HYDROGEN STUDENT DESIGN CONTEST 2011: RESIDENTIAL REFUELING STATION

UNIVERSITY OF WATERLOO
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EXECUTIVE SUMMARY

A request for proposal was sent out by the National Hydrogen Association (NHA) and the US Department of Energy (DOE) to develop a design for a residential hydrogen refueling station. This report presents the preliminary proposed design developed by the University of Waterloo Design Team.

The chosen residential building is a luxury condominium building to allow for scalability of renewable resources and to create a community based on a hydrogen economy. The station is to be located in Waterloo, Ontario, a city renowned for its innovation in technology and business activity and, more recently, in energy research and fuel cell technologies.

On-site production is provided by an electrolysis unit capable of producing 32.4 kilograms of hydrogen per day. This production rate is sufficient to fuel 40 cars per day with 0.8 kg of hydrogen – the daily fueling requirement as put in place by the NHA, assuming these cars are light-weight fuel cell vehicles requiring a 5000 psig on-board tank fill pressure. For user convenience, FCV owners will fuel up their vehicles every 4 days with 3-3.2 kilograms of hydrogen fuel – 10 cars thus receive fuel per day. Five cars will fill up before the morning commute and five cars after returning home in the evening hours.

Ground storage is provided by a three-bank cascade capable of containing 34 kilograms of hydrogen compressed to 5000 psig at an ambient temperature of 22 °C. A primary compressor is used to fill up the cascade tanks, and a secondary booster compressor is incorporated into the system to complete the fill when cascade pressures are insufficient to do so. A single dispenser will accommodate the demands of the residents and complete the fueling process in 3-10 minutes per vehicle. All major components of the fueling station (electrolysis unit, primary and booster compressors, and storage cascade) will be housed within a blast-proof room on the ground floor of the building. The dispensing unit will be housed in the parking garage.

In addition to the hydrogen system, the residential unit will also incorporate renewable energy to reduce the carbon emissions and reliance on grid electricity. Wind turbines, solar panels, and even human kinetic power will be employed to generate such electricity. Heat recovery from the electrolysis unit will offset a portion of natural gas heating, further reducing the amount of carbon emissions into the atmosphere. The building will be designed to comply with LEED® Certified (Gold) standards.

System components have been designed and positioned according to accepted convention and applicable codes and standards. Potential overpressure and combustion hazards are also being mitigated by process control and pressure relief systems. Potential risks posed by the use of wind, solar and geothermal energy have also been considered, with paths for mitigation identified.

A public awareness and education strategy will be initiated to encourage the acceptance of hydrogen as a fuel and encourage fuel cell vehicle adoption. The operation of this station is to begin in 2011, being the first major step in developing a hydrogen infrastructure in the City of Waterloo.

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1.0 TECHNICAL DESIGN

1.1 PROBLEM IDENTIFICATION

A request for proposal was sent out by the National Hydrogen Association (NHA) and the US Department of Energy (DOE) to develop a design for a residential hydrogen refueling station available for implementation in the Spring of 2011. This project will consist of planning and designing a hydrogen fueling system to be integrated into a home, apartment complex, dorm, or other single residential building.

The station must service a minimum daily capacity of 0.8 kg hydrogen/day/car, based upon a 35 mile/day commute and 44 mile/kg fuel economy associated with light-duty fuel cell vehicles. Hydrogen must be compressed to 35 MPa (5000 psig) (at ambient temperature) to meet the storage pressure requirements of the fuel cell vehicles (Hydrogen Student Design Contest, 2010). The design will include on-site hydrogen production, compression, storage, and dispensing. Hydrogen production is to be done by one of two pathways: natural gas reforming or water electrolysis. A significant amount of energy input should be allotted to renewable sources.

1.2 DESIGN SOLUTION

1.2.1 BUILDING TYPE AND SITE SELECTION

The refueling station must be designed for a single residential building for integration into a home or multi-unit residence. A four-storey condominium unit was chosen as opposed to a single resident home for the design to allow for ease and cost savings of incorporating renewable energy sources such as on-site wind power generation, photovoltaic solar, and geothermal heating. Apart from allowing for capital cost of the hydrogen fueling system equipment to be shared amongst condominium owners, the multi-unit building design will also provide a community with convenience and encouragement for the early adopters of hydrogen fuel cell vehicles and serve as a hub for the further development of hydrogen fuel cell technologies in the area of the residence.

The station is to be located in the city of Waterloo, a Canadian city of 122,000 people located in south-western Ontario. Waterloo's economy is based primarily in knowledge and technology sectors and is part of Canada's Technology Triangle – an economic development initiative covering the tri-city area of Kitchener, Cambridge, and Waterloo that has a world renowned reputation for the vast number of innovative high-tech enterprises growing within the community. With think-tank organizations like the Perimeter Institute for Theoretical Physics, the Institute of Quantum Computing, and the Centre for International Governance Innovation, Waterloo has established itself as a leader in innovative technologies and economics (City of Waterloo, 2010). With the launch of the Energy Research Centre at the University of Waterloo in conjunction with the Waterloo Institute for Sustainable Energy (WISE) and Hydro One in October 2010, the "full spectrum" of sustainable energy research and development, education, partnerships, and commercialization will be addressed with fuel cell laboratories, energy and pollution modeling, and the Centre for Advanced Photovoltaic Devices and Systems (University of Waterloo, 2010).

A site was chosen in Waterloo's Research and Technology Park, just north of the University of Waterloo campus and amidst some of the more prominent high-tech research firms in the city (such as Sybase, TechTown, Innotech, OpenText, the Accelerator Building, and the UW Research Advancement Centre). Conveniently located near Laurel Creek and the Columbia Lake where the potential to harness wind turbine energy exists, the R&T Park will serve as an ideal location for a condominium unit targeted towards the early adopters already working and residing in the area. A site plan is included on the following page, with descriptions and justification of major equipment to follow.

1.2.2 HYDROGEN PRODUCTION METHOD

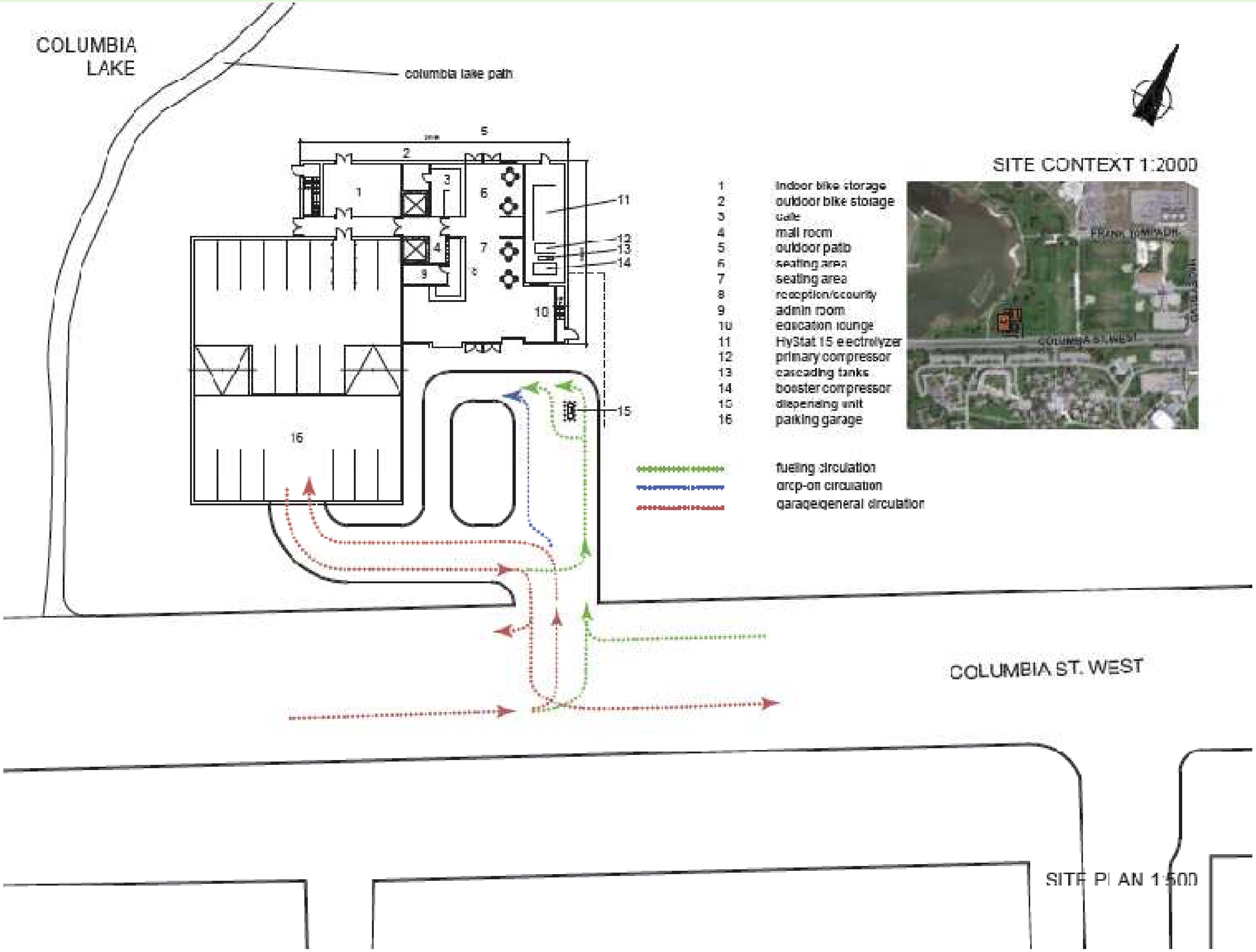
To decrease reliance on fossil fuel energy sources, the proposed residential hydrogen fueling station will include on-site production via water electrolysis instead of steam methane reforming from distributed natural gas. Although electrolysis is an energy-intensive process, requiring vast amounts of electricity to dissociate the water molecule to diatomic hydrogen and oxygen gases, the station's Canadian location allows for electrolysis to be the favorable option due to a heavy reliance on nuclear hydroelectric power (over 70% combined) for grid electricity as opposed to the fossil fuel sources predominating the grid mix in the USA. Canada is one of only five major nations where electrolytic hydrogen production for fuel cell vehicles will reduce greenhouse gas emissions considerably when compared to reformed hydrogen from natural gas (Thomas C.E., 2001). Having an electricity-based production scheme also allows for easier incorporation of on-site renewable power sources to generate electricity for electrolysis operation.

