2017-18 Hydrogen Student Design Contest

Project Mobius
"Revitalizing the Spirit of the '74 World's Fair"

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NOMENCLATURE

ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
NFPA	National Fire Protection Agency
OSHA	Occupational Safety and Health Administration
SAE	Society of Automotive Engineers
WAC	Washington Administrative Code
DOT	Department of Transportation
UL	Underwriters Laboratories
NEC	National Electrical Codes

EXECUTIVE SUMMARY

Avista Corporation, a local power and gas utility, owns and operates a hydroelectric power plant in Riverfront Park in Spokane, Washington. Urbanova, a joint urban development project of Avista and the city of Spokane has the opportunity to reutilize 576 kW from a minimum flow requirement through the Upper Falls diversion dam in Riverfront Park. This proposal outlines a power-to-gas (P2G) system which converts the carbon-free hydroelectric power into a multipurpose clean hydrogen fuel. The uses of hydrogen range from carbon-free transportation fuel to supplementing natural gas delivery systems through pipeline injection.

Riverfront Park has access to excess power generating capacity, abundant water, and is located on the edge of Spokane's developing smart-city U-district. Spokane, and Riverfront Park, has the historical recognition as host of the first environmentally themed World's Fair, cementing the Northwest's conservation leadership in 1974. The proposed P2G system would be contained within three standard 20-foot shipping containers. An aerial view of the installation would reflect the logo of the '74 Expo, a Mobius strip. This design choice reinvigorates the spirit of '74 with a new view for the future of environment and energy in the Northwest.

The proposed P2G plant will be owned by Avista, including the primary components; an electrolyser from an international manufacturer and a compressed hydrogen tube-trailer. The capital expenditure is estimated to be $2 million. Annual operating costs of $191,868 will support daily production of 225 kg of hydrogen. The projected uptime of the P2G trailer station is 90%. During tube trailer exchanges and routine maintenance, hydrogen production will be injected into the local natural gas pipeline. Existing hydrogen stations purchase hydrogen at wholesale rates between $6 and $12 per kg. The production of hydrogen for regional transportation may yield annual revenue of $794,307. Assuming complete utilization of the fuel, a payback period of two and a half years is expected.

The P2G station is in accordance with all federal, state, and local codes and regulations ensuring public safety. Thermal and pressure safety features as well as real-time monitoring of all components ensures safe station operation.

1. INTRODUCTION

'Stluputqu' or 'Swift Water' as it was known by the native tribe describes the series of waterfalls in the heart of Spokane, Washington. A small diversion dam at the base of the falls completed in 1890, 5 years before the Niagara Falls powerplant, is the longest running hydropower facility in Washington State. The neighboring Riverfront Park was constructed to celebrate this history for the 1974 World's Fair, the first environmentally themed World's Fair. Washington's Innovation for Sustainable Energy Organization seeks to celebrate this storied location by implementing a Power-to-Gas system in Riverfront Park in the shape of a Mobius strip – the continuous and cyclical geometry symbolizing the spirit of the 1974 World's Fair.

Launched at the 2017 World Economic Forum, the Global Hydrogen Council (GHC) was initiated by 13 international companies with the mission to further hydrogen in the world energy transition. The GHC released a roadmap for the adoption of hydrogen technologies that concludes: by 2050, hydrogen could meet 18% of the world's final energy demands, avoid 6 Gt of C02 emissions, i.e. 20% of C02 emission reduction targets by 2050, create a market with revenues by 2.5 trillion dollars each year, provide 30 million jobs and reduce C02 in sectors like transport, industry and residential by between 40% and 60% [14]. This effort parallels that of the United States Department of Energy's H2@Scale initiative to further deep decarbonization of fuels [17].

Power-to-gas (P2G) systems offer a unique opportunity by utilizing the excess energy to split water into hydrogen and oxygen gas. By utilizing an electrolyser and hydroelectric power, the hydrogen is cleanly produced, justifying its usage as a zero-emission technology. The resulting pure hydrogen gas has utility for many needs, including the fueling of zero emission, hydrogen powered vehicles. Hydrogen Fuel Cell Vehicles (FCVs) have seen an unprecedented 300% growth since 2016 [13]. This corresponds to about 2,500 vehicles being sold or leased. However, by 2035 this number is expected to rise to 22.2 million [8]. By taking an average FCV traveling 10,000 miles a year, this translates to roughly 3.7 billion kg of hydrogen needed by 2035 [2]. Major infrastructure development is required to meet this estimated demand, making P2G a great option to supply this market.

Inland Washington has the most affordable low carbon electricity in the country with rates 50% below the national average [19]. 71% of the state's electricity is provided by hydroelectric, a clean and renewable resource. As of 2016, Washington State provided 52% of the United States renewable power generation. Washington offers a unique opportunity for intermittent production issues due to its access to renewables, such as the Wild Horse Wind & Solar Facility, located in central Washington that produces 273 MW of wind and 502 kW of solar, making the issue of intermittent energy production prevalent in the state. Unfortunately, the region lacks storage capacity or alternative revenue streams, such as the production of hydrogen from these intermittent sources [20][15]. The resources available have the potential to create an environment in which a local utility can tackle the challenges renewable intermittent energy sources present while creating an opportunity to expand business into hydrogen based technology.

