doors and car lift, the design uses wall mounted fixtures. This would also allow adequate lighting whether the vehicle is lifted or is on the ground.

4.2.2 Heating. The QMark ICG18041B electric heater is a wall mounted cabinet convection heater used in garage. This heater meets the Class 1 Division 2, Group B requirement of the garage. The power output of the heater is 6140 Btu/h. Its current rating is 7.5 A and voltage rating is 240 VAC [9].

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5. HYDROGEN FUELING STATION COMPONENTS

Figure 5 shows the hydrogen fueling station at the E^3 Commons facility. It consists of several components including an on-site steam methane reformer and electrolyzer, three carbon composite hydrogen storage tanks, high pressure compressor, a 350 bar hydrogen dispenser and a stationary Polymer Electrolyte Membrane (PEM) fuel cell.

Figure 5 – Hydrogen fueling station

Figure 6 provides the Piping and Instrumentation Diagram outlining major components at E^3 Commons. Hydrogen is produced on-site at 218 psi by FuelGen 12 low pressure hydrogen generator and is compressed to 6,000 psi by Hydro Pac's multi stage compressor. The compressed hydrogen is stored in three hydrogen storage tanks ST_1, ST_2 and ST_3. Check valve CV_1 ensures that hydrogen does not flow back into the electrolyzer. The stored hydrogen is then fed to the fuel cell to produce back-up power of 5,000 W. Compressed hydrogen is also supplied to the 350 bar Greenfield H_2V Refueling systems dispenser. SAE J2600 compliant dispenser is used for dispensing the hydrogen into the vehicle. Pressure safety valves and pressure transducers are attuned so that pressure inside the compressor and storage tanks are maintained at the required level. Constant flow valve administers the uniform flow of hydrogen from the storage tanks to the fuel cell and the dispenser.

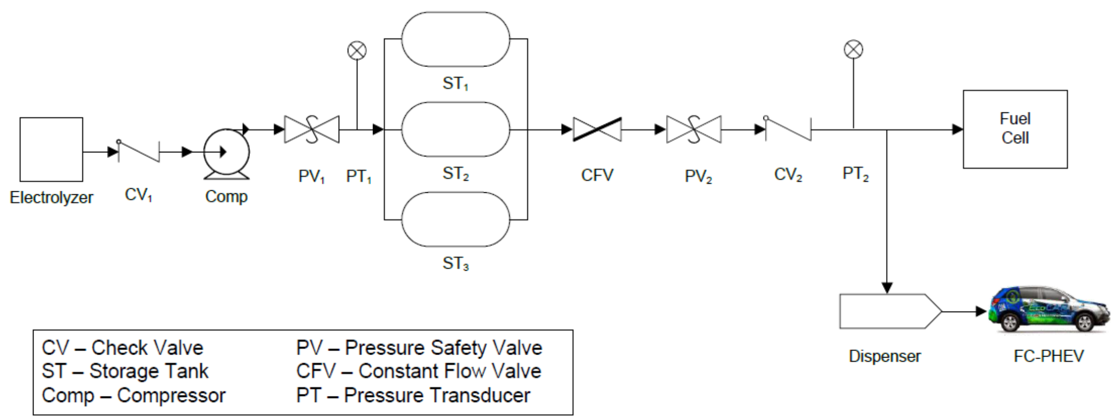

Figure 6 – Major components of residential hydrogen filling station

5.1 HYDROGEN PRODUCTION

Electrolysis of water is the method used at the E^3 Commons, where the hydrogen is produced by splitting the water molecule into hydrogen and oxygen with the help of electricity.

The Proton Energy Systems electrolyzer, employed at the facility consists of a Polymer Electrolyte Membrane (PEM) fuel cell stack producing 4.3 kg of hydrogen per day. Some of the important features of the electrolyzer include automatic tank-topping operation, on-board water purification system, integrated dew point monitoring system and remote monitoring options. Table 2 lists some of the specifications of the electrolyzer.

Table 2 – Specifications of electrolyzer [12]

Model	FuelGen 12
Production rate	4.3 kg/day
Nominal Delivery pressure	218 psig
Applicable standards	NFPA 70, NFPA 79, NFPA 69, NFPA 52
Feed water rate	54 l/h
Electrical supply	420-480 VAC

5.2 HYDROGEN COMPRESSION

The two stage high pressure Hydro- Pac's hydrogen compressor is employed to compress the hydrogen to a pressure of 6000 psig. The compressors is designed to operate over a wide range of inlet pressures and are suitable for direct as well as cascade methods of filling. Table 3 provides the important data pertaining to the hydrogen compressor.

Table 3 – Specifications of hydrogen compressor [13]

Model	C06-05-70/140LX
Type	High- pressure Gas compressor
Discharge pressure	6000 psig
Range of inlet pressure	70-140 psig
Max inlet temperature of H2 gas	27°C
Standards	ASME sec. VIII, div. 1,2,3

5.3 HYDROGEN STORAGE

The hydrogen gas is stored in steel tanks in a three bank cascade configuration having a total capacity of 33 kg. The service pressure is around 6600 psig. The pressure relief valves prevent the over-pressurizing of hydrogen in the storage tanks.

5.4 HYDROGEN DISPENSING

A 350 bar hydrogen dispenser is used to dispense hydrogen to FC-PHEV. The dispenser is by Greenfield H_2V Refueling systems and is complaint with NFPA 52 and SAE J2600 as per SAE TIR J2601 protocols. The dispensing is based on Gas Technology Institute's (GTI) patented Hydrofill technology [14].

5.5 FUEL CELL

Plug power GenCore fuel cell is used to provide back-up power to the facility over a wide range of operating environments. The design is robust and it operates over a range of -40°C to 46°C. The net power output of the fuel cell is 5,000 W which is used to provide backup power for the residential unit; hydrogen detection and ventilation systems, emergency lighting and security cameras in the EcoCAR garage. The additional backup power can be used to generate electricity to power the electrolyzer at the hydrogen fueling station and to recharge the batteries of FC-PHEV. The GenCore stationary fuel cell which is CE certified and of a FCC Class A standard. Table 4 details some of the characteristics of fuel cell.

Table 4 – Characteristics of fuel cell [15]

Model	GenCore 5U120
Rated Net Output	5,000 W
Fuel Consumption	75 slpm or 9 kg/day
Temperature range	-40°C to 46°C
Sensors	Gas hazard detection, low fuel alarm
Emissions	Water : Maximum 1.75 liters per hour CO, CO_2, NO_X, SO_2 : Less than 1ppm

6. SAFETY ANALYSIS

Safety is the primary concern for the operation of any residential hydrogen filling station. Any failure or accident leads to negative perception among the public regarding hydrogen systems and can adversely impact the commercialization of this technology. Special concerns are taken to identify and mitigate the risks, and prove it as a viable source of energy [16]. Different failure modes applicable to hydrogen components at the E^3 Commons are summarized inTable 5.

Table 5 – Fundamental failure mode analysis

Equipment	Potential Failure modes	Potential effects of failure	Safety features and prevention
Hydrogen fueling station	Hydrogen leaks, equipment fault	Fire and combustion of hydrogen	Hydrogen leak detection system, emergency shutdown devices
Electrolyzer	Hydrogen gas leak, Water purification failure, oxygen leakage, electrolyte leak	Fire and combustion, injury, product rupture, suffocation	Hydrogen leak detection system, low fuel alarm, remote alarm and shutdown
Compressor	Overpressure, high temperature, reverse and low flow, hydrogen leak	Explosion, fire	Internal monitors and external pressure gauges to detect abnormal changes in pressure
Storage tanks	Over pressurized tanks, hydrogen leak, overfill, mechanical failure, hydrogen embrittlement	Bursting of tanks, fire and explosion, suffocation	Pressure relief valves, safety valves, emergency alarm
Fuel cell	Hydrogen leak, fuel cell degradation	Fire and combustion of hydrogen, decrease in the power output	Hydrogen leak detection system, fuel monitoring and remote system
Dispenser	Hydrogen leak, backflow of gas, leakage in hose, nozzle fault, vehicle collision, underground pipe rupture	Fire and combustion of hydrogen, other emergencies	Hydrogen sensors, emergency shutdown devices, safety valves, fuel disconnect, emergency alarm

Some of the installed safety systems include a fire suppression system, power ventilation system, hydrogen leak detection system, hydrogen flame detectors, and an alarm system with siren, strobe lights and autodial emergency response notification system.

According to NFPA 52 standards, when a maximum of one-quarter of the lower flammable limit is reached, hydrogen gas detection system should be equipped to sound a latched alarm and provide a visual indication of the same [11]. H_2Scan's HY-ALERTA™ 2600 Explosion Proof Area Hydrogen Monitor is selected for hydrogen leak detection and measures hydrogen concentrations upto 4,000 ppm. If the hydrogen concentration reaches 25% of the lower flammability limit, audible alarms with strobes will be activated, ventilation will remain on, power will be shut off, and remote security personnel will be notified [9].

Dayton 7A918 spark resistant blower is selected for the ventilation in the garage. It is rated for the hazardous location and has the motor totally enclosed and non-ventilated. The flow rate is 0.59 m^3/s (1246 cfm) and 0.44 m^3/s (922 cfm) at 6.35 mm.SP (0.250-In) and 25.4 mm.SP (1.000-In.) respectively, which is greater than garage's requirement of 0.47 m^3/s (1000 cfm) [9].

7. CONCLUSION

In the recent years, the growth of FC-PHEV technology has led to the development of hydrogen infrastructure around the world. Fuel cells used in combination with solar energy assist in advancing the global energy security; improve energy efficiency and offer an opportunity for sustainable economic growth. At the E^3 Commons, the EcoCAR garage is fully equipped to handle the development of hydrogen FC-PHEV. The power produced (2.3 kW) from photovoltaic solar laminates runs auxiliary devices along with providing power to the residential unit. Safety analysis of the various hydrogen systems was performed; installed safety systems and the potential failure modes have been discussed.

8. ACKNOWLEDGEMENT

The authors would like to take this opportunity to convey our sincere regards and gratitude to our Graduate Research Advisor, Dr. John W. Sheffield for introducing and guiding us through the area of fuel cell technology and hydrogen applications. They would also like to thank Mathew Thomas and fellow EcoCAR team members for providing the support and sharing their technical expertise during this period.