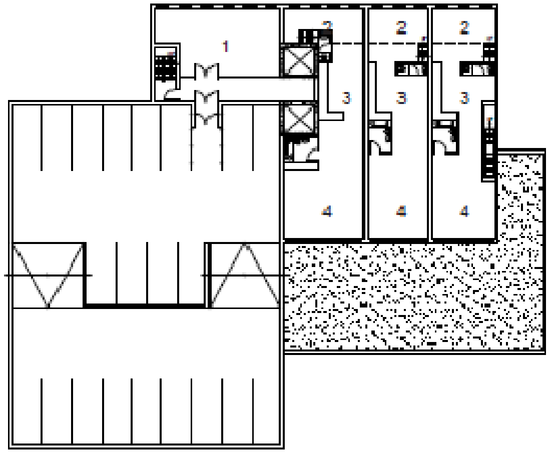
Hydrogen will be produced at the building site using an electrolysis unit from Hydrogenics. Capable of producing 32.4 kilograms of hydrogen per day (15 Nm^3/hr) with 24 hour operation, Hydrogenics' HySTAT 15 unit includes a water treatment system for municipal water input and a hydrogen purification system for discharge of fuel-cell vehicle purity hydrogen (99.999% H_2) at 10 barg (145 psig) (Hydrogenics, 2010). The 683,280 kWh of electricity required to operate this electrolysis unit will be supplied primarily by grid electricity, with on-site wind turbines, photovoltaic solar panels installed on the building roof, and human powered kinetic machines incorporated as renewable sources for powering the electrolysis operation. The precise breakdown and application of these renewable energy resources to the electrolysis unit are addressed further in the Environmental Analysis section of the report.

1.2.3 DESIGN CONSTRAINTS AND ASSUMPTIONS

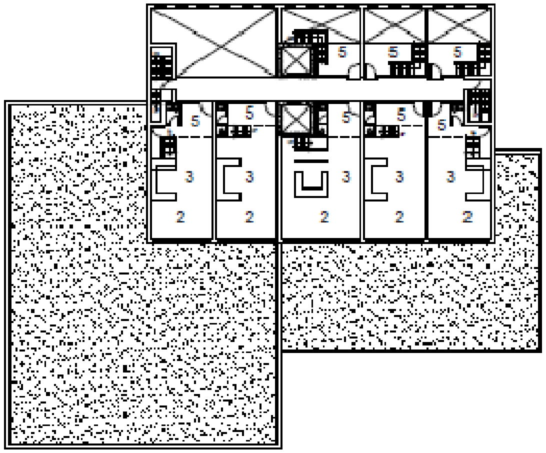
The proposed hydrogen station was designed around the electrolysis unit production rate of 32.4 kg/day, delivering gaseous hydrogen to light-duty fuel cell vehicles requiring 35 MPa (5000 psig) delivery pressures to on-board cylinders. Based on the imposed design constraints, the electrolysis unit is capable of fueling a maximum of 40 cars per day with 0.8 kg hydrogen to meet their daily commute requirements. Assuming that the average fuel cell vehicle has a storage tank capacity of 4 kg hydrogen and that automobile owners fuel up once approximately 75% of the tank fuel is used, the fueling model is based on filling 10 cars with 3 to 3.2 kilograms of hydrogen every 4 days instead of each day, for a

SITE PLAN


COLUMBIA LAKE
columbia lake path
SITE CONTEXT 1:2000
FRANK TOMPA DR.
COLUMBIA ST. WEST
1 indoor bike storage
2 outdoor bike storage
3 cafe
4 mail room
5 outdoor patio
6 seating area
7 seating area
8 reception/security
9 admin room
10 education lounge
11 HyStat 15 electrolyzer
12 primary compressor
13 cascading tanks
14 booster compressor
15 dispensing unit
16 parking garage
fueling circulation
drop-off circulation
garage/general circulation
COLUMBIA ST. WEST
SITE PLAN 1:500

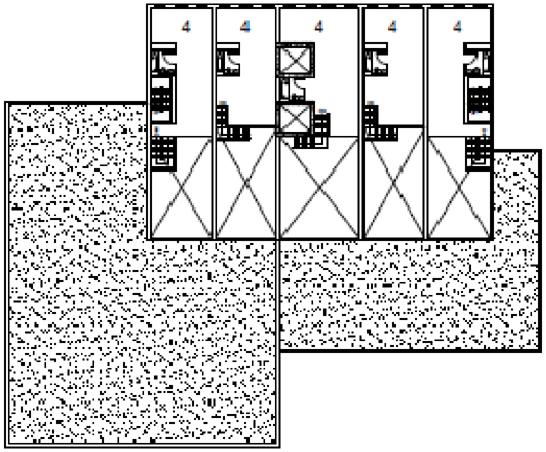


SECOND LEVEL PLAN 1:500

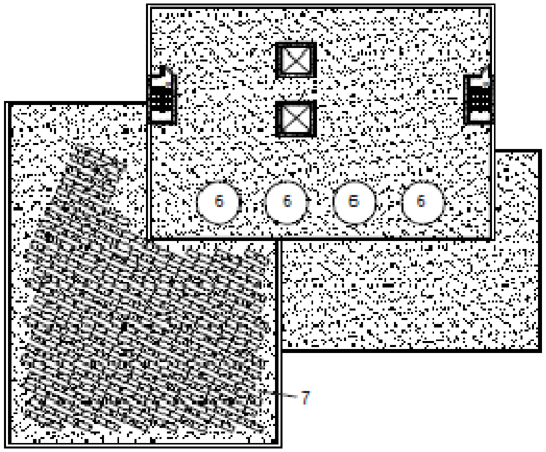


THIRD LEVEL PLAN 1:500

1	exercise gym
2	living area
3	kitchen/dining area
4	sleeping/study area
5	entrance vestibule
6	wind turbine
7	solar panel array



FOURTH LEVEL PLAN 1:500



ROOF PLAN 1:500

total of 40 cars refueling every 4 days. Since the station is located at the residence of the vehicle owner and is not a public access station, a regular peaking pattern rather than random fueling pattern can be applied, in which there will be two main peak refueling times assumed: one during the pre-commute hours of 6-9 am, the other during the after-work hours of 4-7 pm. It is assumed that 5 cars will fill up in the morning period and 5 cars in the evening. Stochastic fueling behaviours are out of the scope of this design problem and it is assumed that this fueling arrangement will be scheduled within the condominium procedures.

The ambient temperature was taken to be 22°C for storage tank sizing calculation purposes. This is average daily temperature in Waterloo in the summer months of June through August (The Weather Network, 2010). The effects of cold temperatures during winter, spring, and autumn are neglected since temperature controls will be placed on the housing of major process equipment.

1.2.4 HYDROGEN STORAGE AND COMPRESSION SCHEME

In order to allow for 5000 psig delivery to fuel cell vehicles, the hydrogen discharged from the electrolysis unit requires compression and, because this is not an on-demand system, ground storage. Since the fueling system is for a condominium residence where convenience is a key aspect and goal of the design, a compression scheme complete with stationary storage capacity is desired to allow for residents to fuel up their vehicles in minutes rather than the overnight time-filling necessitated by a compression scheme lacking a storage system. This also avoids the need for the individual dispensing posts that would be required should an overnight fill be chosen, eliminating the costs that would be associated with such a system. The addition of a storage system allows for 24-hour hydrogen production to maximize the number of cars that can receive fuel daily.

A cascading storage system has been chosen for the proposed station, comprised of a series of three compressed gas storage tanks to be dispensed in a priority sequence based on prescribed pressure designations (low, medium, and high pressure). In a conventional cascade system, all three storage tanks are pressurized to above the required 5000 psig fuel cell vehicle pressure (up to 7000 psig) and deliver hydrogen in sequence: vehicles first receive hydrogen from a prescribed low pressure bank until a pressure equilibrium is reached between the storage tank and the onboard fuel cell vehicle tank and the medium pressure bank is called upon to dispense. The medium bank dispenses until equilibrium is reached and then the high pressure bank completes the fill. This sequencing is performed by a control that senses a minimum pressure differential between the storage tank and the vehicle storage and determines when it is necessary to switch to the next priority tank to properly complete the fill. The conventional cascade filling allows for filling times of 3 – 10 minutes (Gas Technology Institute, 2008)

The gas compressor is operating throughout the dispensing process to recharge the banks with hydrogen, beginning with the high pressure bank to ensure that there is always at least one tank available that will complete the fill. Since all three tanks will be used to fill one vehicle, the overall fuel system requires extended time-out periods to ensure sufficient recharge from the compressor or higher initial storage pressures to ensure all tanks fueled in succession can be filled to the required 5000 psig. These challenges will be overcome through the use of booster compression.

The use of booster compression in a hydrogen dispensing scheme allows for hydrogen to be retrieved from storage cascades unable to complete the fuel cell vehicle on-board tank fill and hydraulically intensify or boost the pressure from the lower pressure of the cascade tank (1000 – 5000 psig) to over 5000 psig for delivery to the fuel cell vehicle. The booster compressor effectively “tops-off” the dispensing of the last 0.05 to 1.2 kilograms of hydrogen required to reach full 5000 psig pressure of the on-board fuel cylinders in 1 to 5 minutes. This eliminates the need for excessive storage pressures and extended time-out periods for recharging the storage cascade, improving the utilization of the cascade tanks and enhancing fuel delivery performance (Gas Technology Institute, 2008).

A cascade storage system with booster compression has been chosen as the storage and compression scheme of the residential refueling station to eliminate the need for excessive ground storage on the condominium site and the costs that coincide with greater storage and compression capacities. The three storage tanks of the cascade system will be pressurized to 5000 psig via a primary compressor, and and a control system will monitor when the booster compression is required after equilibrium between each of the cascade tanks and the vehicle tank has been reached. The cost of booster compression has been taken into account and balanced with cascade utilization and recovery, the efficiency of the overall system, and safe storage of hydrogen.

1.2.5 COMPRESSION, STORAGE, AND DISPENSING EQUIPMENT SELECTION

The primary compressor for the fueling station is a two-stage oil-free diaphragm compressor selected from Pressure Products Industries, capable of delivering 15 Nm^3/hr (32.4 kg/day) of hydrogen – equivalent to the production rate of the electrolysis unit – at 5000 psig from a suction pressure of 145 psig (10 barg, the outlet pressure of the electrolyzer unit). The reciprocating compressor design is optimal for lower flow rates requiring high pressure differentials, and the oil-free lubrication and hydraulic systems in PPI`s hydrogen compressors are crucial to preventing contamination of the hydrogen discharged to the downstream fueling system. PPI provides pre- and after-cooling water piping to manage the heating effects of compression as well as an integrated leak detection system with automatic shut-off controls (PPI, 2010).