Avista Corporation is a local utility that provides power to the City of Spokane. Spokane offers a unique location for the Avista Corporation to expand its energy market. Partnered together, the City of Spokane and Avista are working on an urban development project known as Urbanova to expand their smart-city district in the center of the city to a more environmentally-stable zone [3]. The Urbanova Initiative has given Avista the opportunity to utilize 576 kW from the existing Upper Falls plant for the purpose of creating an environmentally friendly bedrock to promote the adoption of hydrogen-based technology.

This report proposes a P2G station located at Riverfront Park in Spokane, Washington and examines the economic viability of this solution. The document will introduce the station's design, applicable codes and public interaction therein. The final outcome of this project is for the adoption of cleaner, zero-emission technologies to not only drive down the world's current C02 emissions, but provide a stable platform to create growth in the hydrogen transportation market not otherwise seeing any investment.

2. SITING

The proposed site of the project, including all local and national codes and regulations, will be discussed in this section. A brief rationale will then explain why the chosen site is beneficial. This section will include a detailed table for correct setback distances for gaseous hydrogen systems, as well as the permitting process required by the City of Spokane.

The power-to-gas system has been sited at Riverfront Park in Spokane, WA for proximity to Spokane's smart-city district and for public engagement and education. A single electrolyser can refuel a 280 kg compressed hydrogen tube-trailer in just over a day for distribution throughout the city. The specific station site will be in the north-western section of Riverfront Park. The park is owned and maintained by the City of Spokane, but shares land with the Avista Corporation that maintains the hydroelectric dams located around the park. Figure 1 references the site location in respect to Spokane's Smart City District. Figure 2 shows the system in proximity to the north-western corner of Riverfront Park.

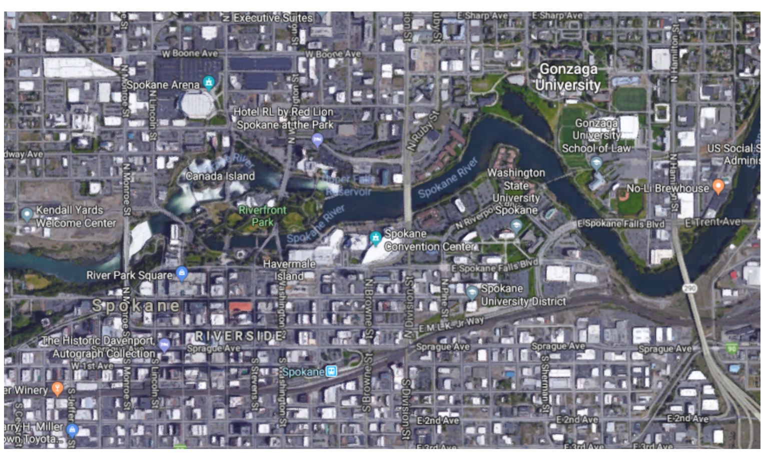


Figure 1: P2G site location relative to Spokane's Smart City District. The site location is marked by a yellow star.

This location was not only picked for its access to power and water but for its location on the edge of Spokane's developing smart-city U-district. When observ-

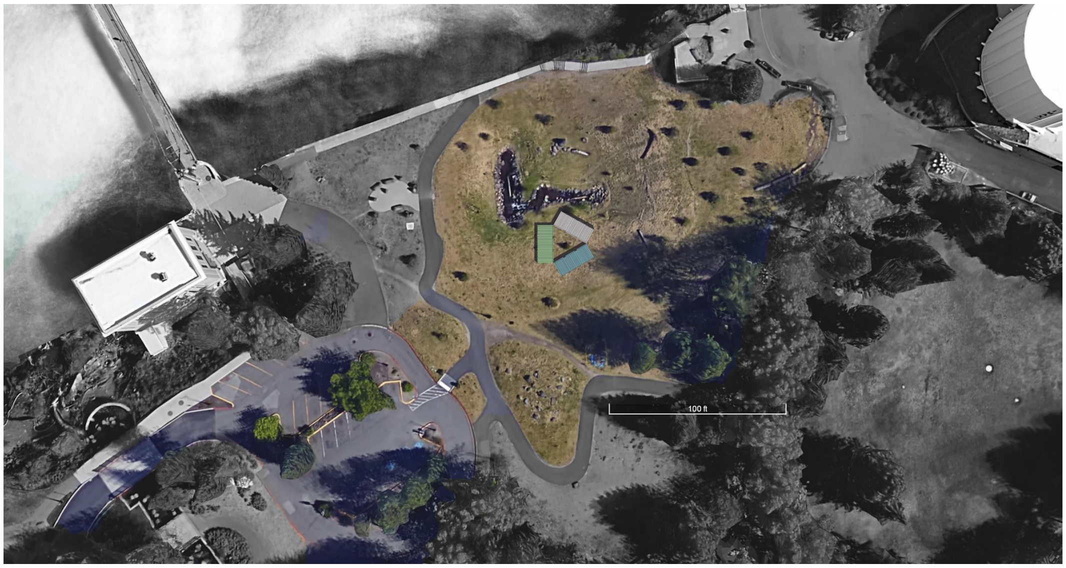


Figure 2: P2G system location in the north-western corner of Riverfront Park.

ing the system design, it can be seen that each ISO container forms the sides of a equilateral triangle. This corresponds to the logo of the '74 Expo, based off of the Mobius strip. This was done in part to keep the spirit of the fair alive, as well as promoting clean hydrogen technology within the Spokane region. With these reasons and with being within reach of Avista's monitoring station, this region was chosen as the primary site of this P2G station. Figure 3 gives a side view rendering of the system.

Figure 3: Side view rendering of the site.