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2. CONCLUSIONS

This article describes the conceptual design of a residential hydrogen fueling station at Wallingford, Connecticut. Sixty solar panels generate 90 kWh/day or approximately 94.7% of the electricity required by the hydrogen home. A well-to-wheel analysis is performed and the carbon dioxide emissions produced by a fuel cell vehicle is also computed which is approximately 13% of a conventional gasoline vehicle. Hydrogen safety is a critical area and has been extensively addressed through this article. The design also deals with failure modes and the safety procedures have been followed in and around the residential hydrogen fueling station. The emissions of a fuel cell vehicle and gasoline vehicle have been compared using GREET analysis software. Onboard vehicle storage of hydrogen, cost and durability of fuel cells are some of the challenges facing the commercialization of fuel cell vehicles.

The second paper explains the residential hydrogen fueling station facility at E^3 Commons. 2.3 kW is produced from solar photovoltaic solar laminates installed over the residential building which powers auxiliary devices of the hydrogen fueling station along with powering the residential unit. The facility also consists of a two-car detached garage or EcoCAR garage which is fully equipped to handle the development of hydrogen FC-PHEV.

APPENDIX

National Hydrogen Association 2011 Hydrogen Student Design Report

2010-2011 Hydrogen Student Design Contest:

Residential Fueling with Hydrogen

Missouri University of Science and Technology

Design Report

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Executive Summary

Interest towards hydrogen and fuel cell technologies has been growing in the past few decades. Even though there is a rising trend in the use of hydrogen fuel cells for stationary power and material handling applications, the number of fuel cell vehicles and commercial hydrogen fueling stations are relatively low. A major obstacle for the transition to using hydrogen as a fuel is the lack of hydrogen fueling infrastructure. An innovative solution to this problem may be the development of a residential hydrogen fueling system. With residential fueling, the customers will be able to fill hydrogen vehicles at their residence and will not have to depend on the large scale commercial deployment of hydrogen fueling stations.

This design introduces hydrogen refueling systems into residential settings, allowing the general public to readily embrace hydrogen technology as its use becomes more prevalent. Since residential hydrogen fueling system is a relatively new concept, the ultimate goal is to make the incorporation of the refueling system as convenient, safe, and user-friendly as possible. The Missouri University of Science and Technology (Missouri S&T) team investigated different options for producing, compressing, storing, and dispensing hydrogen. Specifically, the team analyzed hydrogen production from natural gas reformation, water electrolysis using renewable energy, high pressure compression, need for hydrogen storage, and benefits of slow versus fast dispensing. The team selected a high pressure hydrogen generator to produce on-site hydrogen from renewable energy produced from solar panels. The hydrogen is stored in three hydrogen cylinders and is fueled directly into the vehicle through cascading via SAE J2600 connection. The design follows the SAE TIR J2601 fueling protocol for light duty gaseous hydrogen surface vehicles. The hydrogen technologies and systems selected are commercially available and possible to implement for practical, real-world use by February 2011.

Residential hydrogen fueling for three different settings is portrayed in this report with primary focus on a newly constructed house in Wallingford, Connecticut. The design adheres to all local, national, and model codes and standards. Comprehensive safety analysis was performed for the safe installation and operation of the residential fueling system. An economic and environmental analysis was also completed to compare hydrogen and conventional vehicle technologies. Finally, a marketing and education plan was prepared to raise awareness of the benefits of the hydrogen and fuel cell technologies and attract new customers for residential hydrogen fueling.

1.0 Introduction

The past few decades saw a rise in interest in hydrogen infrastructure and hydrogen powered vehicles. Part of this is due to high gasoline prices, environmental consciousness, improvement in hydrogen technologies, and desire for higher efficiency, safety, and energy security. Even though major automotive companies and energy companies have invested heavily into the hydrogen transportation sector, transition to using hydrogen as a fuel has been very slow. A major obstacle to this transition is the lack of hydrogen fueling infrastructure. An innovative solution to this problem may be the development of a residential hydrogen fueling system. With residential fueling, the customers will be able to fill hydrogen vehicles at their residence and will not have to depend on the large scale commercial deployment of hydrogen fueling stations.

Residential hydrogen fueling at three different settings is portrayed in this report with primary focus on a newly constructed house in Wallingford, Connecticut. All the designs use solar photovoltaic (PV) panels and produce renewable hydrogen through electrolysis. Reasons for selecting the different locations and hydrogen systems are explained in the appropriate sections. The hydrogen system was designed to fulfill the daily requirement of the hydrogen vehicle with emphasis on safety and sustainability. A safety analysis was performed to identify the major concerns and potential risks associated with the system. An economic and environmental analysis was also completed to compare hydrogen and conventional vehicle technologies. Recognizing the importance of attracting potential customers and educating general public about hydrogen technologies, a marketing and education plan was also prepared.

2.0 Residential Hydrogen Fueling Station Design

2.1 Hydrogen Home

In the early stages of the design process, several locations which have existing or developing hydrogen infrastructure were considered for the location of the Hydrogen Home. As a result of this initial evaluation, the team chose to focus primarily on designing a new-construction single family residence located in a region that is not considered to have the best return on investment for solar equipment. The team proved that the concept is feasible in a difficult climate and it follows that it is possible to deliver designs, which have the possibility for greater returns, in locations with more hours of annual solar exposure.

The Hydrogen Home is a contemporary single family home located in Wallingford, Connecticut. Wallingford has experienced a significant development of local hydrogen infrastructure by Proton Energy Systems and the Hydrogen Highway which will connect the hydrogen home to the growing community of hydrogen users and services on the east coast of the United States. Since this technology has already been introduced to the local market, it is expected that there will be a greater public acceptance of hydrogen technology in a residential setting.

In addition to the new-construction Hydrogen Home, a second residence in Connecticut was designed to illustrate how a hydrogen refueling system could be incorporated into an existing structure. A bed & breakfast was selected because it would allow for guests to become familiar with the hydrogen technology in a comfortable and familiar atmosphere, as well as provide a destination for drivers of hydrogen and electric vehicles traveling on the Hydrogen Highway.

A third design was developed in Burbank, California to illustrate the home hydrogen refueling system being utilized in a completely different climate than the northeastern United States. The Los Angeles region provides an ideal atmosphere for a hydrogen home due to its existing hydrogen infrastructure and a higher public awareness and acceptance of hydrogen technology. Socio-economic conditions of the Burbank area also make it a prime location for incorporating renewable energy systems into a home.

2.1.1 New Hydrogen Home in Wallingford, CT

The Hydrogen Home design is inspired by New England's strong architectural heritage with steep sloped roofs and traditional exterior finishes while incorporating contemporary sustainable building systems throughout the structure (Figure 1-2). The home's blue metal roofing provides not only a durable and economic roof, but it also gives visitors and guests a visual clue that this home is not just a home, it is a *Hydrogen Home*. The floor plan is designed to be ADA (American with Disabilities Act) compliant, allowing improved accessibility to it's residents by providing easily accessible appliances, an open floor plan, wide doorways and two ADA compliant bathrooms on the first floor.

A total of 60 SunPower™ 315 solar panels will be installed across the roof and the power produced from it will be used to generate renewable hydrogen through electrolysis Figure 3. The Hydrogen Home design complies with Wallingford's zoning regulations as well as all the safety codes for the hydrogen refueling system. The electrolyzer for the hydrogen production and dispenser are housed in an insulated portion of the garage. The building's design incorporates a ground source heating and cooling system to efficiently keep the interior of the home at a constant, comfortable temperature throughout the year. In order to protect the electrolyzer against freezing temperatures, a heat loop will feed back to the electrolyzer, keeping it a constant temperature of 50-55°F during the winter months. The vestibule located in the front of the house creates an "air lock" entry, minimizing the loss of conditioned air as people enter and leave the Hydrogen Home.

The Hydrogen Home design is compliant with multiple safety codes including 2003 International Residential Code put in place by Connecticut Government, National Fire Protection Association (NFPA) 52, Vehicular Fuel Systems Code, (2006), and the International Fire Code 2003. All lighting inside the garage is wall mounted and is strategically placed to satisfy the setoff distances thus eliminating any ignition sources near the hydrogen equipment. Roof vents are located on the very top of the garage, providing ample ventilation. A hydrogen detector is also installed at the highest part of the roof (Figure 4). There are no solar panels over the hydrogen equipment so that the expensive solar panel equipment will not be damaged in the extreme case of failure. The Concrete-Insulation-Concrete (C-I-C) walls utilized in the design are rated for two hour fire resistance and a fire break wall was incorporated into the garage to protect the house in the event of a failure of the equipment. The hydrogen dispenser as well as the outdoor hydrogen storage enclousure is surrounded with concrete car barriers to protect against accidental collisions into the equipment. An AC power disconnect is included in the design for the solar panels and inverters to prevent the home's solar array system from sending power to the grid when the grid is down, eliminating concern of live wires on a down power line.