Calculations have been performed to determine the required capacity of the three tanks in the storage cascade, assuming a temperature controlled atmosphere of 22 °C by a thermostat in the equipment housing – a blast-proof room located on the ground floor of the condominium building. The compressibility of hydrogen has been accounted for by finding the impact of pressure on gasesous hydrogen density at the chosen ambient temperature (NIST, 2010). It has been determined favourable to slightly stagger the sizes of the cascade tanks to improve overall cascade utilization and achieve more rapid recovery of the pressure in the high pressure storage tank. The low pressure tank will hold 14 kg of hydrogen (0.60 m^3 in volume), while medium and high pressure tanks will hold 10 kg (0.43 m^3), for a total station storage capacity of 34 kg hydrogen in 1.43 m^3 of storage space.

Options for storage vessels include steel or carbon-fibre composite materials. Due to the increasing costs of steel and the savings in support structure, weight-bearing requirements for the concrete pad on which the vessels will be stored, and structural requirements of the major component housing, composite tanks (6-8 times lighter than steel containers with equivalent pressure rating) will be chosen (GTI, 2008). The tanks, sourced from Dynetek Industries, will be rated for 6000 psig at 22 °C and and certified to the CSA B51 standard governing Boiler, Pressure Vessel, and Pressure Piping Code. Then tanks will be mounted in a vertical riser and will be equipped with individual isolation piping and valves for independent recharge and discharge (Dynetek Industries Ltd, 2010).

A booster compressor is available from Hydro-Pac that will effectively intensify the gas pressure in the depleted cascade vessels from as low as 1500 psig to a maximum pressure of 6000 psig. Equipped with interstage cooling to aid in mitigating the fast-fill temperature effects associated with high pressure gas transfer, the chosen booster compressor has a maximum discharge flow rate of 0.894 kg/minute that decreases with decreasing inlet pressure from the depleting high pressure cascade. The booster is capable of intensifying hydrogen pressures from a minimum of 1500 psig (the lowest pressure experienced in the high pressure cascade tank feeding the booster) to the 5000 psig required for the fuel cell vehicle delivery in 1 to 5 minutes, depending on the mass of hydrogen required to complete the fill in the fuel cell vehicle.

From the storage cascade and booster compressor, insulated high pressure pipelines will run underground to the dispensing system. A pressure regulator will be used to control the pressure of the hydrogen stream entering the single-hose dispenser in the parking garage. The dispensing unit chosen, provided by Kraus Global, includes a three-line charging system that allows for hydrogen inlet pressures up to 6700 psi for flow rates of up to 3.6 kg/min and includes an overfill protection system to electronically compensate for pressure and temperature. The stand-alone dispenser is complete with SAE J2600 compliant nozzles with SAE J2601 compliant dispenser-vehicle communications, safety breakaway on the dispensing hose, a grounding cable, and a retail-style cabinet to bring an important sense of familiarity to the residential users. It includes a self-contained electronic sequencing control system to detect differential pressures in the onboard FCV tank and in the pressure cascades and is controlled using solenoid valves (Kraus Global, 2010).

The filling model is based on a worst-case scenario of 5 cars dispensing consecutively, considering no cascade recharge in between or during these fill times. Since the maximum pressure in the tanks will be 5000 psig, some booster compression will be required to complete the fill of each vehicle. The booster will draw from the high pressure cascade tank to complete the fueling process. The following figures display the pressure in each tank during the 5-car fueling period and the corresponding mass of hydrogen delivered to each vehicle.

Fast-filling storage options like that proposed for this station dispense high pressure hydrogen into onboard fuel cell vehicle tanks in only a matter of minutes. The gas (thus the onboard tank) will heat up during filling operation and when the gas cools after time, pressure will fall to lower than the filling pressure. Thus, to achieve a full 5000 psig in the onboard fuel cell vehicle tank after cooling, the filling pressure must be greater (Thomas et al, 2001). The requirement for the onboard tank burst pressure capability (in withstanding increased pressures) is beyond the scope of the current fueling station design, but the required overpressure that must be provided by the cascade/booster system should be considered to ensure sufficient pressures can be achieved within the production abilities of the chosen equipment.

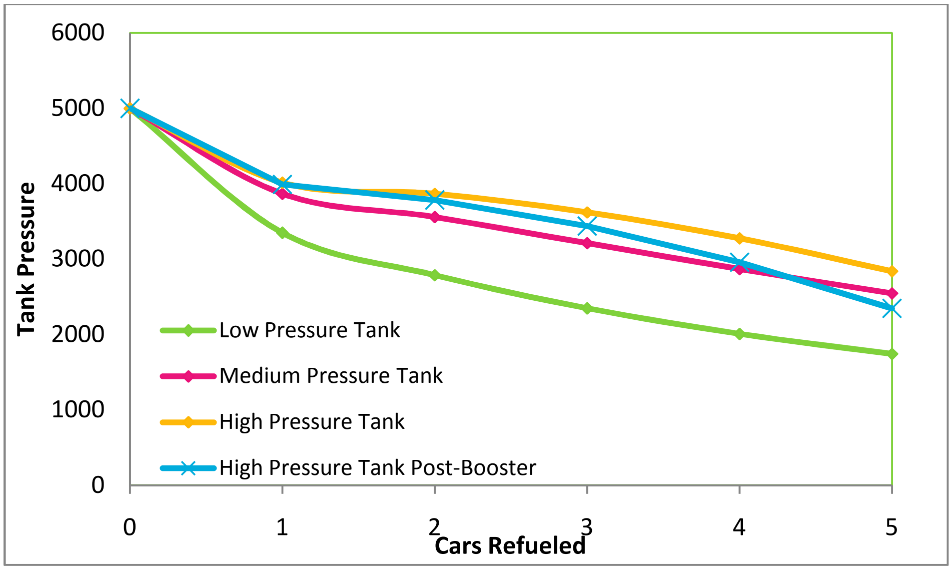


Figure 1: Cascade tank pressure during five car refueling period

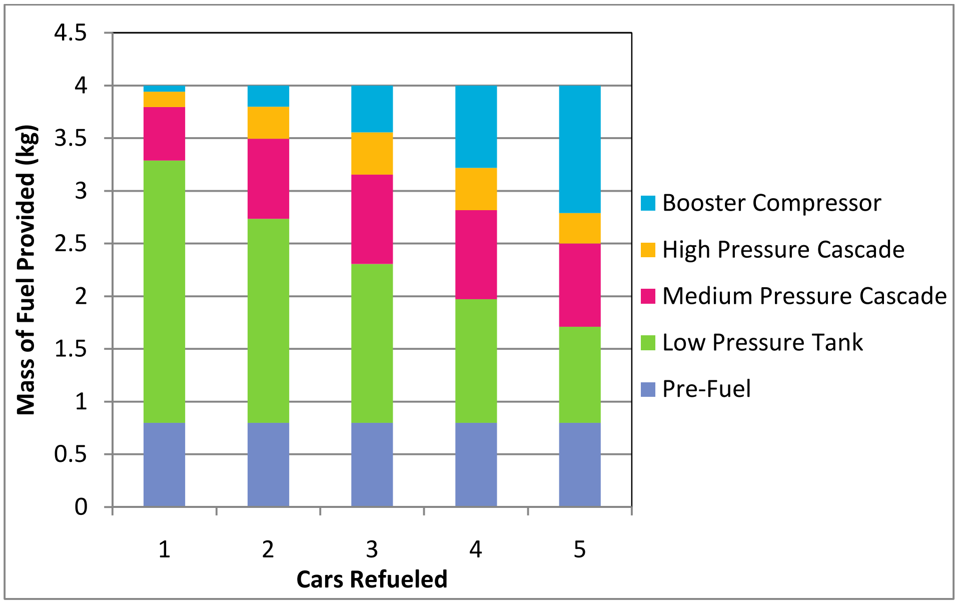


Figure 2: Tank mass and dependence on cascade tanks/booster compressor during five car refueling period

1.2.6 COMPONENT LAYOUT

A process flow sheet depicting all major components of the design is shown on the following page. Nitrogen purge tanks have been included as a safety mechanism to purge system piping with inert gas in the case of leak detection and/or equipment failure. This will be discussed further in the next section as well as in the Safety Analysis.

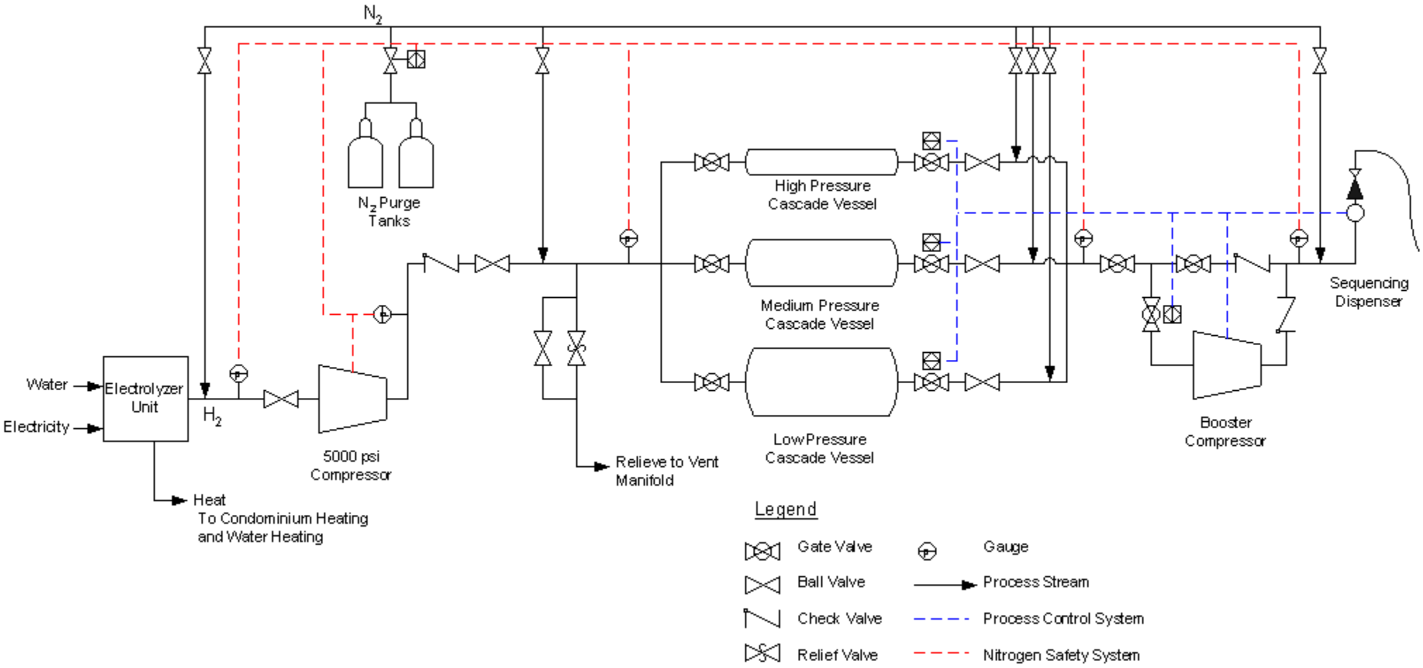


Figure 3: Process flow diagram of major fueling station components with basic process control

Secure entry is required for access to the refueling station, which is located fully above ground for adequate ventilation. The dispensing unit will be located outdoors and will be accessible to cars both exiting and entering the underground parking garage located beneath the building structure. All other major components of the fueling station (i.e., electrolysis unit, primary compressor, cascade storage rack, and booster compressor) will be located in a temperature controlled, blast-wall protected room within the ground floor of the condominium building with accessibility limited to station maintenance staff. On the following page, Figure 4 displays the layout of major components in the hydrogen station equipment room of the building while Figure 5 displays the dispensing unit of the fueling station at the parking garage entrance.