The implementation of the power-to-gas system on Riverfront Park was evaluated using the Site Planning Process from the City of Spokane in addition to the

Washington Administrative Code (WAC) and NFPA 55. The WAC provides codes and regulations that are specific to the State of Washington and are generally in addition to, or more limiting than national regulations. Therefore, if the power-to-gas system abides by the WAC, it also abides by national regulations and likely abides by all other state regulations. NFPA 55 encompasses codes surrounding implementation of hydrogen systems. Units in this section will be expressed in feet and cubic-feet to be consistent with local regulations and permits.

The City of Spokane has a regulated commercial permitting process for new construction. This process encompasses multiple steps and requirements that must fall under the city's Plan Review and must comply with the city's Comprehensive Plan and applicable building, mechanical, electrical, plumbing, fire, and energy codes. Upon application submission and payment of appropriate fees through Spokane Business & Development, the project plans and supplemental reports are forwarded to 11 separate agencies located at Spokane City Hall for review of the various reports. Upon acceptance, a building permit may be granted [18].

The Washington Administrative Code (WAC 296-24-31503) (apps.leg.wa.gov 2017) provides the specific requirements for gaseous hydrogen system design, location, site considerations, operations, and maintenance that must be met in the state of Washington. This code is in addition to standards set forth by NFPA 55 and NFPA 2. The P2G station also falls under WAC 296-24-31503 regarding gaseous hydrogen systems because of the storage of compressed hydrogen gas in the system buffer storage. All internal plumbing, sensors, pressure relief, and ventilation components included with the system fall in accordance with NFPA 55 and local WAC requirements. Each of the regulations is determined based on the volume or size of the hydrogen storage tanks in cubic feet. Table 1 shows the required setback distances for the storage tank used in this P2G station.

Table 1: Minimum distance (in feet) from gaseous hydrogen system to exposure from Table H-2 of WAC-294-24-31503

Types of Exposure	Description	Gaseous Hydrogen Storage ($<$ 3,000 CF)
Air compressor intakes or inlets to ventilating or air-condition equipment	N/A	50
Concentration of people*	N/A	25
Public sidewalks	N/A	15

** In congested areas such as offices, lunchrooms, locker rooms, time-clock areas, and places of public assembly.*

Further information for set-back distances of gaseous hydrogen systems can be located from Table H-2 of the previously stated standard (WAC-294-24-31503).

Figure 4 shows a diagram of the site with the required setback distances from the power-to-gas station. The site has existing electric and water infrastructure, and is within 100 feet of a city roadway.

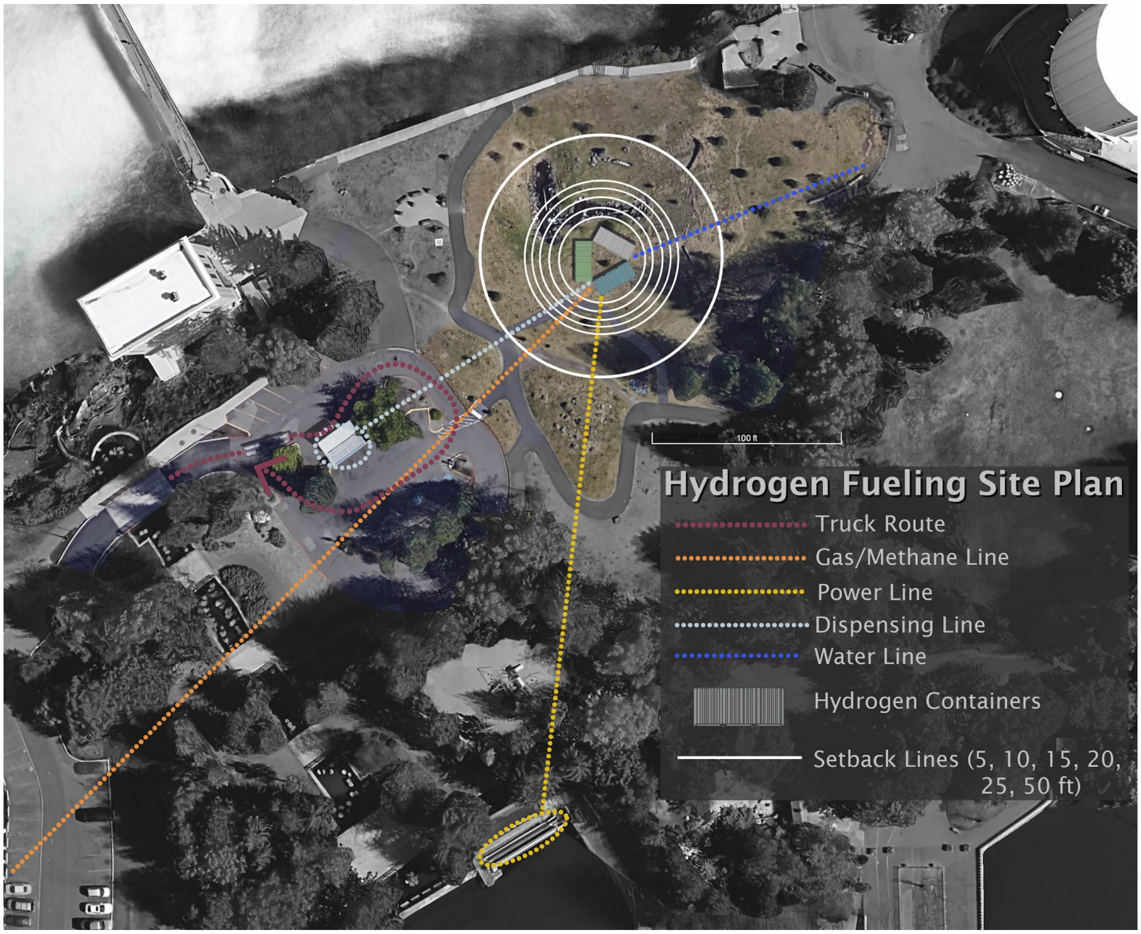


Figure 4: Site layout on the Riverfront Park grounds showing setback distances surrounding the P2G station.