Figure 1. New Hydrogen Home in Wallingford, CT

Figure 2. New Hydrogen Home in Wallingford, CT (front view)

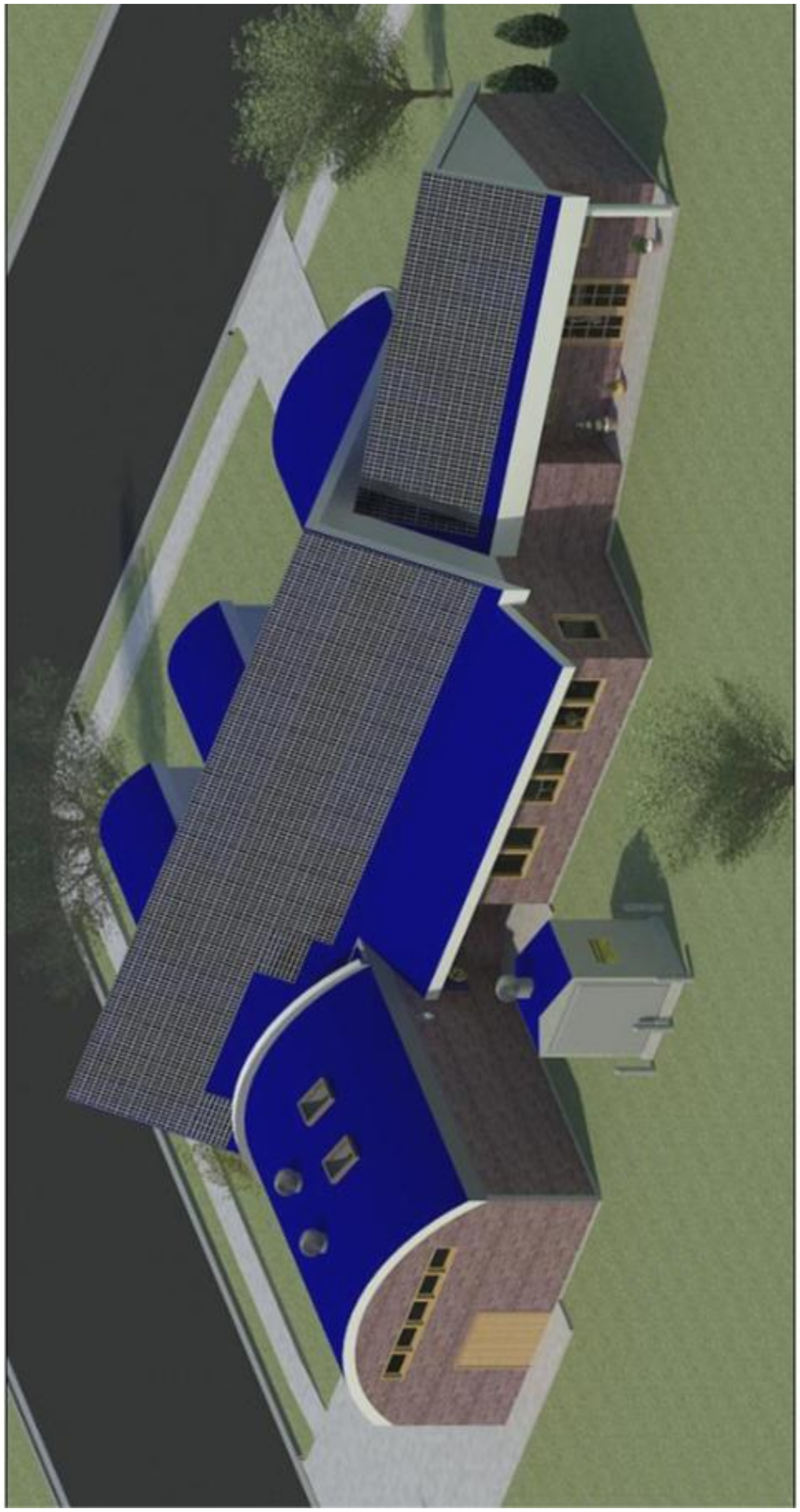

Figure 3. New Hydrogen Home in Wallingford, CT (solar panels, garage, and hydrogen storage)

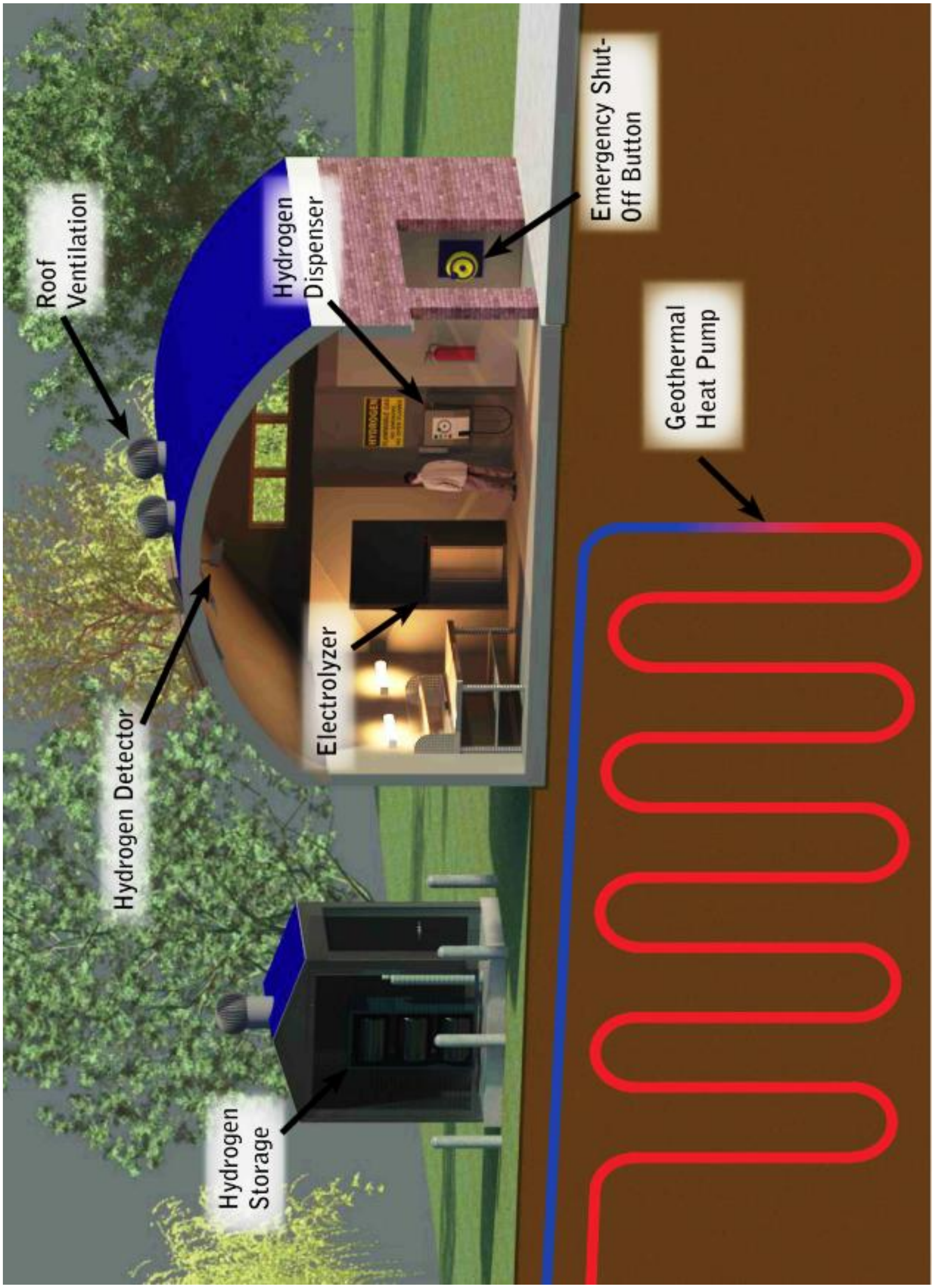

Figure 4. Hydrogen System at Hydrogen Home

2.1.2 Bed & Breakfast in Wallingford, CT

The bed & breakfast is designed to illustrate how the hydrogen refueling system can be incorporated into an existing home in the New England area. The bed & breakfast design complies with Wallingford's zoning regulations as well as all the safety codes for the hydrogen refueling system. Similar to the new construction house, the bed and breakfast boasts 48 solar panels affixed to the back roof facing south allowing for the home to produce renewable energy for the house and hydrogen production equipment. Additional equipment needed for the solar panels are housed in the attic space, keeping transmission loss minimal between the solar panels and inverter.

The electrolyzer for the hydrogen production is housed in an insulated portion of the garage. In order to protect it against freezing temperatures, a solar thermal water heating system has been included. Similar to the solar panels, the solar water heater panels face south to capture the greatest amount of heat from the sun, heating the water (Figure 5). Once the water has been heated, it is directed back to a radiant heat floor system in the concrete slab in the room where the electrolyzer is stored. This system will pre-heat the concrete slab in the daytime hours, warming the concrete and allowing the floor slab to retain heat during cold New England winter nights. A thermostat is located in the room monitoring the temperature. If there is a severe storm and the room temperature drops below 50°F, the system will begin heating the floor utilizing the home's hot water tank as an auxiliary heat source.

The bed & breakfast can accommodate both electrical and hydrogen fuel cell vehicles. The parking area includes four charging stations for electric vehicles and can be expanded if more are desired (Figure 6). Hydrogen vehicle fueling will be offered in the attached garage through the wall dispenser system. Approximately one car per day can be filled.

The estimate to add a hydrogen garage to a home with no garage accommodations is $400,000. With federal tax incentives for solar panels, that drops to roughly $370,000. The system includes high pressure electrolyzer, storage tanks, priority panels, solar panels, inverter, solar thermal heating for the radiant floor and building the whole two car plus work area garage. Capital cost of the equipment will be discussed in detail in the economic analysis and business plan section.

2.1.3 Hydrogen Home in Burbank, CA

The Burbank, California house illustrates how easy incorporating the hydrogen storage house is in a warm weather climate. Concerns of keeping the electrolyzer from freezing are nonexistent in the western climate. The electrolyzer and dispenser fit seamlessly into the garage, while the hydrogen storage shed is placed behind the garage. The return on investment of solar equipment is higher due to ample sunlight in southern California climate as well as reduced heating and cooling costs on structure. The excess power produced by the solar panels is put back into the grid via net metering.