1.2.7 PROCESS CONTROL SCHEME

A process control system has been incorporated into this fueling station design for two purposes: to ensure immediate response by the electrolysis unit as fueling starts and stops, and to shut down the system in the event of accidental overpressure, leakage or fire. With respect to the former objective, a flow sensor on the dispenser signals whether it is currently in use at a given time. With respect to the latter, overpressure sensors are placed at the electrolysis unit, each of the three storage tanks, and at the dispenser. A number of hydrogen gas detectors are placed at potential leak points in the system, near air vents from the room, and at potential gas-accumulation points in the room. Finally, fire detection sensors are positioned in the room accommodating the system, and near the outdoor dispenser. Signals from any of these devices indicating one or more of the contingencies mentioned above will shut down the electrolysis unit and compressors, and close valves to isolate pressurized parts of the system.

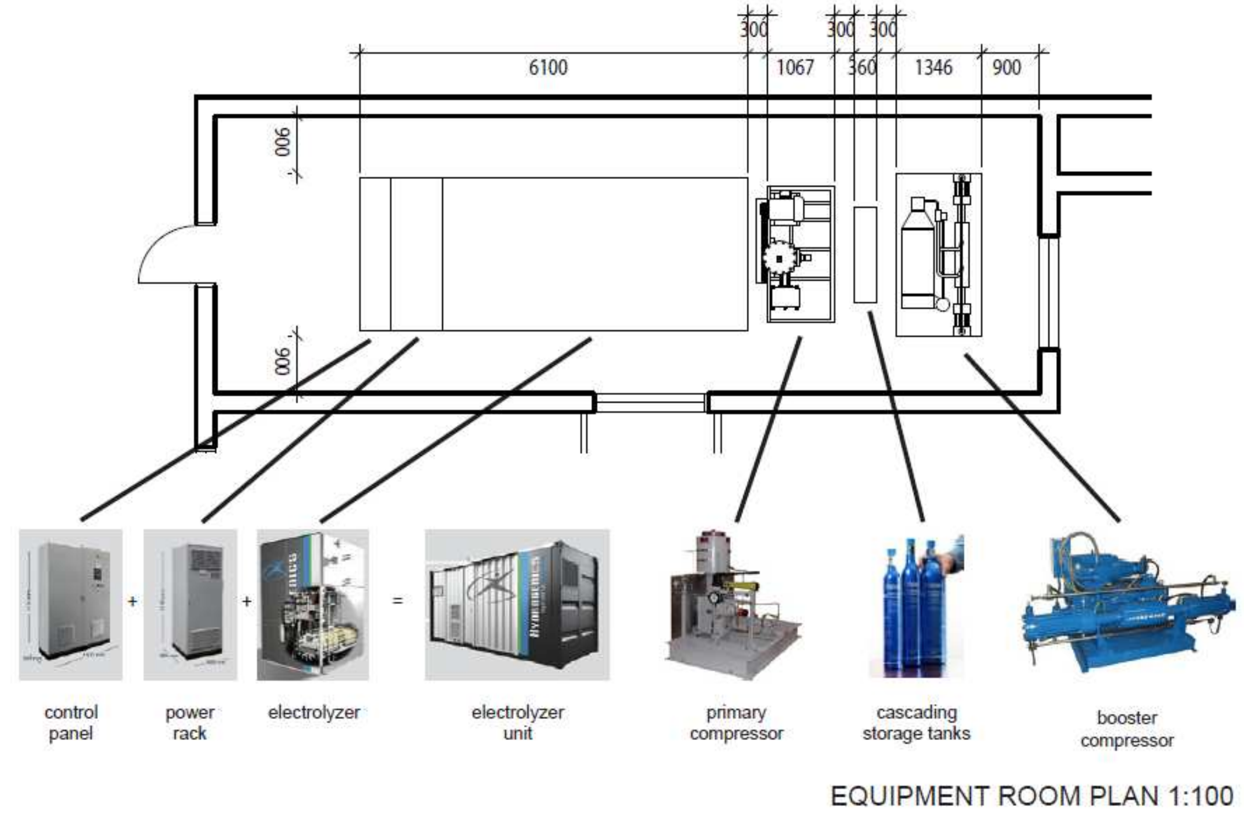


Figure 4: Layout plan of major hydrogen fueling station equipment

Figure 5: Dispensing unit of hydrogen fueling station in proximity to condominium building

2.0 SAFETY ANALYSIS

The purpose of identifying and mitigating safety hazards for this hydrogen fueling station and associated residential building is twofold. Firstly, it is to maintain the health and safety of future customers and users. Secondly, it is to assure potential stakeholders and the public of the safety of this usage of hydrogen to encourage investment in this technology.

To achieve these goals, a preliminary Failure Modes and Effects Analysis was conducted on the hydrogen system to systematically determine all deviations from expected operation and estimate the safety risks posed by each. Next, codes and standards pertaining to hydrogen generation, storage and fueling were reviewed and applied to the system where applicable to mitigate the identified risks. Risks not specifically addressed by those codes were given separate consideration. Finally, hazards associated with those forms of alternative energy that have been employed in powering the system, namely wind and solar, were considered.

2.1 PRELIMINARY FAILURE MODES AND EFFECTS ANALYSIS

For the purposes of this analysis, the hydrogen system was broken down into its constituents and the possible types of failure that each could experience were listed, along with likely causes and possible effects. In order to generate entries in our analysis, the California Energy Commission (TIAX LLC, 2004) along with the Center for Canadian Process Safety (1998) were consulted for reference. Effects were rated for severity (S) on a scale of 1 to 10 where 1 is minimal and 10 could potentially cause injury or death. Causes were ranked based on likelihood of occurrence (O) on a scale of 1 to 10 where 1 is remote and 10 is certain. The severity and occurrence scores are then multiplied to form a criticality number (CRIT), which reflect the magnitude of identified risks. Since the goal of this preliminary analysis was to identify those risks for which controls and procedures must be developed or implemented, detection ratings for such controls and procedures have not been assessed here.

The complete analysis is presented in Table 1. 41 failure modes were identified, the most significant of which were related to the dispensing of hydrogen: collision of a vehicle with the dispenser, and a vehicle driving away with the dispenser hose still attached, each with a criticality score of 50. The next most significant potential hazards, all with scores of 30, include intentional damage inflicted by vandalism or terrorism, external fires heating the storage tanks, external flooding around the storage tanks, and reverse flow to the dispenser from a vehicle with a failed check valve. Also included is uncontrolled inflow or outflow of gas in different components caused by control failures; overpressure effects caused in components due to blockages in pipes, valve failures or compressor suction leaks; and rupture of underground pipes to the dispenser due to corrosion or cold temperatures.

All of these failure modes could potentially result in fire, explosion, suffocation of an individual, or some combination of the three, as the components involved deal with compressed gas, in most places flammable hydrogen, and most of these components are located indoors. The objective of the safety measures described below will be to avert or mitigate these contingencies.

Table 1: Preliminary Failure Modes and Effects Analysis for Hydrogen Fueling Station

Function	Potential Failure Mode	Potential Failure Effects	S	Potential Causes of Failure	O	CRIT
Electrolysis	Electrolysis not taking place while unit operates	lack of product	2	Loss of power; water leakage; low water flow	5	10
	Oxygen accumulation	rupture; fire	10	blockage of vent	2	20
	Water Purification Failure	residue build-up	1	high impurity levels	3	3
	Electrolyte Leak	injury	8	mechanical failure	1	8
	Hydrogen gas leak	suffocation; fire	10	mechanical failure	1	10
	Oxygen gas leak	suffocation; fire	8	mechanical failure	1	8
Primary Compression	Overpressure	explosion; leak; suffocation; fire	10	failure of downstream valve; failure to remove a downstream blind; leakage on suction side	3	30
	High Temperature	explosion; leak; suffocation; fire	10	failure of lubrication system; failure of cooling system	1	10
	Low Flow	leak; suffocation; fire	10	reduced flow	1	10
	Reverse Flow	leak; suffocation; fire	10	high discharge side pressure	1	10
	Overspeed	leak; suffocation; fire	10	speed control system failure	1	10
	Loss of Containment	suffocation; fire	10	operation at fraction of capacity	1	10
Hydrogen Storage	Overpressure	explosion; fire; suffocation	10	excessive fill rate; ignition; external fire; obstructed vent; (excessive heat input); ambient temperature change	3	30
	Underpressure	implosion; fire; suffocation	10	obstructed vent; excessive withdrawal rate; ambient temperature change;	1	10
	High Temperature		10	external fire	3	30
	High External Liquid Level	implosion; fire; suffocation	10	flooding	3	30
	Overfill		10	level control failure; uncontrolled inflow	3	30
	Low Level	implosion; fire; suffocation	10	level control failure; uncontrolled outflow	3	30
Booster Compression	Overpressure	explosion; leak; suffocation; fire	10	failure of downstream valve; failure to remove a downstream blind; leakage on suction side	3	30
	High Temperature	explosion; leak; suffocation; fire	10	failure of lubrication system; failure of cooling system	1	10
	Low Flow	leak; suffocation; fire	10	reduced flow	1	10
	Reverse Flow	leak; suffocation; fire	10	high discharge side pressure	1	10
	Overspeed	leak; suffocation; fire	10	speed control system failure	1	10
	Loss of Containment	suffocation; fire	10	operation at fraction of capacity	1	10
Dispensing	Leak in hose	fire; explosion	10	mechanical failure	1	10
	Car drives away with hose attached	fire; explosion	10	human error	5	50
	Hose discharges or nozzle leaks when not attached to vehicle	fire; explosion	10	human error	3	30
	Backflow of gas from vehicle to dispenser	fire; explosion	10	vehicle check valve fails open	3	30
	Vehicle collision	fire; explosion	10	human error	5	50
	Underground pipe rupture	fire; explosion	10	corrosion; cold temperatures	3	30
N2 Tanks	Overpressure	explosion; suffocation	10	excessive fill rate; external fire; obstructed vent; ambient temperature change	3	30
	Under pressure	implosion; suffocation	10	excessive withdrawal rate; ambient	1	10

				temperature change;		
	High Temperature	explosion; suffocation	10	external fire	3	30
	High External Liquid Level	implosion; suffocation	10	flooding	3	30
	Overfill		10	level control failure; uncontrolled inflow	2	20
	Low Level		10	level control failure; uncontrolled outflow	2	20
Piping / Valves	Overpressure	rupture; fire; suffocation	10	blockage in line	1	10
	High Temperature	rupture; fire; suffocation	10	external fire	3	30
	High Flow	rupture; fire; suffocation	10	upstream mechanical failure or human error	3	30
	Loss of Containment	fire; suffocation	10	overpressure in pressure and temperature gages; thermal stress	2	20
All components	Large applied external force	explosion; fire	10	vandalism; terrorism; any other deliberate attack	3	30

2.2 MITIGATION OF IDENTIFIED RISKS

For this design, applicable codes and standards include the following:

- BNQ Hydrogen Installation Code (2005)
- ASME Boiler and Pressure Vessel Code (2007)
- SAE J2600 (2010)
- NFPA 52 (2010)
- OHSAS 18001 (2007)

These codes and standards have been applied along with other measures as follows to mitigate the hazards identified in the section above.