This power to gas station adheres to state WAC regulations, has access to both the required electricity and water infrastructure, and meets the local conditions and requirements set forth by the City of Spokane.

3. DESIGN DATA & EQUIPMENT DRAWINGS

The P2G system centers on an electrolyser that derives its electricity from 576 kW of power produced from local hydroelectric turbines. The hydrogen generated from the electrolyser will be used to fill a 280 kg tube trailer or injected into the local natural gas grid. The major equipment, hydrogen utilization, and monitoring system will be discussed in this section.

3.1 ELECTRICITY TO HYDROGEN CONVERSION

Hydrogen gas will be produced with a PEM electrolyser using water supplied by the City of Spokane and electricity supplied by Avista. The HGas system utilizes polymer exchange membrane (PEM) electrolysis technology the main components of which are a polymer membrane that is selectively permeable to hydrogen and water, and two electrodes. Applying an electric potential to the electrodes splits water at the anode into its constitutive elements: hydrogen and oxygen. The hydrogen ions diffuse through the membrane where they combine with electrons to form hydrogen gas. Several membrane electrode assemblies are stacked in electrical series to produce the desired amount of hydrogen. Figures 5 and 6 shows the process of electrolysis and a PEM stack.

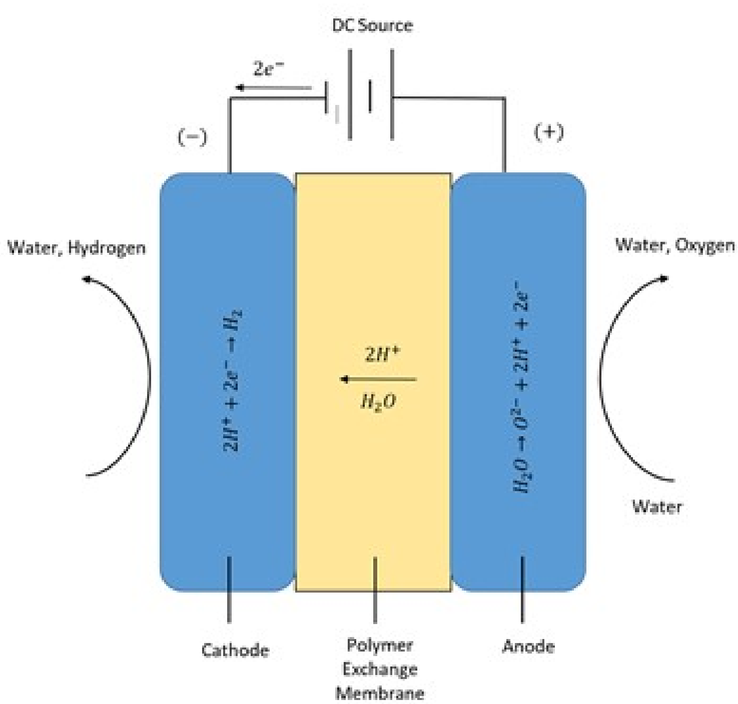


Figure 5: PEM Electrolysis Diagram.