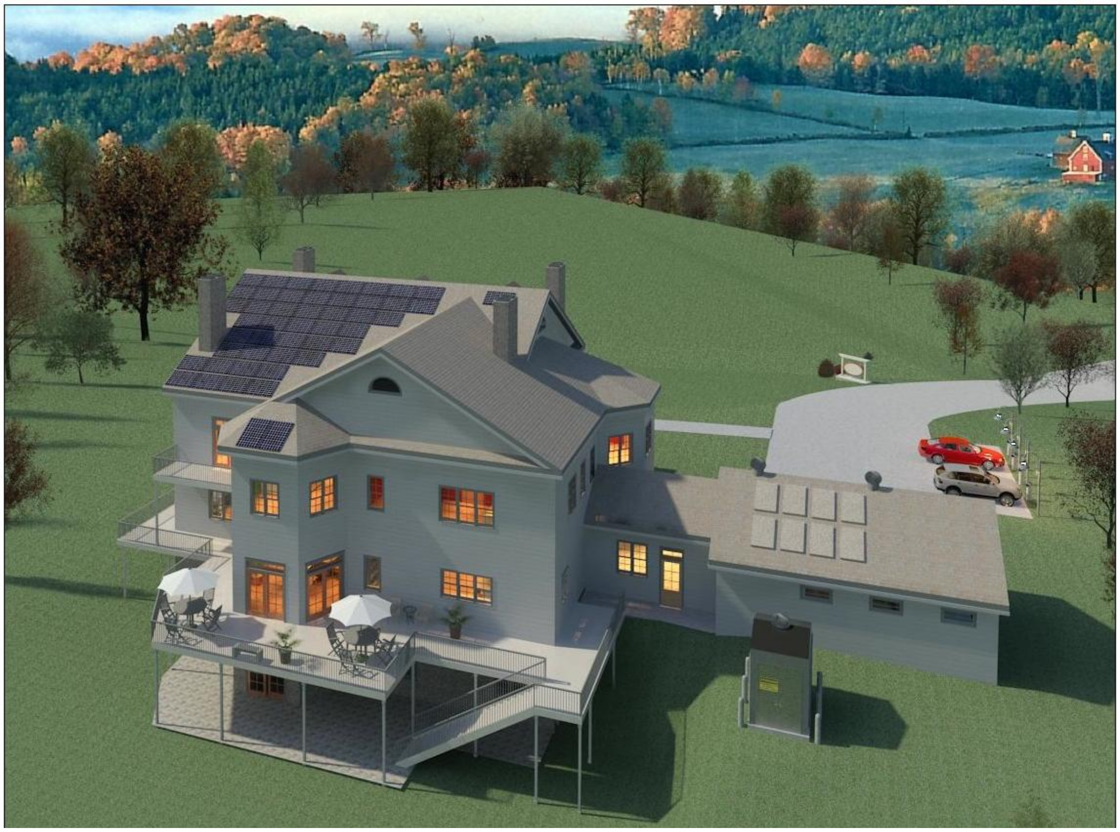

Figure 5. Bed & Breakfast in Wallingford, CT (solar panels, garage, and hydrogen storage)

Figure 6. Bed & Breakfast in Wallingford, CT (parking lot with electric charging stations)

2.2 Hydrogen System Components

The major components of the residential hydrogen fueling station consist of on-site renewable hydrogen production through electrolysis, hydrogen storage, and a dispenser. The factors leading to the selection of these components are discussed in the following sections. Figure 7 shows the major equipment used for residential hydrogen fueling.

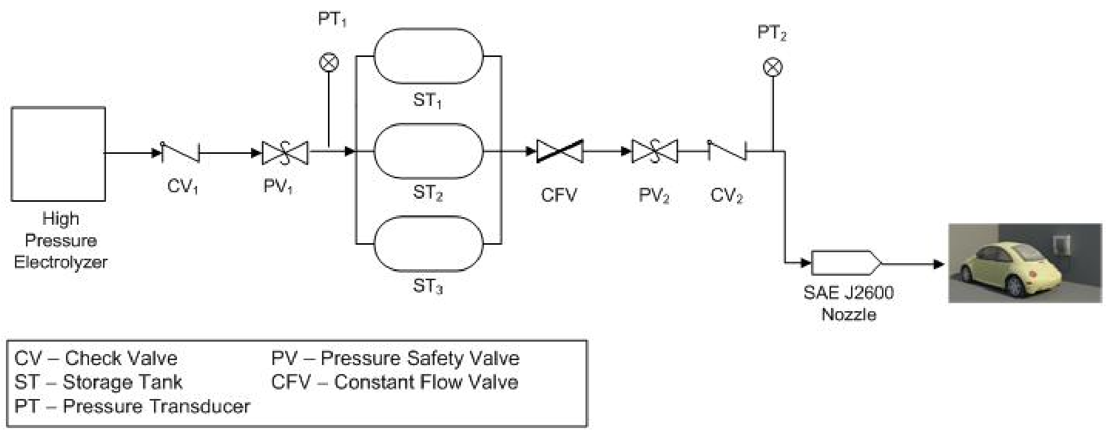

Figure 7. Major components of the residential hydrogen fueling station

Hydrogen is produced on-site at 2,400 psi by a HOGEN® HP 40 high pressure hydrogen generator and is stored in three hydrogen storage tanks ST1, ST2, and ST3. Check valve CV1 ensures that hydrogen does not flow back into the electrolyzer under any circumstance. The set point of the electrolyzer is adjusted such that the unit will turn 'On' if the pressure in any of the three tanks falls below 2,000 psi and will turn 'Off' when all the three storage tanks reach 2,400 psi. A hydrogen priority panel designed by Gas Technology Institute (GTI) is used to prioritize filling of the three hydrogen storage tanks and sequence the flow of hydrogen from the storage tanks to the dispenser. This system is designed such that the maximum allowable ramp rate (MARR) is not exceeded during hydrogen dispensing. Pressure transducer PT2 determines the pressure inside the on-board vehicle storage tank and vehicle fueling is initiated only if it is less than the pressure inside the hydrogen storage tanks. A nozzle complaint with SAE J2600 standard is used for dispensing the hydrogen into the vehicle.

2.2.1 Vehicle Parameters

The residential hydrogen fueling system was designed primarily for hydrogen vehicles that follow non communication fill protocol and will be able to partially fill vehicles with 5,000 psi or 10,000 psi storage tanks. The hydrogen vehicle requirements described in the completion rules is shown in Table 1. Based on the competition rules, the daily commute of the vehicle is 35 miles and the vehicle fuel mileage is 44 miles per kilogram of hydrogen. Therefore the daily hydrogen demand is 0.8 kg of hydrogen. Cascading results and the amount of hydrogen transferred into the vehicle is discussed in Section 2.2.3. During the design, it was assumed the total on-board storage capacity of the vehicle is 4.2 kg of gaseous hydrogen at 5,000 psi.

Table 1. Hydrogen Vehicle Requirements

Parameter	Value
Annual Mileage	12,000 miles
Daily Commute	35 miles total
Fuel Economy	44 miles per kilogram
Daily Requirement	0.8 kilogram of hydrogen

2.2.2 Hydrogen Production

Various hydrogen production alternatives were investigated during the design in order to meet the on-site hydrogen demand and are discussed below.

1. *Steam-Methane Reformation* – In this process, natural gas or methane is reacted with the steam forming hydrogen and carbon dioxide as the end products. Though it has an efficiency of up to 80%, it cannot be selected due to the following reasons:

a. The reaction results in the emissions of carbon dioxide which is a greenhouse gas.
b. A very high temperature of 1,100 °C is required to support steam-methane reaction.
c. Price of natural gas is highly fluctuating, thus the cost of hydrogen produced is very unreliable.
d. High capital cost and low efficiency of small steam methane reformation system. Capital cost was estimated to be $750/kW for 1 million scf/day (2,544 kg/day) and $4,000/kW for 100,000 scf/day (254 kg/day) steam methane reformation system respectively[1]. This is only expected to increase as the capacity decreases.

2. *Reversible PEM Fuel Cell* – Hydrogen can also be generated by operating a reversible fuel cell as an electrolyzer. Due to the inefficiency associated with the reversible fuel cells, this method is only economical if hydrogen is produced during off-peak periods or if electricity is produced during peak periods. It was not chosen as there are currently no commercially available reversible PEM fuel cells capable of producing at least 1 kg/day of hydrogen.

3. *Low-Temperature Electrolysis* – Hydrogen can be generated by splitting water into hydrogen and oxygen using electricity. This method is preferred due of the following reasons:

a. There are no carbon dioxide emissions if the electrolyzer is coupled with renewable energy sources
b. A fairly low temperature of less than 100 °C is involved
c. Cost of hydrogen depends more on electricity which is fairly stable
d. Capital cost is estimated to be $2,000/kW-$4,000/kW for 3-12 kg/day[1]. This is expected to decrease with technological advancements.

Based on the research and calculated values, HOGEN® HP 40 high pressure hydrogen generator (Figure 8) was chosen since it has the low energy consumption, high efficiency, and high output pressure. The HOGEN® HP 40 can produce up to 2.24 kg of hydrogen per day at 2,400 psi and can be located indoors in a non hazardous/classified area. The use of high pressure electrolyzer also negates the need for a hydrogen compressor which is a major source of energy loss.

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[1] Ogden, J. Review of Small Stationary Reformers for Hydrogen Production. International Energy Agency, Report IEA/H2/TR-02/002 2002

Figure 8. HOGEN® HP 40 High Pressure Hydrogen Generator

2.2.3 Hydrogen Compression

Since the design employ a high pressure electrolyzer with an output of 2,400 psi, a hydrogen compressor is not necessary to achieve the daily fill requirement. From the cascading results (Figures 9-12) it can be seen that the total amount on hydrogen inside the onboard vehicle storage system is 1.86 kg of hydrogen (773 scf) after the fueling operation is complete. This is more than the daily requirement of 0.8 kg of hydrogen. The daily vehicle route was set to 147 miles (Figure 9) to bring down the on-board storage pressure to the 500 psi range before the fueling operation as seen in Figure 10. From these cascading results it can be seen that the vehicle can be filled in 10 minutes without the use of a compressor. This saves both capital costs and reduces operational cost of the residential hydrogen refueling.