Firstly, a process control system has been incorporated into the design, as described previously. Overpressure and high temperature detectors are located on all system units; if any of these issues are detected, signals will be sent to the electrolysis unit, compressors and applicable valves along the system to shut down the system, as previously described. Shutdown will also occur in case of fire or of hydrogen levels in excess of 25% of the lower flammability limit of hydrogen, as per the BNQ Hydrogen Installation Code (2005). Following from the same code, hydrogen gas detectors will be located in all areas around the system where hydrogen could leak or pool, and at vents exiting the room in which the system is located. Fire detectors will also be located within the room. Excess hydrogen will be vented using inert nitrogen gas, and the shutdown sequence will take no longer than 10 seconds as per the BNQ Hydrogen Installation Code (2005). The ventilation scheme of the system is depicted in Figure 6 of the Environmental Analysis section.

Secondly, a pressure relief system will also be included in the design in accordance with the ASME Boiler and Pressure Vessel Code (2007). Pressure relief valves, in the form of rupture discs, are positioned at the electrolysis unit outlet, at the outlets of the compressors, at the dispensing pump outlet, and on each of the three cascading storage tanks. Additionally, check valves are placed after each of the compressors to prevent overpressure of the storage tanks or electrolysis unit caused by unplanned shutdown of either compressor.

Thirdly, the components of the hydrogen system have been positioned according to the BNQ Hydrogen Installation Code (2005). The system, since it contains approximately less than 35 kg hydrogen in total, will be positioned in a specially-designed room on the ground floor wall of the building, for which all walls, the ceiling, and the floor are composed of non-combustible materials, and the windows are glazed with a thermoplastic material. The walls will have a fire-resistance rating of at least 2 hours. The room will also have incorporated an explosion relief system, so that sufficient internal pressures will cause venting directly to the outside of the building. It will be well-ventilated, minimizing fire and suffocation risks, and waterproof to avoid substantial flooding. It will also be secured from general access to prevent deliberate acts of abuse, and to protect public safety.

Fourthly, the fuel dispensers themselves will be located outdoors on an elevated island, again designed according to the BNQ Hydrogen Installation Code (2005). It will be 150 mm above ground level. The island will be positioned at least 0.9 m away from any projected roof or canopy. The island will be surrounded by vertical concrete-filled pipes to prevent vehicular impact. The pipes will be placed around the island at 1 m intervals, and will be 100 mm in diameter and 750 mm in height above ground level, running 915 mm below ground. The below ground sections will be entirely encased in concrete blocks of 305 mm diameter. Each post will be at least 300 mm from any of the dispensers.

Lastly, individual system components have already been designed and/or sized to meet the requirements of their respective codes. The 3-tank cascade for hydrogen storage is designed to the ASME Boiler and Pressure Vessel Code (2007). The hydrogen dispensing pump is designed according to SAE J2600 (2010) and NFPA 52 (2010). It will include a safety breakaway mechanism for the hose, in case a vehicle drives away while still engaged. The electrolysis unit itself is OHSAS 18001 (2007) compliant.

2.2 WIND TURBINES

A primary safety concern presented by wind turbines is related to the vibrations which they generate, as these may be transmitted to structures on which the turbine may be situated (Clarke, 2003). If the power generation of a turbine situated on a rooftop exceeds 1 kW, structural problems and significant noise may result. A second important concern is that strong winds may cause a wind turbine to exceed its maximum possible speed (Clarke, 2003), causing damage to the turbine and possibly resulting in dangerous projections of components away from the roof of the building at high velocities.

However, the four wind turbines proposed for this design, each having an output of approximately 0.2 kW, are small enough not to cause significant vibration of this type, thus addressing the issue. To avoid the second contingency, a braking and locking mechanism will be employed in both wind turbines to prevent them from exceeding maximum speed.

A third concern, which is specifically relevant to zoning considerations in the intended building site in Waterloo, Ontario, is the accumulation of ice on the blades during winter, which may come dislodged and be projected at high speeds through the air causing possible damage or injury. In order to address the concerns for the sake of approval by the City of Waterloo, an ice detection and monitoring system will be employed which will shut down the turbines if ice is detected (City of Waterloo, 2008).

2.3 SOLAR PANELS

Safety issues associated with solar power generation primarily include the risk of electric shock due to large voltages being generated by the panels (Gevorkian, 2007). This risk will, in general, be minimal for this application as the solar panels involved will be located on the roof of the building where there is expected to be minimal human activity. However, all electrical wiring and components will be carefully designed to minimize risk to maintenance personnel.

3.0 ENVIRONMENTAL ANALYSIS

3.1 ENVIRONMENTAL DESIGN OF BUILDING

The movement towards sustainable and green buildings initiated the US Green Building Council to develop a certification system, Leadership in Energy and Environmental Design (LEED®) to be recognized internationally to accelerate transformation of buildings to more sustainable design.

It is of best interest to obtain a LEED® Certification of Gold for the construction of the building hosting the residential hydrogen refueling station. This new building hopes to market that living in a sustainable building is possible and rewarding at the same time. Residents of this building will reap the benefits of reducing their carbon equivalent emissions in the atmosphere and saving costs on utility bills. This building hopes to provide an example for future sustainable residential buildings. The credits required to obtain a LEED certification are outlined in Appendix B.

The units in the building are laid out in such a way that they allow natural cross ventilation from one side of the building to the other, reducing cooling and ventilation loads in the summer months. Most of the windows are located on the warmer south side of the building, and less on the north side to reduce heat loss in the winter. South windows are also easy to shade with continuous external horizontal shading devices such as shelves or slats. In this way, the high-angled summer sun is blocked from overheating the units, while the low-angled winter sun is allowed in and reduces heating loads for the building. The units give their owners access to views both of the street and of the lake, instead of the one-sided views of most condominiums, and daylight can reach rooms from both sides. An open floor layout encourages cross ventilation and daylight penetration.

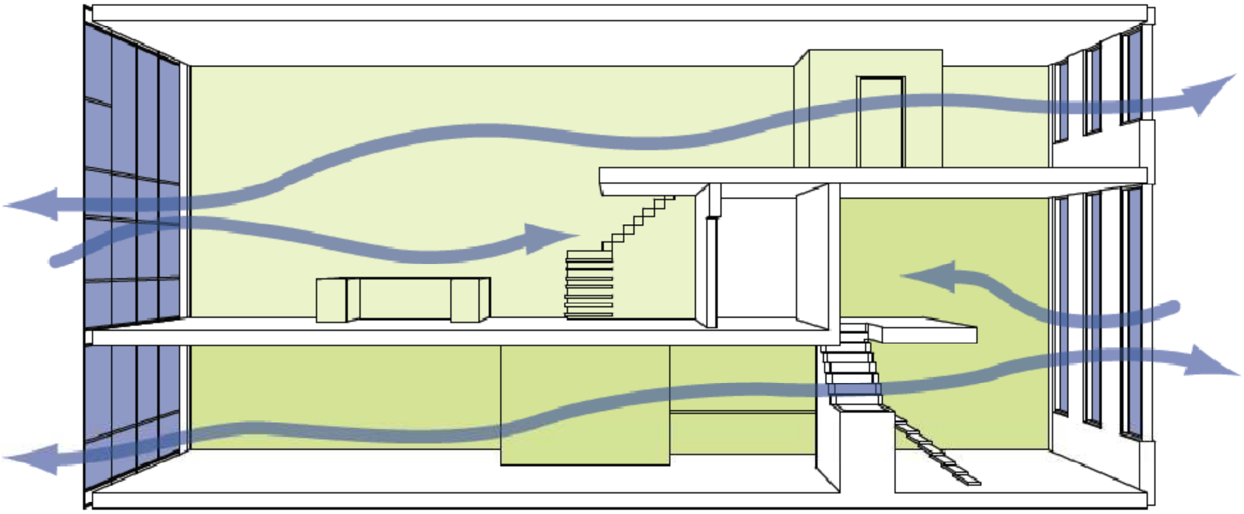


Figure 6: Natural ventilation scheme for two condominium units

3.1.1 RENEWABLE ENERGY SOURCES

Renewable energy sources will be incorporated into the system mainly to offset the electricity use of the electrolysis unit from the grid, in turn reducing carbon emissions upstream. The total amount of electricity consumption by the electrolysis unit totals to 683,280 kWh/year (Hydrogenics, 2010).

Solar and wind renewable sources are abundant in the Region of Waterloo and will be used as electricity sources for the electrolysis unit. Human bike generators in the fitness room of the building are also included in generating electricity for the electrolysis unit. The goal of implementing these systems is to move away from conventional methods of operating a building to new carbon reducing technologies.