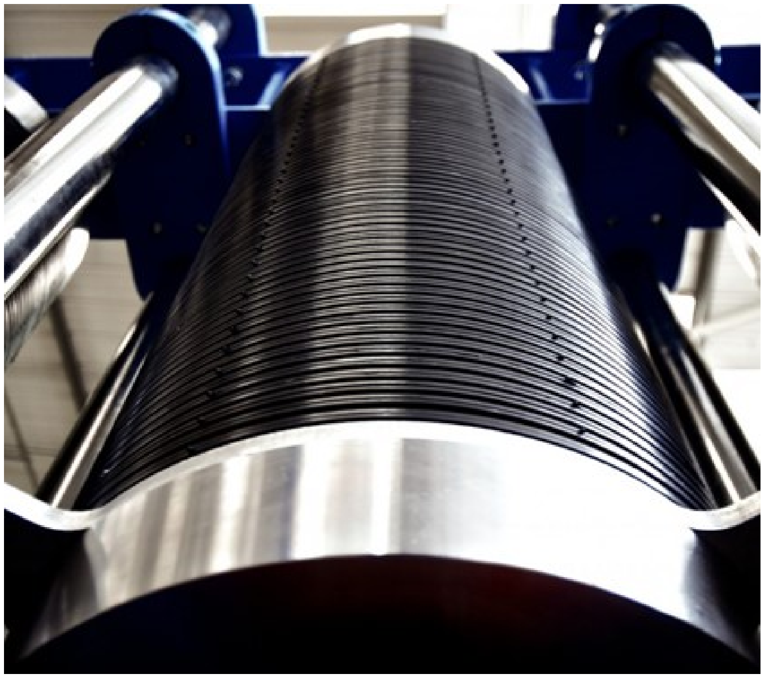


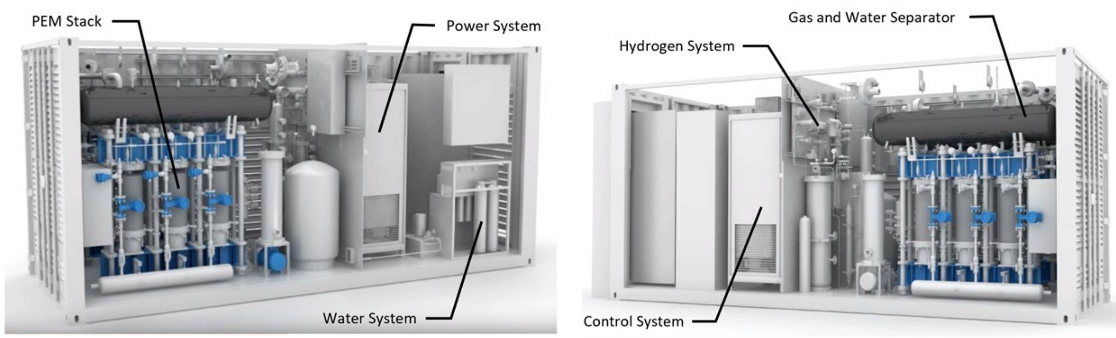
Figure 6: PEM Electrolyser Stack

The specifications of the PEM electrolyser system for this project are listed below in Table 2.

Table 2: Electrolyser system specifications

Specification	Data
# PEM stacks	1
Maximum power use	672 kW
Nominal power use	550 kW
Maximum hydrogen generation	267 kg/24hr
Nominal hydrogen generation	225 kg/24hr
Hydrogen generation pressure	20 bar
System efficiency range	53-60 kWh/kg
System efficiency at nominal operation	58.5 kWh/kg
Ambient temperature range	-15 to 40 (^{o}C)
Buffer storage tank pressure rating	20 bar
Buffer storage volume	15 m^3

The components of the PEM electrolyser system includes an on-board power transformer, water and hydrogen purifier, gas separator and control system. The power system converts alternating current to direct current and regulates the power to all components. A purification system ensures the city water supply does not contaminate the PEM stack. The hydrogen produced is extracted through a water and gas separator to the appropriate fuel cell grade of 99.999%. A control system controls the feedstock water flow, exhaust oxygen flow, the gas and water separator, the power system, and the hydrogen system. The control system is also used to monitor the components, determine if a fault has occurred and perform further analysis, automatically reconfigure the system, alert an operator, or shut the system down for maintenance or repair. Figures 7a and 7b include a schematic of the system components [11].



(a) Right Side (b) Left Side

Figure 7: PEM electrolyser System

3.2 EQUIPMENT

3.2.1 Power Generation

The systems power needs are met by utilizing existing hydroelectric turbines that are run and operated by Avista Corporation. There are currently two hydroelectric dams within close proximity of the specified site, which are shown with a yellow and red circle in Figure 8. These local, environmentally friendly power sources include a single 10 MW capacity Francis Turbine [16], located at the Upper Falls Dam, and a 14.8 MW capacity Kaplan Turbine [16], located at the Monroe Street Dam site. The power produced from the turbines are sent to the electrical grid. An Avista representative has helped to determined that 576 kW of power can be drawn from the Upper Falls Dam for use. Therefore, using this pre-existing power source helps to lower the project's environmental impact, while still meeting the electrical needs of the system.

Figure 8: Riverfront Park Map with (a) red circle: Location of Upper Falls 10 MW subterranean Francis Turbine, (b) Yellow circle: Location of Lower Falls 14.8 MW Kaplan Turbine, (c) Blue circle: Planned Site Location.

3.2.2 Hydrogen Compression

Compression needed for safe and efficient fueling of the tube-trailers will be done with a hydrogen-rated compressor capable of inlet pressures as low as 7 bar and as high as the needed 250-bar to fill tube-trailers. The compressor is capable of handling the entirety of the electrolyser's output. This system will be located within the same ISO container as the buffer storage, decreasing the amount of piping needed between the systems.

3.2.3 Connections, fittings & piping

All tubing, connections and fittings will be constructed from certified 316 Stainless Steel to avoid embrittlement. The electrolyser, compressor and buffer storage will all be connected with $\frac{1}{4}$" 316 SS tubing. All fittings between components will be Swagelok VCR fittings to provide maximum leak protection.

The dispensing unit will be equipped with a Staubli GMV 09 Nozzle, which has built in safety features when not connected. These nozzles only allow hydrogen to be dispensed when connected to a tube-trailer and are in accordance with SAE J2600.

All water resources will be directly transported from the city's water main to the electrolyser via schedule 40 $\frac{3}{4}$" piping

3.3 GAS TRANSPORTATION AND STORAGE

3.3.1 Truck Transport

After leaving the electrolyser, hydrogen will enter the system's buffer storage where it will wait to be fed into the system's compressor. After being compressed to 250-bar, the hydrogen will flow to a dispensing unit just off-site. The hydrogen will be dispensed to an industrial gas supplier's tube-trailer. In general, these trailers storage capacity ranges from 250 kg - 280 kg. The tube-trailers will be owned and maintained by separate industrial gas companies and will not be operated by Avista. These trailers will then have the capability of delivering hydrogen throughout the Spokane region. This increased supply of clean, renewable hydrogen enables the adoption of hydrogen fueled cars, buses and other fleet vehicles used in the city. A tube-trailer could be filled every 27 - 30 hours, depending on the size of the available storage. Expected downtime between fueling is 10 to 30 minutes in an ideal scenario.