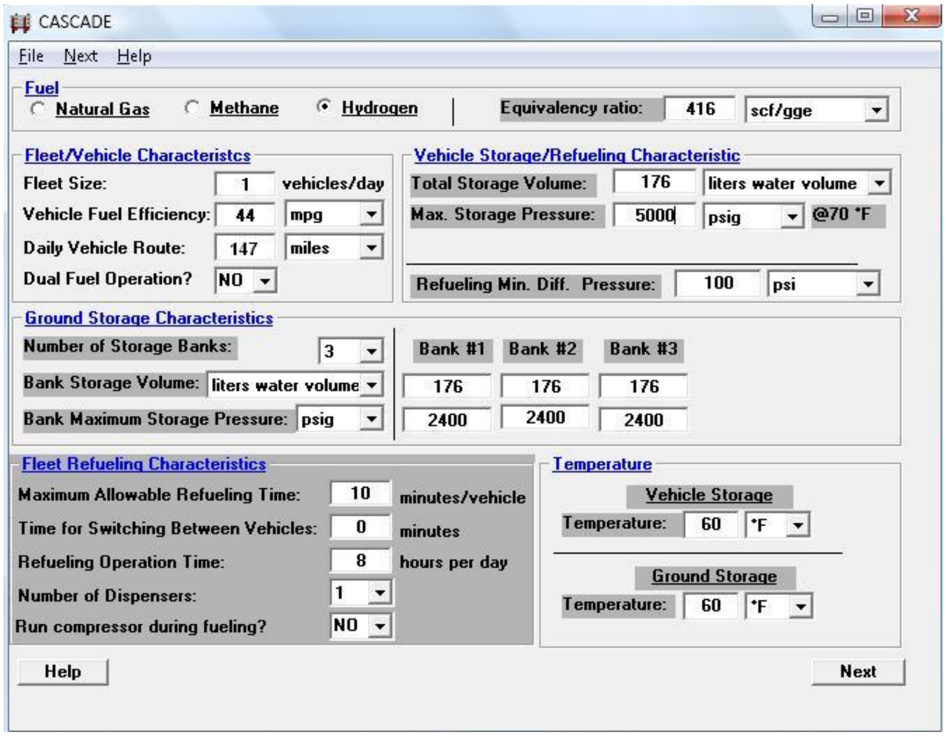


Figure 9. Cascade program input values

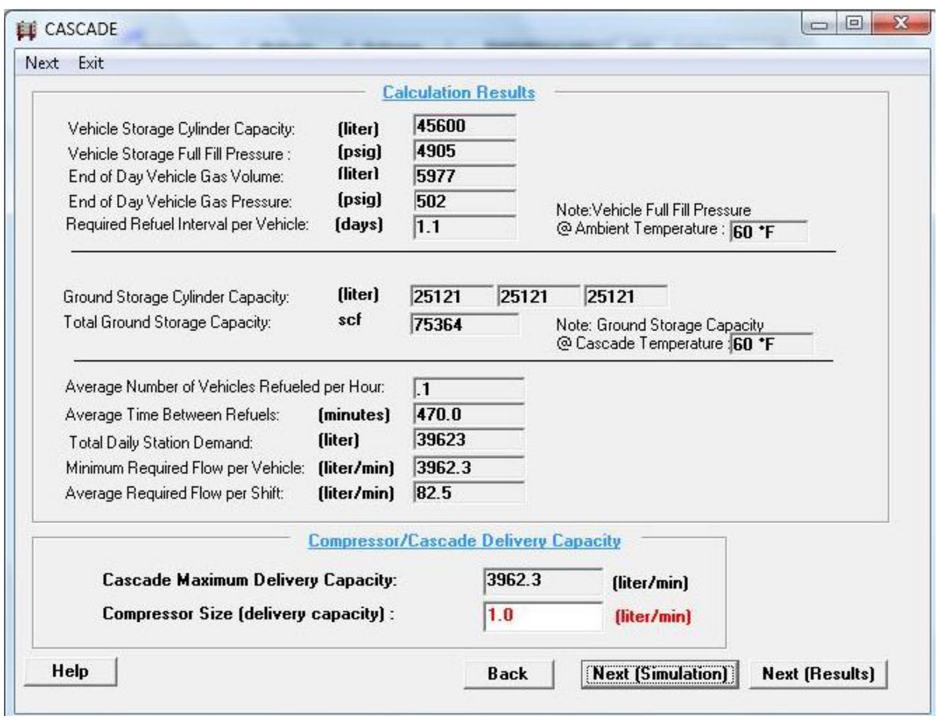


Figure 10. Cascade program calculations

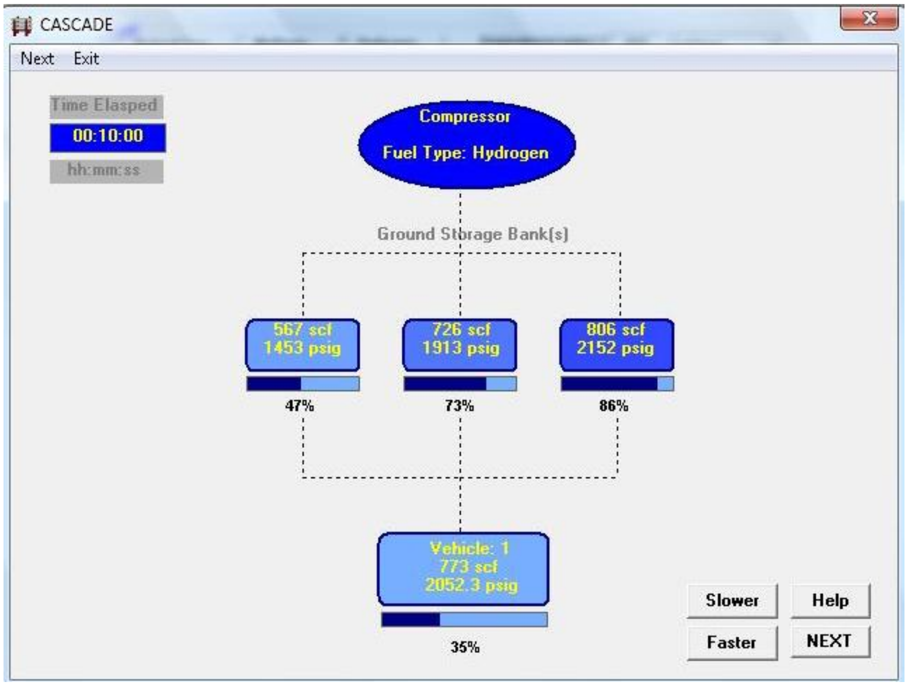


Figure 11. Cascade Simulation Results

Compressor/Storage Refueling Station Analysis

Detailed Report

File Location:

Fuel Type: Hydrogen		*Vehicle*	*Bank 1*	*Bank 2*	*Bank 3*
00:00:00	**Start filling Vehicle 1**	**Compressor->Bank**	**Bank 1 ->Vehicle**		
	Pressure (psig):	502	2,400	2,400	2,400
	Capacity (liter):	5,975	25,117	25,117	25,117
00:02:17	**Vehicle switched to Bank 2**	**Compressor->Bank**	**Bank 2->Vehicle**		
	Pressure (psig):	1,353	1,453	2,400	2,400
	Capacity (liter):	15,036	16,056	25,117	25,117
00:03:26	**Vehicle switched to Bank 3**	**Compressor->Bank**	**Bank 3->Vehicle**		
	Pressure (psig):	1,813	1,453	1,913	2,400
	Capacity (liter):	19,595	16,056	20,558	25,117
00:04:00	**Vehicle switched to Bank 0**	**Compressor->Bank**	**Bank ->Vehicle**		
	Pressure (psig):	2,052	1,453	1,913	2,152
	Capacity (liter):	21,889	16,056	20,558	22,823
00:10:00	**End filling Vehicle 1**	**Compressor->Bank**			
	Pressure (psig):	2,052	1,453	1,913	2,152
	Capacity (liter):	21,889	16,056	20,558	22,823

Figure 12. Cascade Simulation Detailed Report

2.2.4 Hydrogen Storage

Even though the daily hydrogen fueling requirement could be achieved by the high pressure electrolyzer using a 10 hour slow fill procedure, three hydrogen storage tanks were selected to complete fueling in less than 10 minutes. The storage tanks are configured to allow cascading. The storage tanks which were selected are 1.4 ZM180H350M8C-NGV2 model tanks from Dynetek Industries Ltd and are capable of storing up to 4.26 kg of hydrogen at 5,075 psi. The outer diameter of the tank is 602 mm (23.7 in) and the length is 972 mm (38.3 in). Each tank has an internal volume capacity of 176 liters of water. The storage tank is constructed of light weight composite material and can be belly or neck mounted. The storage tank is certified to the following safety standards: ISO11439, NGV2, FMVSS304, CSA B51 Part 2, and permits as appropriate by location.

2.2.5 Hydrogen Dispenser

Hydrogen dispensing will be using SAE J2600 compliant connections per SAE TIR J2601 Appendix A compliant protocols. Since the maximum rated pressure for the on-board vehicle storage will be either 5,000 psi or 10,000 psi and the maximum pressure that the residential fueling system can deliver is only 2,400 psi, the system is not expected to over-pressure and over-heat under any circumstances. The nozzle will be connected to the hydrogen priority panel using a detachable hose connection. The system ensures that the maximum allowable ramp rate (MARR) is not exceeded with the use of proper sequencing of hydrogen flow from the three storage tanks and a constant flow value. A solenoid valve and pressure transducer at the outlet of the priority panel ensure that there is no fueling in the event the storage pressure in the vehicle onboard storage system exceeds the storage pressure inside the stationary storage tank. It is advised that the fueling operation be performed after the vehicle reaches equilibrium with the ambient temperature in the garage. Since the hydrogen fueling requirement per day was less than the actual amount of hydrogen that can be transferred using the selected fueling system, a pre-packaged or commercial hydrogen 5,000 psi dispenser was not selected. This results in significant cost reduction of the hydrogen residential fueling system. The car can be fully refueled from a commercial station for occasional long distance travel of more than 35 miles.

2.2.6 Safety Equipment

Safety was the most important factor during the design of the residential hydrogen fueling system and will not be compromised. Safety equipment in the garage includes a hydrogen detector, break away hoses, easily accessible emergency shutdown buttons, remote e-stop, fire extinguishers, hydrogen storage isolation systems, pressure relief devices, etc. Safety barriers were included in the design to protect the dispenser and hydrogen equipments. Power to the garage will be disconnected in the case of hydrogen detection in the garage to prevent ignition of hydrogen from electrical sources. Emergency lights, alarm and a mechanical ventilation fan rated for hazardous locations (Class 1 Div 2, Group B) will turn ‘On’ in case of hydrogen leak detection by the gas detector.

2.2.7 Sustainable Building Systems

In order for the Hydrogen Home to be practical in the New England climate it was essential to include sustainable building systems which have synergistic interactions with each other. This choice had the effect of reducing the energy demand of the home while simultaneously increasing the comfort experienced by the home’s occupants. Natural day lighting was thoroughly incorporated into the design of the home. Dormers on the front of the home, although facing north, provide natural daylight and exterior views to the interior rooms of house and second floor bedroom. The home's ample natural daylight reduces electrical demand for artificial lighting during daylight hours.