3.1.1.1 WIND GENERATION

To offset the total amount of electricity that the electrolysis unit will be pulling from the grid, there are considerations of harnessing wind energy directly to the electrolysis unit. Wind is an abundant source of energy available all year round in the Region of Waterloo. The following table provides average wind speeds for the city at all times of the year:

Table 2: Wind Speeds for Waterloo (Environment Canada, 2010)

Period	Average Wind Speed (m/s)	Average Wind Energy (W/m^2)
Winter (DJF)	6.86	290.25
Spring (MAM)	5.76	188.25
Summer (JJA)	4.56	90.25
Fall (SON)	5.97	207.88
Annual	5.78	201.88

Waterloo has sufficient year round wind speeds to make it an effective renewable source for electrolysis operation (a minimum of 4.5 m/s at 50 m above ground level) (Environment Canada, 2010). Four V3.5 model wind turbines from CleanField Energy will be implemented to harness wind power for the residential unit. Located on top of the residential unit (approximately 43 m high) for ease of access and maintenance, four installed turbines will be situated on the north end of the building to avoid interference with the solar photovoltaic cells facing south (to be discussed). The turbines will be conveniently away from obstructions such as trees and power lines. Zoning issues have been considered and the plan abides by Waterloo city bylaws (City of Waterloo, 2010).

The four wind turbines will generate 7000+ kWh of energy per year (CleanField Energy, 2010). These turbines will contribute 1% of the total energy used by the electrolysis unit in continuous operation.

3.1.1.2 SOLAR PHOTOVOLTAIC PANELS

Solar photovoltaic (PV) panels will also be installed to provide an offset to electrolysis unit energy use. Located south facing at the top of the building and tilted 42□-45□ (from horizon), the solar PV panels will experience peak conditions daily between 10 am and 3 pm. The arrangement of the panels will allow sufficient space for maintenance and for the ability to change the tilt of the solar PV panel according to season. Solar modules will be purchased from Day4 Energy with peak power of 180.1W.

Table 3: Solar Power Generation (Natural Resources of Canada, 2007)

Month	Mean Daily Global Insulation (kWh/m^2)	Photovoltaic Potential (kWh/kW_p-year)	Electricity Production of each module (kWh/month)
January	2.5-3.3	60-80	1.05
February	3.3-4.2	100-120	1.65
March	4.2-5	100-120	1.65
April	5-5.8	100-120	1.65
May	5-5.8	140-160	2.25
June	5-5.8	140-160	2.25
July	5-5.8	140-160	2.25
August	5-5.8	140-160	2.25
September	4.2-5	100-120	1.65
October	3.3-4.2	80-100	1.35
November	1.7-2.5	40-60	0.75
December	1.7-2.5	40-60	0.75

290 solar modules will be purchased for a maximum amount of energy of 60030 kWh per year under peak conditions. These solar modules will be electrically connected in parallel to be continuously providing power to the system so as to avoid stopping electricity flow in case of a module failure. The solar panels will contribute approximately 8.8% of the total energy used by electrolysis.

3.1.1.3 HUMAN GENERATED POWER

The building will host a fitness room where specially designed exercise machines (elliptical trainers and stationary bicycles) will also be used to provide electricity for the electrolysis. An average person is capable of producing 150 Wh for an hour of vigorous exercise (WindStream Power LLC, 2010). In total, twenty human powered elliptical and bicycle machines will be purchased to contribute to renewable electrolysis power sources – not to mention adding increased motivation to building residents to become active! Assuming that the gym will be almost fully occupied in the early morning (5 am to 9 am) and late evening (5 pm to 10 pm) and half occupied during the day (9 am to 5 pm), these machines will be capable of producing approximately 10676.25 kWh in a year if the system were 75% efficient. This production is approximately 1.5% of the total energy consumption of the electrolysis, for a total renewable contribution of 11.3% to electrolysis operation from wind, solar, and human powered sources.

3.1.1.4 HEAT RECOVERY

Heat recovery will be implemented from the electrolysis unit to the residential unit for boiler water and space heating in common areas. The electrolysis unit is assumed to be 65% efficient (Hydrogenics, 2010), where the waste is primarily in the form of heat. This heat will offset the amount of natural gas required for space heating during the spring/fall where base heating is still needed, but not a large amount is needed. In this instance, heat recovery was considered for space heating displaces for 5.1% of the required amount of natural gas a year.

3.2 CARBON DIOXIDE EQUIVALENT EMISSIONS

A well to tank analysis was conducted to observe the level of CO_2 emissions produced by hydrogen and gasoline fuels. A projection to 2050 was also considered, under the assumption that technologies will change within that timeframe.

GHGenius, a Canadian software program that models the lifecycle assessment and future trend prediction of transportation fuels in Canada, was used for this analysis. Grams of CO_2/km travelled was used to generate comparative results. Gasoline with low sulphur (Low S) and compressed H_2 (CH2) from electrolysis were selected for comparison. The following results were obtained for light-duty vehicles:

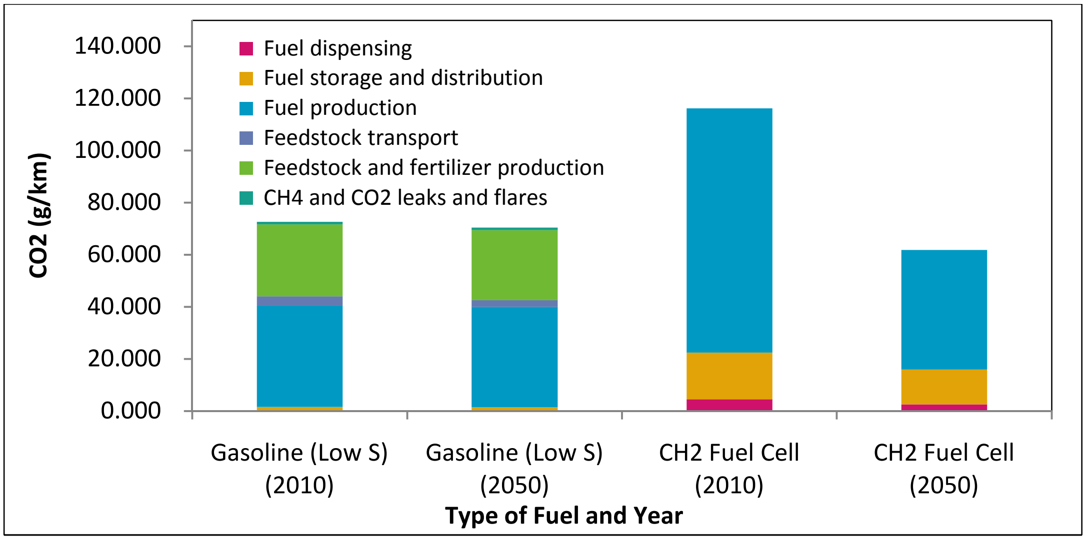


Figure 7: Well-to-tank analysis for gasoline vs hydrogen fuels in 2010 and 2050 (GHGenius 3.19)

As observed in the above figure, fuel cells currently create a large amount of carbon emission – primarily through fuel production. Projections to 2050 however show that carbon emissions will significantly decrease due to technological improvements of hydrogen production via electrolysis. Fuel cells convey much promise for the future, assuming these trends are correct. Gasoline shows very little change in the future and will most likely remain static as long as there is enough oil to produce gasoline.

The following figure displays the carbon equivalent emissions including vehicle operation and vehicle production. It is clear that upstream processes are the dominant source of carbon dioxide emissions for hydrogen-fueled vehicles. However, the lack of emissions during vehicle operation results in the overall amount being drastically reduced. With respect to the contribution made by vehicle production process, little difference is found between conventional and hydrogen vehicles. A decrease from 2010 to 2050 levels shows that these processes are expected to be cleaner in the future, regardless of vehicle type.

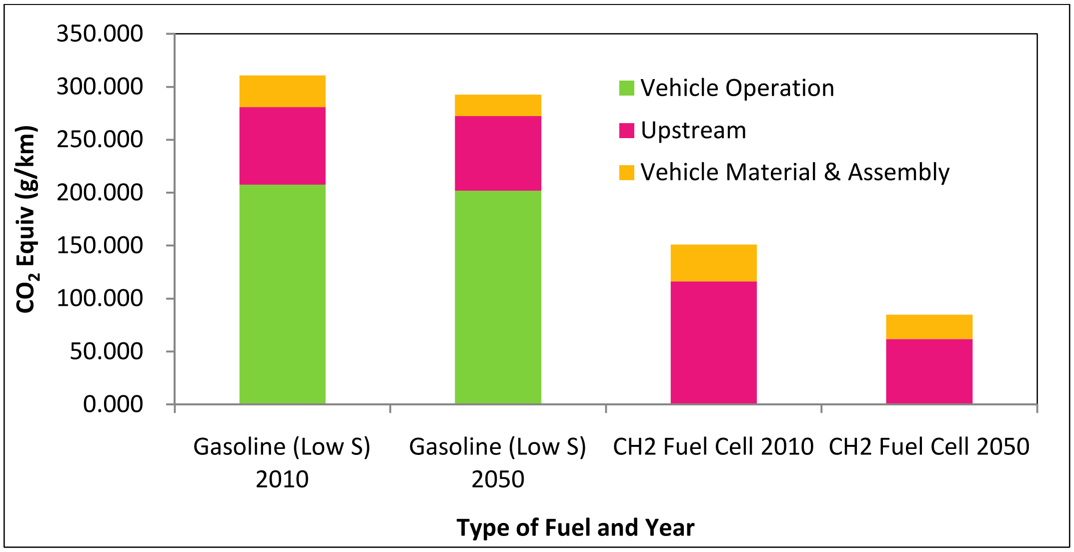


Figure 8: CO_2 Equivalent Emissions (g/km) between ICE and FC Vehicles for 2010 and 2050 (GHGenius 3.19, 2010)

3.3 ENVIRONMENTAL IMPACTS OF MAJOR EQUIPMENT

3.3.1 ELECTROLYSIS UNIT

Using electrolysis for hydrogen production is highly energy-intensive. Depending on the electrical grid mix, this could introduce significant upstream-related emissions (consider Ontario, with fossil fuels contributing approximately 16% and 6% from natural gas). Figure 7 shows that future hydrogen production (electrolysis) is expected to produce less emissions overall, likely from improvements in the technology used (higher efficiency using less energy and consequently less upstream emissions). With fuel cell development rapidly advancing, electrolysis is expected to improve as well.

Electrolysis eliminates local emissions at the fuel production point (as a result, emissions as consolidated at the power generation point enabling technologies such as carbon sequestration). It also allows for heat recovery to further improve process efficiency. With appropriate safety measures to detect and address leaks and proper fuel storage, this technology is environmentally friendly and safe.

3.3.2 SOLAR PHOTOVOLTAIC CELLS

Negative environmental impacts exist in the production, installation, and disposal of solar photovoltaic cells. Large amounts of energy and water are used in these operations as well as dangerous chemicals such as arsenic and cadmium (Union of Concerned Scientists, 2010). It is of best interest to select companies with a history of responsible production, installation, and disposal practices responsible and safe with production, installation, and disposing.

There are, however, nearly zero carbon equivalent emissions in converting solar energy into useable electricity. Inspections can be performed bimonthly to ensure that the solar PV cells are in good condition and no damage has occurred.