Typical hydrogen tube-trailers are rated to carry 18 to 60, 20.5 ft long tubes, which can store 25,395 to 84,668 cf of hydrogen. Hydrogen tube trailers range from 24' to 28' and can weigh between 17,500 to 48,000 pounds. All tubes must follow DOT 3A/3AA-2400 for pressurized gas cylinders [10].

The tube-trailer will be parked 250 ft. to the south-west of the station, in a parking lot where it can fill. Figure 4 shows the parking lot and the truck route.

A dispensing unit will be available just off-site and will offer self-service to the trained tube-trailer drivers. Upon arrival of the trailer, the main cab will detach and leave the trailer for fueling overnight. The tube trailers fill from the compressor through the dispensing nozzle.

3.3.2 Natural Gas Pipeline Injection

The hydrogen produced by the P2G station will be injected into the natural gas pipeline when it is not being used to fill a tube trailer. The amount of hydrogen injected into the gas grid will not exceed 20%. This limitation is based on values provided by the National Renewable Energy Laboratory [7], and is in place to prevent increased risk of ignition. The injection of hydrogen into natural gas pipelines will aid in reducing carbon emissions. This equates to a savings of $3/kg of injected hydrogen for Avista. Hydrogen injection into the gas grid will serve both residential and commercial customers. Direct injection of hydrogen into the gas line was chosen over methanation because it is more cost efficient, requires less processes, and is overall more sustainable.

3.3.3 Hydrogen Storage

The system's buffer storage is contained within a 20' ISO container. The system has a capacity to store 530 cubic-feet (15 m^3) of hydrogen at 20 bar, just over 2.5 hours' worth production capacity. This translates to 24.5 kg within the vessel. The storage tank meets NFPA 2 for gaseous hydrogen storage and is equipped with pressure sensors and relief valves in case of over pressurization.

3.4 COMMUNICATIONS EQUIPMENT

3.4.1 Communication & monitoring systems

This system, as seen in Figure 9, is designed to run completely autonomously. Autonomy requires installation of a control system which is able to transmit current sensor data, report on system faults, and manage emergency system shutdowns.

The heart of the control center for this system will be a programmable logic controller (PLC). To facilitate messaging with Avista employees, the center will be equipped with a remote monitoring system, seen in Figure 10, and cellular uplink that will alert Avista of any warnings or alarms.

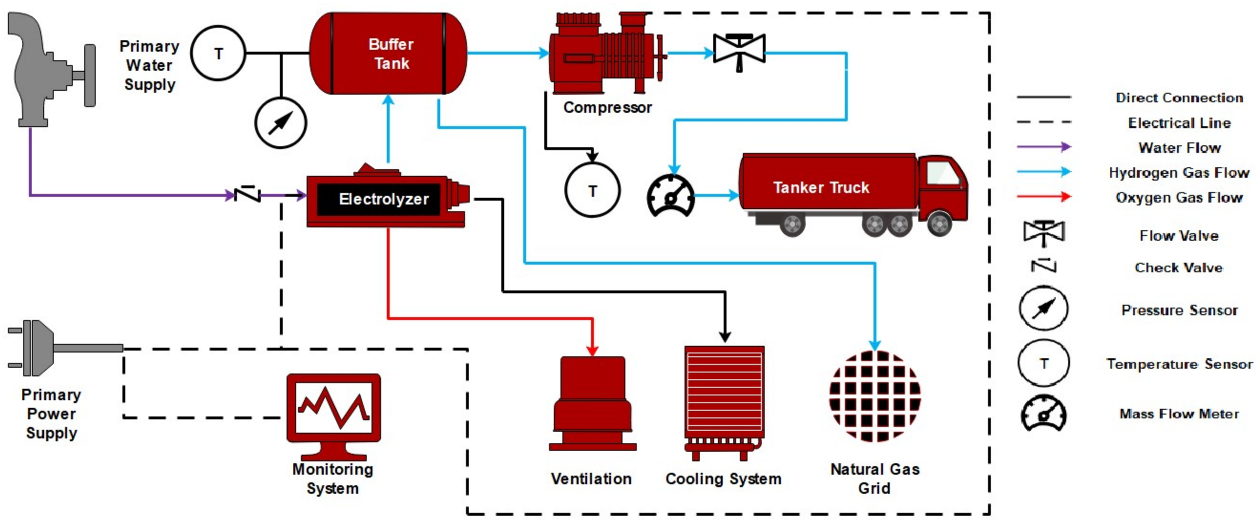


Figure 9: Remote monitoring system.

The PLC will be interfaced with all system components, as shown in Figure 10. The electrolyser features a built in PLC, which manages all subsystems and relays that information to the master control. All other components of the system will be monitored passively by the PLC and the sensor data will be logged.

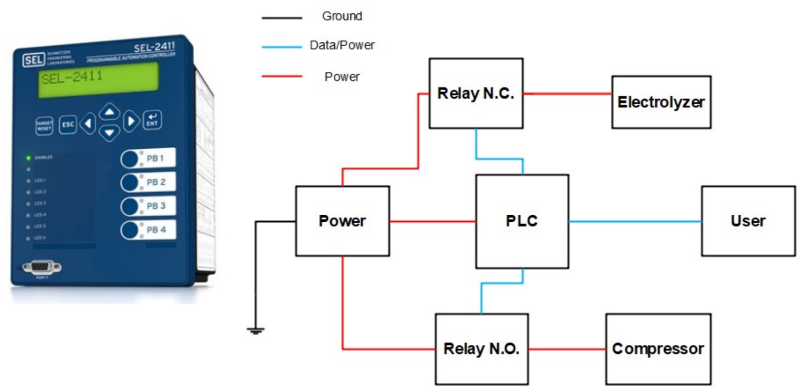


Figure 10: PLC system integration.