Along with natural day lighting, photovoltaic solar panels were researched and determined to be a feasible renewable energy option in Wallingford, Connecticut. An adjustable mounting system having three settings corresponding to the seasonal optimal inclination for the panels will be used to increase the output from the solar panels. The slope of the back roof was designed to be the same as the optimal angle for solar collection during the winter months. This keeps the solar panels close against the roof, which provides the support and stability necessary to withstand heavy snowfalls and harsh winter weather conditions and reduces heat loss through the back portion of the roof. In consideration of the risk of injury due to falling ice, clips will be installed on the array in order to prevent large sheets of ice from dislodging from the solar array. During the spring, summer and fall months the angle of the solar panels will be adjusted by changing the settings on the mounting system. This mounting configuration will reduce the demand on the cooling system by providing shade to the home's roof during the summer months.

Due to the long winter in New England, great measures were taken to keep the home both energy-efficient and comfortable. Thermal performance was a top priority; hence, all windows and doors glazing incorporate triple pane glass and the walls are made of Concrete C-I-C Construction. The benefit of this wall system is that the thermal mass of the interior and exterior concrete layers are separated by foam insulation thus providing a thermal break from the exterior to the interior, keeping the home warm in the winter and cool in the summer. This wall system also reduces the transmittance of sound waves, making the interior more comfortable for its occupants. The blue raised seam metal roof and burgundy brick façade provide low albedo surfaces, which collect and retain solar thermal energy. Point-of-use water heaters for the bathroom and kitchen areas compliment the centralized plumbing design, minimizing construction costs and heat loss from pipes over long distances. The point of use water heaters will also reduce the home's demand for electric energy by eliminating the need to constantly maintain a tank of hot water throughout the year. Other efficiency measures, such as low-flow water fixtures, energy efficient light fixtures and appliances are included in the home as well, all helping to reduce the energy demand of the Hydrogen Home. A dashboard system would be incorporated into the home, providing a touch screen interface for the homeowner. This will allow the residents to easily review the home's energy consumption, energy production, set thermostat schedules and even activate the security system. The dashboard system will also be an educational tool to enlighten homeowners and their guests. The system allows the user to discover energy use patterns and provides suggestions to reduce energy consumption, ultimately saving the owner money.

3.0 Safety Analysis

Safety is of foremost importance in the design and implementation of a residential hydrogen fueling station. Proper design practices must be incorporated in order to prevent any accidents. A consistent track record of safety and reliability will cause the public to become comfortable with residential hydrogen fueling as an alternative to conventional fossil fuels. Hydrogen storage tanks and hydrogen devices including relief valves, check valves, stainless steel piping, tubing, and fittings, J2600 connections and hose, are designed to comply with all applicable safety regulations. These safety regulations include: US Department of Labor Occupational Safety and Health Administration (OSHA) - Regulations (Standards - 29 CFR)[2], Hydrogen 1910.103; ASME Boiler and Pressure Vessel Code, Section VIII; Regulations of the Department of Transportation, 49 CFR Chapter I; ANSI B31.1, "Industrial Gas and Air Piping," Section 2; NFPA 55[3], NFPA 52, and Appendix A of SAE TIR J2601.

3.1 Equipment Safety

1. Hydrogen Storage Tanks: All storage tanks are clearly labeled as hydrogen tanks as per the OSHA 1910.103 regulations. Each tank has an emergency pressure relief valve in case of extreme over-pressurization, or fire to prevent the storage of hydrogen under unsafe conditions. All stationary tanks and cylinders containing compressed gas are required to be marked in order to comply with NFPA 704.
2. Hydrogen Piping and Routing: All piping, fittings, valves, and tubing are stainless steel, as per the ANSI B31.1 specifications. The feed check valve located between the electrolyzer and the storage tanks prevents hydrogen from flowing back into the electrolyzer. The feed check valve between the storage tanks and the J2600 nozzle prevents backfilling from the car's storage tanks to the hydrogen system's storage. A pressure transducer is located before the storage tanks to maintain the pressure at 2,400 psi.
3. J2600 Nozzle: The J2600 type nozzle is a standard connection type for hydrogen fueled vehicles. A breakaway hose that stays connected to the vehicle but breaks away from the priority panel housing in case of vehicle driveway is used in the design. To prevent any chance of static discharge ignition of hydrogen, a grounding system will be used on all equipment.
4. Sensor: Sensor that detects hydrogen will be installed at the highest part of the garage. If the sensor is activated, the fueling operation will be stopped, the storage tanks will be isolated, the electrolyzer will be shutoff, and power to the garage section will be disconnected. An automatic emergency light will come on in with an audible alarm in the event of hydrogen gas detection in the garage.

3.2 Procedure Safety

1. Maintenance and Replacement: In order to ensure optimal safety and performance, weekly visual inspections by a trained operator are required. In the event that the fueling nozzle becomes worn or the fueling hose shows surface cracks, each one must be replaced. Other components must also be replaced as necessary.
2. Safety schematic: A chart depicting potential hazards and risks involved, and the safety measures undertaken to prevent them should be displayed in and around the fueling area to reduce the likelihood of any accidents.

3.3 Significant Safety Risks and Solutions

The fueling system meets all applicable specifications and regulations; however due to human errors and interactions, material failures, and unpredictable events such as lightning, fueling system failure could still occur. Table 2 contains the failures deemed most significant and steps that could be taken in order to prevent those failures.

Table 2. Significant Failure Modes

Failure Mode	Source/Cause	Severity of Failure	Frequency of Failure	Failure Prevention
Car collision with storage tanks or fueling nozzle	Mechanical failure	Ultimate failure; Severe	2	Concrete barrier must be placed around the hydrogen storage tanks, and fueling nozzle must be placed above an impact area.
Slow leak of hydrogen gas	Mechanical failure, improper connection	Partial system failure; Potentially severe	3	Hydrogen detection system and sensors which stop fueling in case of a leak. Allowing natural ventilation to prevent any accumulated gas.
Open flame or smoke	High Flammability	Ultimate failure; Severe	2	Signs will be posted in areas with flammable compressed gas. Smoking or use of open flame should be prohibited within 7.6 m or 25 feet of the storage area[4].
Falling or knocking over of the compressed tanks	Mechanical failure	Ultimate failure; Less severe	3	Securing of the tanks to a frame or fixed object.
Hydrogen leak through hoses and connectors	Human error/ Mechanical failure	Partial system failure; Less severe	2	Personnel training on equipment handling. Regular inspection of hoses and connectors to prevent gas leakage. A checklist to be maintained for additional safety purposes.
Explosion due to combustion of hydrogen	Pressurized hydrogen	Ultimate failure; Most severe	1	Infrared sensors to be installed to detect the hydrogen flame. Detached or structurally isolated hydrogen equipment will limit the risk of loss of life and property.
Hydrogen overfill	Human error	Partial system failure; Less severe	2	Measures taken to avoid overfill may include employment of trained personnel, alarms and hydrogen sensors.

4.0 Economic Analysis/Business Plan

The economic and business plan analysis includes capital cost and installation for all equipments, operating cost, maintenance cost, and business plan for residential hydrogen fueling.

4.1 Capital and Installation Costs

The most important item in the residential hydrogen fueling system is the high pressure electrolyzer and is estimated to cost approximately $200,000. Additional costs include capital cost of hydrogen storage tanks, priority panel, and balance of the plant (BOP) equipment including piping, check values, pressure transducers, hose, nozzle, etc. Cost of safety equipments including hydrogen detection system, emergency lighting, fire extinguisher, mechanical ventilation system are also included in the capital cost of hydrogen equipment and is given in Table 3. Installation cost is assumed to be 10% of the capital cost of the system.

Table 3. Capital Costs of Residential Hydrogen Fueling Equipment

Item	**Cost**
HOGEN® HP 40	$200,000
Hydrogen Storage Tanks	$23,000
Priority Panel and BOP	$10,000
Safety Equipments	$7,000
Installation	$24,000
Total	**$264,000**

Capital costs may be offset by applicable rebates at the time of installation. The solar panels cost approximately $1,500 per panel and the inverters cost approximately $18,000. The total cost of the 60 panel solar power system comes to $75,600 after 30% federal incentives.

4.2 Operating and Maintenance Costs

The residential price of electricity averaged over summer and winter for Wallingford, CT in 2010 was 10.47 cents/kWh for the first 700 kWh and 10.61 cents/kWh over 700 kWh [5]. Table 4 shows the price of hydrogen if it was produced using power from the electric grid. Since the house is powered using grid connected solar panel system, the total power output of the solar panel system and the total power demand of Hydrogen Home must be considered before performing the economic analysis. The anticipated demand of the Hydrogen Home is 95 kWh per day, assuming average power consumption of the house to be 630 kWh/month (21 kWh/day) and the power consumption of the hydrogen system to be 74 kWh/day. The total capacity of the solar panel array is 18.90 kW and the average daily electrical output is estimated to be approximately 90 kWh assuming the useful average day light in Connecticut to be 4.74 hours. The state of Connecticut allows net metering up to 2,000 kW for residential facilities[6]. Hydrogen Home will buy power from the utility company during in the evening and night and will sell power back to them during day. The net power consumption of the home from the electric grid will be approximately 5 kWh per day.

Table 4. Price of Hydrogen

Amount (kg)	Consumption (kWh/month)	Price ($/day)	Price ($/month)	Price ($/year)	Cost ($/mile)
0.8	1776.0	6.28	188.40	2292.20	0.18
1.0	2220.0	7.85	235.50	2865.25	
1.5	3330.0	11.78	353.40	4299.70	
2.0	4440.0	15.7	471.00	5730.50	

Capital costs have not been taken into account in these calculations. Water consumption has been considered a negligible cost, as even at peak capacity, the electrolyzer consumes less than 8 gallons of water per day[7]; similarly, any power consumption by the controller has also been considered negligible in comparison to the electrolyzer. The total operating cost and savings of the Hydrogen Home assuming daily commute of 35 miles is shown in Table 5. The total savings from the solar power and hydrogen system including the hydrogen vehicle will be approximately

$4,700 per year. Amount of gasoline was calculated based on the values given in the competition rules (fuel economy of gasoline vehicle is 32.6 mpg and daily commute is 35 miles). It is assumed that the cost of gasoline is $3.5 per gallon.