3.3.3 WIND TURBINES

Wind turbines are known to have very little impact on the environment, except for possible wildlife habitats (National Wind Watch, n.d.). The wind turbines will have a direct connection to the electrolysis unit to slightly reduce energy consumption from the grid. A vertical axis wind turbine was selected for this application to mitigate the negative impacts on wildlife that conventional horizontal axis turbines impose such as killing of birds. The small size of these turbines and the ability to mount them close to the ground make it suitable and easier to harness wind energy without needing to build a large tower in a field where animal habitats could be disturbed (National Wind Watch, n.d.). Wind turbines do not emit pollution nor use any fuel to power it, making the net output of energy positive (Lenzen & Munksgaard, 2002).

4.0 ECONOMIC AND BUSINESS ANALYSIS

There are many hydrogen fueling stations that have been implemented, especially in California where hydrogen vehicles were the first to market, but the residential unit is the first of its kind. The main goal of this project is to market to early adopters of hydrogen vehicles and locate in an area known for innovation. Placement in the Research and Technology Park (R&T Park) in Waterloo, Ontario, is a strategic location for incorporation of renewable sources while capturing a demographic of innovative and research-minded young professionals and academics and will greatly assist in fostering the hydrogen community that the station is hoping to project. The building will hopefully be LEED® certified once completed, making for a much more marketable opportunity to future clients and shareholders as the hydrogen economy begins its ascent.

4.1 CAPITAL COSTS

All prices in this section are listed in $CAD. Unfortunately there are no further potential tax credits for any of the systems listed before as of March 31, 2011. Table 4 outlines capital (including installation and contingency) and maintenance costs for the hydrogen system equipment, and Table 6 displays the costs associated with environmental equipment.

Table 4: Capital and maintenance cost estimates for the fueling system

Equipment	Total Cost ($CAD)	Maintenance/year ($CAD)
Electrolysis unit	$236,450.00 (Hydrogenics, 2010)	$11,822.50
Compressor	$177,150.00 (Ratkowsky, 2010)	$8,857.50
Storage Tanks	$125,000 (Dynetek Industries Ltd, 2010)	$520.00
Booster Compressor	$82,700.00 (Hartken, 2010)	$4,135.00
Dispenser	$82,700.00 (Broiges, 2010)	$413.50
Controls/Safety	$47,225.00	$425.03

Table 5: Summary of environmental equipment estimates for electricity offset

Environmental Equipment	Number of Units	Total Cost ($CAD)	Maintenance/year ($CAD)
Solar PV Modules	290	$515,100.00	$15,450.30
Bikes	25	$17,852.50	$892.63
Wind Turbines	4	$129,328.00	$1,293.28

4.2 OPERATING COSTS

Operating costs have been obtained from consumption values provided by equipment vendor specifications and the current cost of electricity. The hydrogen system is assumed to run continuously; which leads the total amount of electricity to approximately 65444 kWh/month and the total amount of water used for the system will be 289.03 L/day. Hydro is rated at an average of $0.07/kWh (Waterloo North Hydro Inc, 2010). The water rate in Waterloo is based on the small commercial building at a rate of \$9.66/m^3 (City of Waterloo, n.d.).

The total cost to operate the system will be approximately $4200.41/month. However, additional sources of electricity will be provided to offset the total amount of electricity used by the electrolysis unit. As mentioned previously, wind, solar, and human power will be harnessed into electricity for the electrolysis unit to use instead of relying entirely on the grid.

Wind Turbine: The 4 wind turbines will offset the electricity use of the electrolysis unit by 583.3 kWh/month if there is a constant minimum wind speed of 4.5m/s at approximately 50 m (see Table 2 for details).

Solar Photovoltaic Cells: 290 modules (with dimensions of 1m by 1.1m) will be installed on the rooftop of the high rise complex where sunlight is abundant and strong at peak hours. The solar PV cells can offset electricity use by 5002.5kWh/month (see Table 3).

Human Generator Bikes: 25 bikes will be installed in the fitness area for exercise and electricity generating purposes. They will produce 890 kWh/month.

Considering all these renewable energy systems, the total amount of electricity used from the grid will reduce to 58968.6kWh/month, lowering the price to produce 1kg of H_2 to $3.90.

4.2.1 COMPARISON TO CONVENTIONAL GASOLINE

Assuming the stated vehicle parameters apply to both conventional and light duty hydrogen vehicles, it is observed that for gasoline in Waterloo at an average price of $1.1/L (year 2000), gasoline will cost an average person $1,532.58/year while a resident of the “hydrogen condominium” operating a fuel cell vehicle will pay $1127.78/year - a savings of $404.80/year. As mentioned in the Environmental Analysis section, there will be further improvements to hydrogen production systems in the future whereby the costs to produce hydrogen will reduce. This is highly marketable for those considering fuel cell vehicles.

4.2 MARKETING PRICE

The total cost of the system (not including maintenance) is approximately $626,225 (capital and installation). For the unit prices of the system itself from vendors including piping and connections could be marketed at a value of $530,000 to building owners, not including capital and installation.

To include the environmental aspects of the system (wind turbine, solar PV, and human generator bikes), the total market price for the system could potentially be $1,089,475 if the potential buyer wishes to purchase the exact system to be implemented into a new construction apartment building.

4.3 MARKET GROWTH

The government of Canada and the United States are currently working towards introducing tougher emission controls for vehicle model 2011 to 2016. These new regulations whereby 2016 model vehicles are to reduce their emissions by 25 percent compared to their 2008 models (Macleans, 2010). This requires a target of 100km per six litres for 2016 models (Macleans, 2010). With conventional vehicles producing CO_2 emissions at a large scale, car manufacturers are beginning to consider alternative fuels instead, which leads to hydrogen vehicles as a very marketable product in the near future.

In terms of vehicles, the market for hydrogen fuel cell vehicles are currently small, however research has shown that the increase of hydrogen fuel cell vehicles will be significant in the future. Oak Ridge National Laboratory has predicted a growth of fuel cell vehicles market share by 50 percent by the year 2030 and 90 percent by the year 2050 (Greene, 2008). This allows for a competitive market for fuel cell vehicles. This is assuming that policies and developing hydrogen infrastructures will be put into place to aid transition to hydrogen vehicles. Research was also conducted to evaluate the price of fuel cell vehicles if policies are put into place to aid the industry to produce 1 to 2.5 million cost-competitive, market-ready products by 2025 (Greene, 2008). GHGenius also predicts this type of trend where technologies improve, reducing CO_2 emissions, making the hydrogen fuel cell more marketable (Figure 8). With the research conducted at Oak Ridge National Laboratory, hydrogen fuel cell vehicles have a change amongst the conventional vehicles today, leading to the fact that residential hydrogen fueling units will be needed.

Car manufacturers such as Honda, Toyota, GM, Mercedes and others are joining with fuel providers such as Shell to produce residential fueling station powered by 6 kW solar cells. This fueling station uses steam reforming to produce their hydrogen. They are looking to have these stations implemented in less than five years. Currently a residential refueling station exists for the Honda FCX Clarity on a Honda R&D facility in Torrance, California. (Sandru, 2010). Honda claims their hydrogen refueling station will reduce CO_2 emissions by and energy costs by 50 percent and 30 percent compared to an average family who uses an internal combustion engine and live in an average home powered by the grid.

Two companies have currently built electrolysis units specifically for fueling stations: British firm ITM Power and Canadian-based company Hydrogenics (Home Hydrogen Fueling Stations, 2010). These vast improvements over the years are making a breakthrough more for scientific purposes. So far residential fueling stations have not been sold to any customers; however there is promise from these technologies that it is not too far from seeing it in homes. The benefits for having these fueling stations is the small dependence on foreign fuels compared to local material, such as water or steam is easily accessible in a home.

4.4 CONSTRUCTION COSTS

The capital costs for the building provided below used RSMeans Cost Works. RSMeans provides localized costs for labour, equipment, and construction materials for buildings. Further cost analyses will need to be conducted for exact pricing.

Table 6: Building costs for the condominium

	Cost Per Square Foot	Cost ($CAD)
Substructure	**$18.53**	**$1,774,500**
Standard Foundations, Special Foundations, Slab on Grade, Basement Excavation, Basement Walls		
Shell	**$46.25**	**$4,430,000**
Floor Construction, Roof Construction, Exterior Walls, Exterior Windows, Exterior Doors, Roof Coverings		
Interiors	**$31.69**	**$3,035,000**
Partitions, Interior Doors, Fittings, Stair Construction, Wall Finishes, Floor Finishes, Ceiling Finishes		
Services	**$78.76**	**$7,544,000**
Elevators and Lifts, Plumbing Fixtures, Domestic Water Distribution, Rain Water Drainage, Energy Supply, Cooling Generating Systems, Sprinklers, Standpipes, Electrical Service/Distribution, Lighting and Branch Wiring, Communications and Security, Other Electrical Systems		
Equipment & Furnishings	**$2.21**	**$211,500**
Other Equipment		
Subtotal	**$177.44**	**$16,995,000**
Contractor Fees (General Conditions, Overhead, Profit)	$44.36	$4,249,000
Architectural Fees	$13.31	$1,274,500
Total Building Cost		**$22,518,500**

Architectural and contractor fees (for general conditions, overhead, and profit) were included totaling the cost to be $22,518,500, excluding the hydrogen system. This was used to provide estimates for those interested in building another hydrogen residential unit. LEED® implementation costs also need to be included. However, they will need to estimated by a LEED® AP.

5.0 MARKETING AND EDUCATION STRATEGY

5.1 OBJECTIVE / TARGET AUDIENCE

The marketing and information campaign purpose is to introduce the viable concept of residentially fuelled hydrogen powered vehicles to the city of Waterloo, Ontario. This campaign would target early adopters of fuel cell vehicles with the goal of creating excitement for a hydrogen based community built upon renewable resources and green living. Through the implementation of a successful marketing strategy it is hoped that hydrogen fueling will become known as a safe, reliable way to offer the ability to lower an individual's carbon footprint. It is hoped that this strategy will would attract public interest to the new hydrogen-based condo community.

5.2 MARKETING STRATEGY

The first stage of the campaign is to brand the building and fueling station with a business name – H_2 Incorporated (shortened to H_2 Inc) has been chosen to given a business edge to the idea of living in a hydrogen based community. The branding campaign will incorporate a viral marketing wave targeting online media, the two University campuses in the Waterloo Region (the University of Waterloo and Wilfrid Laurier University), high profile professional organizations, and environmental advocacy groups. This will involve stickers/posters introduced in high-traffic high-visibility areas displaying the H_2 logo and directing viewers to a media rich website. The online component of the viral campaign centres around a website and two YouTube videos. The first focuses on the social and environmental benefits of the new luxury condominium building and is aimed to generate buzz regarding the hydrogen fueling, LEED certification, and incorporated renewable energy. The aim is to tie the hydrogen vehicles and green lifestyle to luxury condominium living and entice early adopters to see the benefit in this new exciting community. The second contains information on hydrogen fuel including safety and reliability information and environmental statistics; not only is this new building buzz-worthy but it is also dependable and sustainable.