As safety is of paramount importance, the PLC will be interfaced with a fire safety monitoring system and have the ability to shut down the system as a whole in an emergency. Shutdown will be facilitated by a master relay, controlled by the PLC, which is able to terminate the power to all systems.

Sensor information will be accessible onsite, utilizing a workstation similar to Figure 11. In addition, this stream of information and control will be available to Avista headquarters, so real-time shutdown and monitoring is possible. This workstation will provide the capability to selectively shutdown systems when maintenance is required. The accessible sensor data will be displayed onscreen for the user to review.

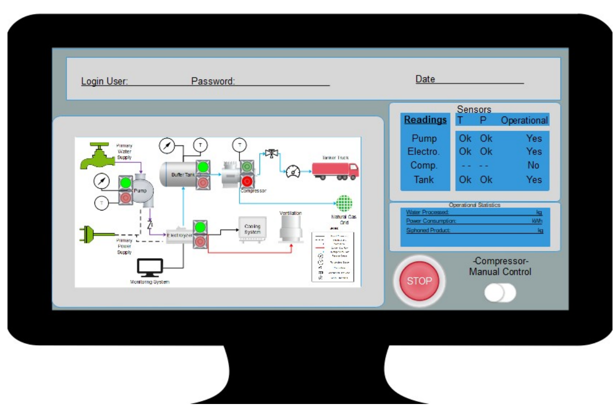


Figure 11: Workstation view showing real-time sensor information.

3.4.2 Safety Equipment

The PEM system that will be put in place has automatic safety features, including automatic shutoff. There will be hydrogen detectors present outside of the electrolyser and along the pipes where hydrogen will be flowing to detect any leakage. There will also be cameras with night time lighting so that all parts of the system can be seen at any time to deter vandalism. The monitoring system mentioned previously will not only have an automatic shutoff feature, but will also have a fire suppression system, a temperature monitoring system, a pressure monitoring system, pressure relief valves and an alert system, all of which are specified in Table 3. There will be relevant safety personnel (firemen, policemen, and specialized Avista personnel) informed automatically with the specifics about what is going wrong with the system. Other Avista employees responsible for the system will also be automatically contacted. The public will be notified through floodlights and an alarm telling them to evacuate the area. A small fence will also be placed around the perimeter to comply with set-back distances set in Table 1.

3.5 HYDROGEN USE

3.5.1 Vehicle Refueling

Hydrogen will be used to fill tube-trailers that are owned by industrial gas companies. This allows these companies to provide hydrogen to the local market and enables the distribution of hydrogen to consumers for FCVs and hydrogen powered buses.

3.5.2 Natural Gas Pipeline Injection

When the tube-trailers are not filling, the hydrogen will be injected into the city's natural gas grid. This increases the lower heating value of the hydrogen-natural gas mixture, allowing for cleaner burning natural gas.

3.6 EQUIPMENT FOOTPRINT

Table 3 shows the footprint of all major components in the design of the P2G station. All components self-contained within ISO containers will be omitted

Table 3: Major component footprints.

Equipment	Dimensions (L,W,H)	Weight (lbs)
20' ISO Container	20',8',8'6"	5,050
Electrolyser	20',8',8'6"	7,000
Buffer Storage	15',3',3'	6,000
Natural Gas Mixing Plant	8',5',5'	2,500

4. COST AND ECONOMIC ANALYSIS, COMMERCIAL VIABILITY

The P2G station's economic success depends on the system's capital costs, profit margin and projected return on investment. A detailed analysis for the station's commercial viability is given below.

4.1 OPERATING COSTS

The monthly operating costs associated with the power to gas plant are provided in Table 4.

Table 4: Fixed monthly costs

Expense Item	Monthly Cost*
Power	8,415.33
Water	1,083.33
Maintenance	6,652.75
Total	16,112.08

** Costs are approximate based on nominal use.*

The monthly water demand is based off of needed input into the electrolyser and is purchased from the City of Spokane. All maintenance is based on estimates provided by the major equipment manufactures. The annual maintenance cost of the electorylser components is 4% of the capital cost. All other components are approximated to have a maintenance cost that is 10% of their capital cost. The cost of hydropower provided by Avista is expected to be $0.2/kWh.

4.2 CAPITAL COSTS

Table 5 provides an itemized list of all the system components which represents the capital cost for the power to gas plant. These costs were obtained by getting quotes from each manufacturer. The estimated capital cost of the station is $1,967,680.

Table 5: Itemized list of station.