Table 5. Total Savings from Solar Power and Hydrogen Systems

Description	Day	Month	Year
Net Power Consumption of House (kWh)	5	150	1825
Power Generated (kWh)	90	2700	32850
Amount of Gasoline Needed (gal)	1.07	32.10	390.55
Energy Cost ($)	0.53	15.90	193.45
Energy Saving ($)	9.55	286.50	3485.75
Fuel Cost Saving ($)	3.76	112.80	1372.40
Total Savings ($)	**12.78**	**383.40**	**4664.70**

Table 6 show a comparison between gasoline, hydrogen produced using power from electric grid, and renewable hydrogen produced using solar power. It can be seen that renewable hydrogen has the lowest operational cost followed by gasoline and hydrogen generated using power from electric grid.

Table 6. Comparison between Gasoline and Hydrogen

	Gasoline	H_2 Grid Power	Renewable H_2
Annual Mileage (miles)	12,000	12,000	12,000
Fuel Economy (mpg or mpkg)	32.6	44	44
Price ($/gallon or $/kg)	3.5	7.85	0
Cost ($/mile)	0.107	0.18	0
Total Annual Cost ($)	1,284	2,160	0

4.3 Marketing

As a package, the filling system would be priced at approximately $264,000 before any applicable rebates and incentives; this figure should cover all required components as well as any necessary overhead. Market prospectus for these systems appears very optimistic. The relatively low cost of installation and maintenance, simple system and possibility for zero, possibly even negative, net cost for day-to-day operation of a vehicle in the intended range regardless of current fuel prices is highly attractive. The most prohibitive factor to the system in the current state is the high capital cost associated with the system, even with rebates the system presents a large initial expenditure that even zero-cost operation cannot overcome.

5.0 Environmental Analysis

The design utilizes renewable energy produced from the solar panels to produce hydrogen through electrolysis. Table 7 compares the annual green house gas emissions from gasoline, hydrogen produced from grid power, and renewable hydrogen produced from solar power. It may be noted that the emissions data used were specific to Wallingford, CT (PPL Wallingford Energy, LLC)[8]. It may also be noted that the emissions from the manufacturing of the various components have not been taken into account in these calculations.

Table 7. Annual Green House Gas Emissions

	Power Consumption (kWh)	Amount of CO_2 (kg)	Amount of SO_2 (kg)	Amount of NO_x (kg)
H_2 Grid Power	21,608.00	7879.50	5.35	5.90
Renewable H_2	21,608.00	0	0	0
Hydrogen Home	1,825.00	665.50	0.45	0.50

The power consumed shown in Table 8 gives the energy used for the production of each fuel. Since the residential hydrogen refueling system design does not have a compressor the energy used for compression is zero. Energy necessary for operating the control system is negligible when compared to the energy used for hydrogen production.

Table 8. Well-to-Tank Analysis

Fuel	**Amount of CO_2 (kg/mile)**
Gasoline	0.422
H_2 Grid Power	0.610
Renewable H_2	0

6.0 Marketing Plan and Educational Plan

6.1 Marketing Plan

Commercialization and market penetration of energy production by hydrogen fuel and its applications depends on a variety of factors such as efficiency, cost, performance, storage density and most importantly safety. The technological breakthroughs achieved in developing hydrogen as a fuel will also help in galvanizing hydrogen energy programs around the world. In addition to providing benefits to consumers of various hydrogen fueled products, the key objective of marketing is to instill the idea of hydrogen economy into the minds of the general public. The community should be provided with credible information regarding the safety aspects considered during the design of the residential hydrogen fueling station. The methods employed to emphasize the various benefits of hydrogen as a fuel and its applications for residential purposes are:

1. Promoting hydrogen fuel technologies through mass media which includes advertisements through newspapers, television and radio and more significantly internet to communicate the benefits of hydrogen. This will help in convincing the public that hydrogen energy can indeed be used to power the future. The media can also act as an interface between the government and general public, thus informing the public about the latest updates regarding the government’s view on hydrogen energy. It can also give an update on the various hydrogen programs undertaken in different parts of the world.
2. Highlighting the advantages of hydrogen over gasoline and other conventional fuels such as reduced emissions and energy independence, at a large community event. Hydrogen product distributors and suppliers can be invited to provide the necessary information about the progress made towards a potential hydrogen economy. This can include research, development and marketing of hydrogen vehicles; advancements in the field of fuel-cell technology and the proposed development in hydrogen infrastructure which includes transportation of hydrogen fuel and refueling stations.

3. Emphasizing the economic and environmental advantages of employing hydrogen as an energy source and its applications by circulating handouts at public spaces. A study conducted shows that the hydrogen generated from diverse domestic resources can reduce demand for oil by more than 11 million barrels per day by the year 2040[9].
4. The government along with the support of various public agencies should provide more tax benefits and regulatory incentives for owners of hydrogen fuel vehicles and for residents possessing hydrogen fueling stations at their homes. This will encourage public to look into the area of hydrogen as a potential replacement to conventional fuels.
5. The government and the industry should collaborate further to generate interest among the citizens to produce hydrogen by cleaner sources such as landfill gas, biogas and renewable energy sources such as sun and wind. These sources can be used to generate electricity required to power the electrolyzer to produce hydrogen which in turn can be used to run the vehicles[9]. Thus the electricity generated using solar panels and wind turbines will help the consumers by reducing energy consumption from the grid. Using localized sources of renewable energy also eliminates concerns of overburdening the existing power distribution grid as more consumers turn to hydrogen technology to meet their transportation needs. The consumer has a potential to give back the excess electricity to the grid which provides an added value for the surplus energy generated.

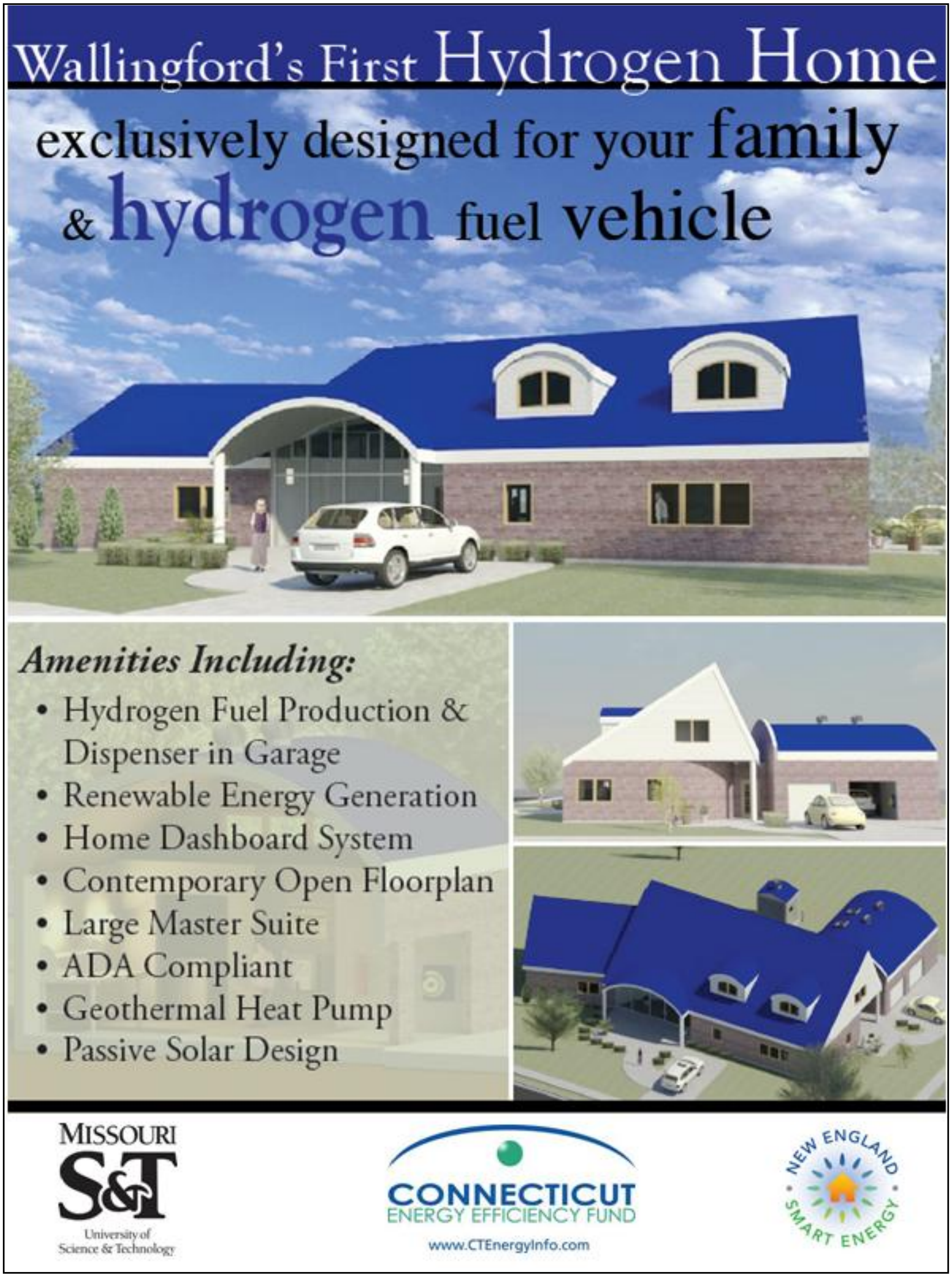
6.2 Education Plan

The vision statement of U.S. Department of Energy is “Hydrogen will become America’s clean energy choice. Hydrogen will be affordable, safe, domestically produced, and used in all sectors of the economy and in all regions of the country[11].” The education plan plays an integral role to promote hydrogen and its various applications. The overall objective of the program is to educate people about the long term benefits and sustainability associated with hydrogen as a fuel. Commercial and residential market’s growing awareness about energy efficiency, sustainability issues and our deteriorating environment leads to a desire to work in a healthy environment. The bed and breakfast facility illustrated in the report will be used as a prime location to educate the general public about hydrogen and alternative fuel technologies in a residential setting. The different strategies which can facilitate the market acceptance to achieve a basic level of understanding among the consumers are:

1. Emphasis on hydrogen as a sustainable energy source should be incorporated at different levels of education. Specific seminars and science fairs can be conducted to introduce the concept and notion of hydrogen applications and its advantages. Conferences and technical paper presentations must be organized in schools and colleges to encourage the youth to start thinking about clean energy and various benefits of hydrogen as a safe and sustainable fuel.
2. Training general public and explaining them the common myths of hydrogen to them will increase the awareness and acceptance to this technology. Essential codes and standards of operation for different processes must be made available and discussed during residential community meetings. The required safety precautions should be undertaken while demonstrating the various hydrogen technology products.
3. Focus should be laid on informing the public about the long term financial benefits of hydrogen in-spite of its high initial investments. This can be attained by discussing it in general information sessions. The public should be made aware of energy savings per month, environmental benefits and the cost savings in utility bills possible with hydrogen fuel.
4. Encouraging research and development on the integration of hydrogen with various alternative sources of renewable energy such as solar and wind energies. Educational campaigns must be organized to inform people about the positive impact of clean fuels on society and sustainability of the environment. Special solar power oriented educational

activities can also be organized. Different learning labs can be setup to promote awareness and benefits of solar power.