The second phase of the marketing strategy is to approach local and national newspapers with the unfolding story of a hydrogen powered vehicle community being introduced in the City of Waterloo. Five newspapers would be specifically targeted: the Kitchener-Waterloo Record, the Globe and Mail, Imprint and the Iron Warrior (the University of Waterloo student newspapers), and the Cord (the Wilfred Laurier University student newspaper). These stories would be timed with a newspaper ad (see below) for a full spectrum of information to reach a wide distribution audience in the printed media. Bus and bus stop advertisements in the City of Waterloo would also be run at this time to further raise the level of public consciousness of the fueling system. For further advertising within the streets of Waterloo, H2 Inc is prepared to sponsor the University of Waterloo Alternative Fuels Team (UWAFT) to drive their self-built fuel cell vehicle, upon its completion, around major arterial roads in the City of Waterloo after branding the vehicle with the company logo and website.

The focus of the marketing campaign is to bring attention to the concept of green living with the hydrogen-based condominium being a convenient way to buy a fuel cell vehicle and incorporate it into a green lifestyle.

5.3 EDUCATION STRATEGY

The education strategy seeks to balance the marketing strategy by ensuring that safety, environmental, and economic facts and statistics are made available to the public alongside the marketing campaign.

The first component is a series of public open houses based at the University of Waterloo that discuss in detail the components of the hydrogen fueling station, the safety features incorporated into the design, and other examples of hydrogen fueling in operation around the world. The open houses will also discuss the environmental and economic benefits of owning and operating a fuel cell vehicle and the convenience of residential refueling. The open house will be delivered by H_2 Inc and the format will be a brief presentation and a ‘did you know session’ as well as a Q&A period.

There is also a sustainment plan for keeping the community informed and with ready access to hydrogen information after the building has been constructed. The building foyer will serve as a permanent home for information including brochures covering the different aspects of design including safety, reliability, and environmental areas. The equipment room that houses the main components of the refueling station will be located on the main level of the building and will be viewable via wide widows to provide transparency of the process to the public eye.

Part of the sustainment plan is a café designed into the building, operated by a third party. This component creates a public aspect of the building that is inviting and draws people in; it gives them reason to linger where they could also be exposed to hydrogen lifestyle concept as well as the material described above. It is believed that a café in this location would be successful with a clientele of faculty and students from the University of Waterloo as well as professionals from several technology companies in the nearby research and innovation park. A depiction of the café in proximity to the hydrogen station equipment room is shown below.

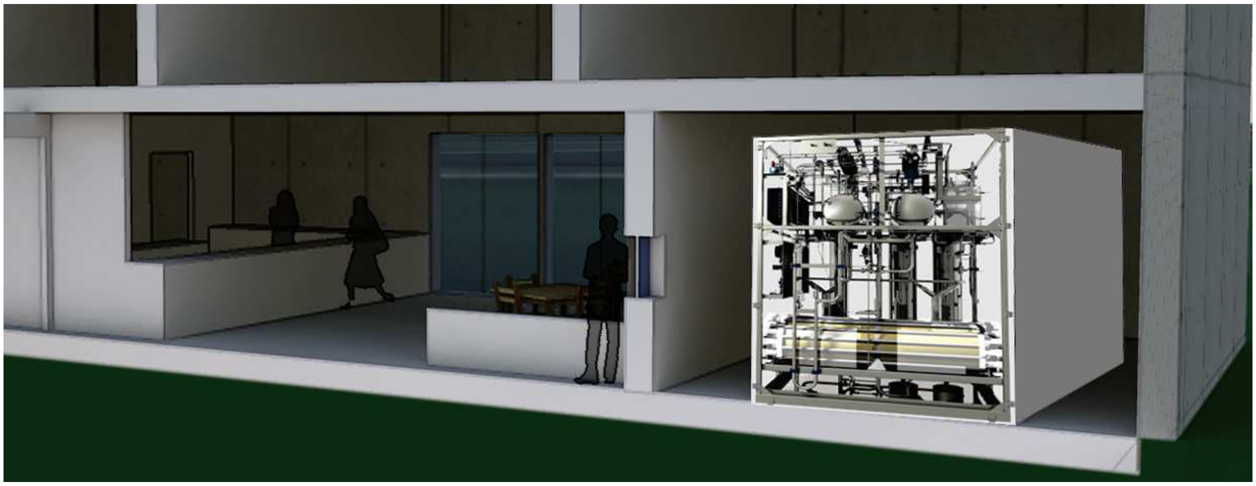


Figure 9: Publicly accessible cafe located next to hydrogen fueling station equipment room

The focus of the education campaign is to talk candidly about the implications of owning a fuel cell vehicle and living in the community and what this means to a person's life.

5.4 IMPLEMENTATION COSTS

The approximate costs of implementation of the marketing and educational strategies are summarized in the table below.

Table 7: Estimated marketing costs

Marketing/Education Material	Cost ($CAD)
Viral campaign stickers (1000)	$2500 (Staples Business Depot, 2010)
Viral campaign YouTube videos (2)	$3000
Kitchener-Waterloo Record (quarter-page ad)	$4610 (Waterloo Region Record, 2010)
Globe and Mail (eighth-page ad)	$5490 (Globe Media, 2010)
Bus shelter ads (two ads for four weeks)	$1600 (StreetSeen, 2010)
Bus exterior ads (two buses for four weeks)	$2400 (StreetSeen, 2010)
Hydrogen car branding and sponsorship	$1200
Brochures (5000)	$2000 (Staples Business Depot, 2010)
Website	$10/month

5.5 PRINT ADVERTISEMENT

Tired of the gasoline gridlock?

The hydrogen community is coming.

Be part of the solution

Introducing H_2 Inc Residential Refueling Systems

Bringing emission-free driving to your doorstep.

Coming soon to Waterloo Ontario

www.residentialh2.ca/waterloo

APPENDIX A: FUELING CALCULATIONS AND STORAGE SIZING

Hydrogen Cascading Tanks

Initial Pressure:	5000	psig
Initial Temperature:	273	K

	Mass When Full	Mol Density	Mass Density	Volume	Side Length	Length	Radius
	(kg)	(mol/L)	(kg/m3)	(m^3)	(m)	(m)	(m)
Tank 1 (LP)	14	11.522	23.22697	0.602748	0.844718	1.5	0.357641
Tank 2 (MP)	10	11.522	23.22697	0.430534	0.755097	1.5	0.302262
Tank 3 (HP	10	11.522	23.22697	0.430534	0.755097	1.5	0.302262

Cars Refuelled

Car Refuelled	0	1	2	3	4	5
Pressure Tank 1 (psig)	5000.00	3349.06	2785.86	2347.81	2007.10	1742.11
Mass LP Tank (kg H2)	14.00	11.51	9.58	8.07	6.90	5.99
Mass Car Tank (kg H2) - 1	-	3.29	2.74	2.31	1.97	1.71
Pressure Tank 2 (psig)	5000.00	3866.29	3557.60	3211.94	2867.70	2546.11
Mass MP Tank (kg H2)	10.00	9.49	8.73	7.89	7.04	6.25
Mass Car Tank (kg H2) - 2	-	3.80	3.49	3.15	2.82	2.50
Pressure Tank 3 (psig)	5000.00	4014.07	3866.76	3620.69	3276.27	2839.96
Mass HP Tank (kg H2)	10.00	9.85	9.49	8.89	8.04	6.97
Mass Car Tank (kg H2) - 3	-	3.94	3.80	3.56	3.22	2.79
Additional Pump Req (kg)	0.00	0.06	0.20	0.44	0.78	1.21
Pressure Tank 3 (psig) after boost	5000.00	3990.43	3784.19	3439.70	2957.50	2346.67
Mass Tank 3 (kg H2) after boost	10.00	9.80	9.29	8.44	7.26	5.76
Mass Car Tank (kg) - Final	-	4.00	4.00	4.00	4.00	4.00
Cumulative Pump Req (kg)	0.00	0.06	0.26	0.71	1.49	2.70

Fueling Characteristics

Total Hydrogen Refuelled	16	kg H2	Cascade Mass	34.000	kg H2
Total H2 Produced in 12hr	16.2	kg H2	Cascade Utilization	0.391	kg/total kg
Total Pump Requirement	2.699	kg H2	Booster Utilization	0.079	kg/total kg
			Compressor/Electrol Prod	32.400	kg/day
			Cascade Recov Time	11.852	hours

APPENDIX B: LEED CERTIFICATION REQUIREMENTS

The following table below overviews the following LEED credits to be obtained:

Total # of Points	Credit	Points to Be Awarded
3,6	Alternative Transportation: Public Transportation Access	6
1	Alternative Transportation: Bicycle Storage and Changing Rooms	1
3	Alternative Transportation: Low-Emitting and Fuel-Efficient Vehicles	3
2	Alternative Transportation: Parking Capacity	2
1	Site Development: Protect or Restore Habitat	1
1	Heat Island Effect: Non-Roof	1
1	Light Pollution Reduction	1
2,4	Water Efficient Landscaping	4
2	Innovative Wastewater Technologies	2
3	Fundamental Refrigerant Management	3
1-19	Optimize Energy Performance (30%)	4
1-7	On site Renewable Energy	7
2	Enhanced Commissioning	2
3	Measurement and Verification	3
2	Green Power	2
2	Construction Waste Management	1
2	Materials Reuse: 10%	2
2	Recycled Content: 10%	1
2	Regional Materials: 20%	1
1	Rapidly Renewable Materials	1
1	Certified Wood	1
1	Increased Ventilation	1
1	Construction IAQ Management Plan: During Construction	1
1	Construction IAQ Management Plan: Before Occupancy	1
1	Low Emitting Materials: Paint and Coatings	1
1	Low Emitting Materials: Flooring Systems	1
1	Low Emitting Materials: Composite Wood and Agrifiber Products	1
1	Indoor Chemical and Pollutant Source Control	1
1	Controllability of Systems: Lighting	1
1	Controllability of Systems: Thermal Comfort	1
1	Thermal Comfort: Design	1
1	Thermal Comfort: Verification	1
1	Daylight and Views: Daylight	1
1	Daylight and Views: Views	1
1	LEED(R) Accredited Professional	1
1	Durable Building	1

TOTAL POINTS: 63

Certification: Gold

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