5. Career prospects in the United States as well as around the world are certainly opening up in the field of renewable energy. As the hydrogen energy sector continues to grow, the educational institutions and the industry must collaborate to provide opportunities to students to work on real-time projects. This will assist in better understanding of the concepts and students can appreciate the benefits of hydrogen over conventional fuels.


Wallingford's First Hydrogen Home
exclusively designed for your family
& hydrogen fuel vehicle
Amenities Including:
• Hydrogen Fuel Production & Dispenser in Garage
• Renewable Energy Generation
• Home Dashboard System
• Contemporary Open Floorplan
• Large Master Suite
• ADA Compliant
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10. Appendix

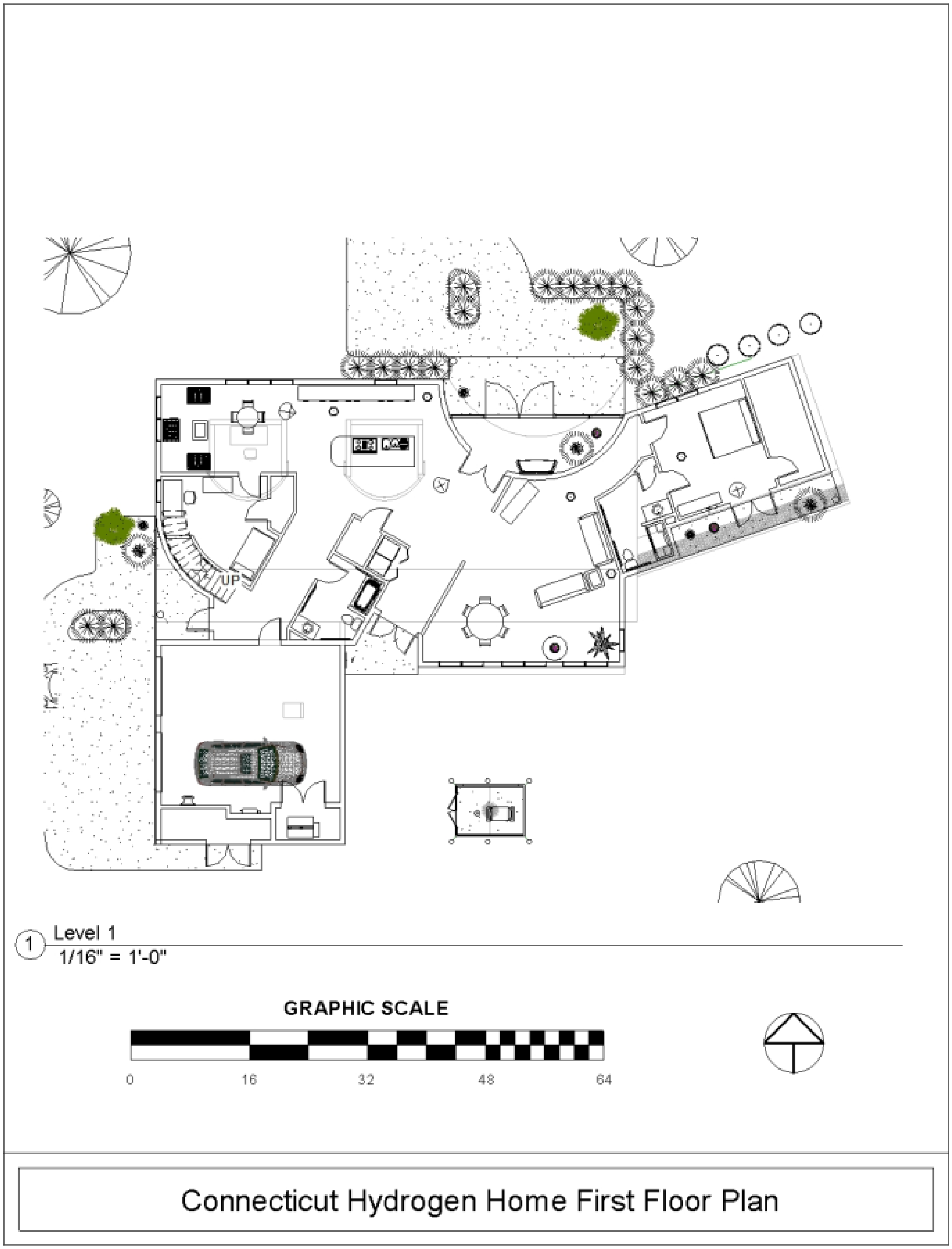

Figure I. New Hydrogen Home in Wallingford, CT First Floor Plan

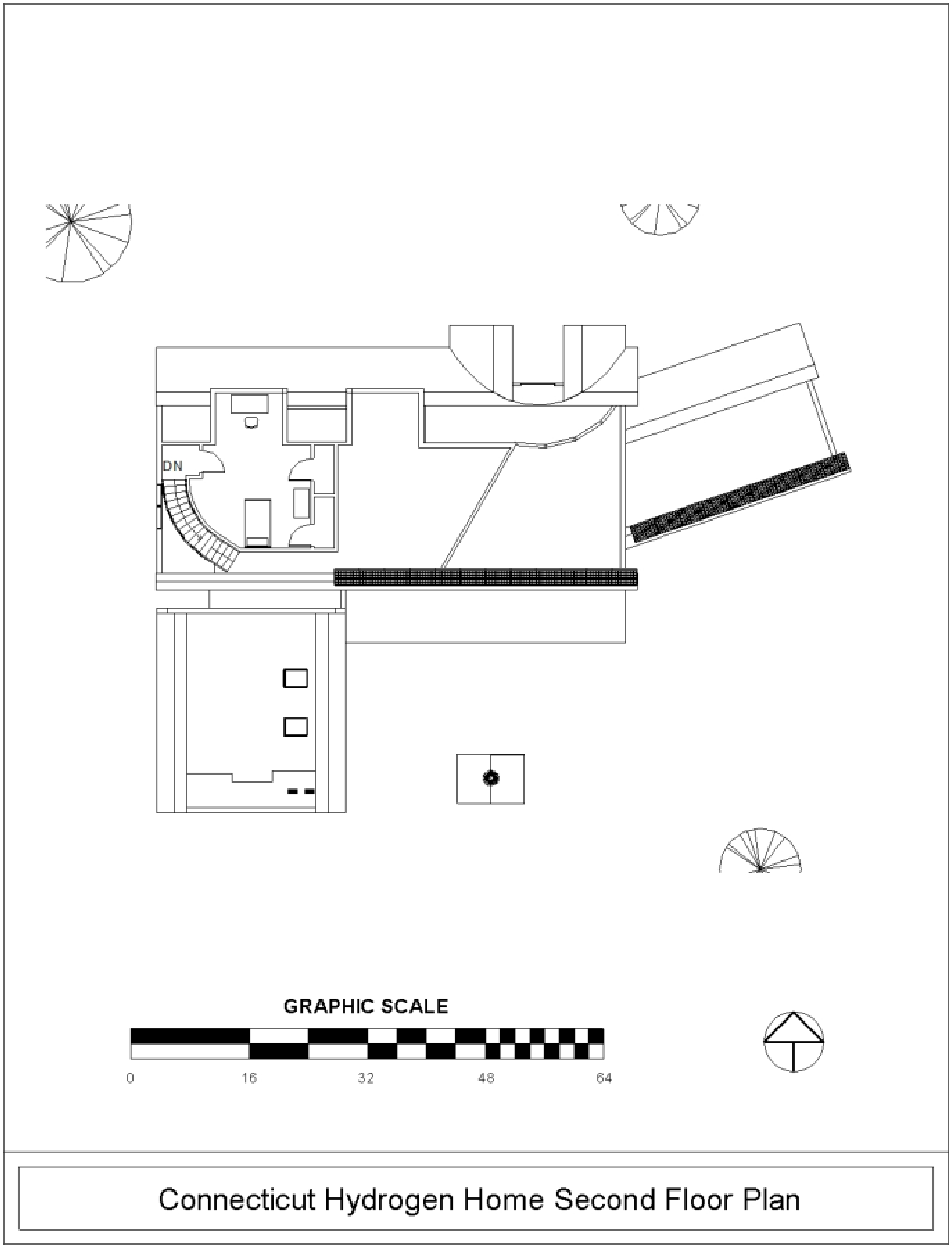

Figure II. New Hydrogen Home in Wallingford, CT First Second Plan

Figure III. Front View Bed & Breakfast in Wallingford, CT

Figure IV. Front View Hydrogen Home in Burbank, CA

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VITA

Aanchal Shah was born on February 17, 1987 in India and did her schooling at Holy Angels Convent School. She completed her Bachelor of Technology (B.Tech) in Mechanical Engineering at JSS Academy of technical Education, Noida and accomplished her degree in 2008. Before coming to school at Missouri S&T in 2009, she worked at MothersonSumi Infotech & Design Ltd for around 13 months in the field of design and FEA analysis of automotive components. At Missouri S&T, due to her experience in designing an electric hybrid vehicle as an undergraduate, she was given an opportunity to work with Dr. John Sheffield and be one of the team members of the EcoCAR team. During her two years at Missouri S&T, she accomplished many awards and the honors of Grand Prize Winner award at 2010 National Hydrogen Association Student Design Contest and honorable certificate at 2010 World Hydrogen Energy Conference, Essen, Germany. She has submitted two papers, one to the International Journal of Hydrogen Energy and the other to the 2011 Fuel cell Hydrogen Energy Association. She has also been a Summer Intern at Massachusetts Department of Energy Resources, Clean Cities.