Equipment	Manufacturer	Qty.	Cost*(ea.)	Total
Electrolyser	ITM Power	1	1,316,643	1,316,643
Hydrogen Compressor	Hydropac	1	25,000.00	25,000.00
Compressor Control & Piping	Hydropac	1	29,000.00	29,000.00
H2 Dispensing Nozzle	Saubli	1	10,947.00	10,947.00
Dispensing hose	WEH	1	1,948.00	1,948.00
Natural Gas Mixing plant	NetzDienste	1	300,000.00	300,000.00
Natural Gas Piping (feet)	McMaster-Carr	810	9.87	8,000.00
20' ISO Storage Units	Port Containers LLC	1	4,900.00	4,900.00
Buffer Storage	Fibatech	1	100,000	100,000
SS Tube Fitting	Swagelok	5	11.80	59.00
SS Tube Fitting, 90^o Union Elbow	Swagelok	5	17.08	85.40
Medium Pressure Tube Fitting, 90^o Union Elbow	Swagelok	5	95.85	479.25
Medium Pressure Tube Fitting	Swagelok	2	82.08	164.16
SS Tubing (feet)	McMaster-Carr	250	20.58	5145.80
Pressure Sensors	Omega	4	250.00	1000.00
Temperature Sensors	Omega	1	33.00	33.00
Hydrogen Sensors	Honeywell	3	240.53	721.59
Pressure Relief Valves	Swagelok	1	155.00	155.00
Fire Control Panel	Fire-Lite	1	608.56	608.56
Remote Annunciator	Silent Knight	1	179.95	179.95
Multi-Sensor Detector	Fire-Lite	3	59.00	177.00
Speak-Strobe Fire Alarm	Wheelock	6	75.00	450.00
Fire Suppression System	Cease Fire	5	1095.00	5475.00
Video Surveillance	VideoSurveillance.com	1	3499.00	3499.00
Lighting	Utilitech Pro	6	69.98	419.88
Sound Barrier Sheets (sq. feet)	Audioseal	135	2.44	330.00
Sound Masking Generator	Atlas Sound	1	214.36	214.36
Installation Fees	Hired Contractor	1	150,000	150,000.00
Fees and Permits	City of Spokane	1	2,045.80	2,045.80
Total				1,967,680

** In congested areas such as offices, lunchrooms, locker rooms, time-clock areas, and places of public assembly.*

4.3 ECONOMIC ANALYSIS

The main two revenue streams proposed for this system are hydrogen injection into the natural gas grid and hydrogen fueling of tube-trailers, valued at $3/kgand$6-12/kg, respectively.

The commercial viability of the proposed power-to-gas system is a necessary component of the project's success. Commercial viability depends on the required rate of return and the market demand at the necessary prices. Since the rate of return dictates the minimum allowable price Avista will accept, there is a price floor and corresponding demand that dictates which prices provide an acceptable return.

In this case, Avista faces a maximization problem in which they must choose price p to maximize profits. The decision is complicated by two factors. The first is that any hydrogen not sold can be injected into natural gas pipelines, serving as an alternative market to absorb excess hydrogen production. Hydrogen injected into the natural gas pipelines has a value equivalent to $3 per kilogram. The second is that estimating the demand function in a nascent market with few actors is notoriously difficult, more so in the case of fuel.

The first issue is addressed directly in formulating Avista's profit maximization problem as a choice of optimal price p, which has the form

$$\{p_t\} = \arg\max_{\{p_t\}} \sum_{t=0}^{T} \left[p_t q(p_t) + 3(Q - q(p_t)) - cQ\right](1-\delta)^t - c_0,$$

where p_t is the price of hydrogen set by the owner at time t, q(p_t) is the annual demand for hydrogen as a function of price p_t, Q is the total annual production of hydrogen, c is the marginal cost of production, and c_0 is initial capital costs. Due to the project guidelines, the return on investment cannot exceed ten years. The discount rate is given by δ and is set at 6%.

The above equation captures the profit dynamic that in each year total hydrogen Q is produced, at operating cost cQ. Avista chooses p_t and sells q(p_t) for a profit of pq(p), and injects the remaining (Q-q(p)) earning $3 per kilogram injected.

Since we assume a time-invariant demand function, we can simplify the above equation to

$$p = \arg\max_{\{p\}} T\left[pq(p) + 3(Q - q(p)) - cQ\right] - c_0,$$

with the solution being the price that solves $T\left[q(p) + (p-3)\frac{\partial q(p)}{\partial p}\right] = 0$.

It remains to estimate the demand function q(p). Currently hydrogen providers in the Spokane area manufacture hydrogen in California and transport it to Spokane at an estimated cost of $12-15 per kilogram. Assuming a competitive market, hydrogen providers will find it more profitable to purchase hydrogen from the P2G operator and demand will exceed total supply Q. However, above $15 hydrogen providers will find it more profitable to obtain hydrogen from outside the Spokane region. We therefore estimate demand q(p) as a function of total production and of price, where

$$q(p) = \begin{cases} Q & \text{if } p < 12 \\ \frac{15-p}{3}Q & \text{if } 12 \leq p \leq 15 \\ 0 & \text{if } p > 15 \end{cases}$$

With this estimate of demand, the optimal price choice set by Avista is $12, yielding profit of T[12Q-cQ]-c_0. Given capital costs of $1,967,680 and annual operating costs of $191,868 as shown in Table 5, annual profits are estimated at $794,307. Of annual operating costs, $12,177 are from consumed water and $100,984 are from consumed electricity, with the remainder being maintenance and operating costs of the P2G system. The net present value of total profit over ten years is $3,773,858. The sharp profit-maximizing price point is due to the price ranges on estimates of current costs to transport hydrogen.

4.4 COMMERCIAL VIABILITY

An assessment of the commercial viability of a project depends not just solely on its profits, but also on its profits relative to potential profits of other similar projects. For this reason, a useful metric is return on investment (ROI), defined as the ratio of total profits and initial costs. Figure 12 shows the corresponding ROI at different price points given the estimated demand function. The shaded area comprises the range of annual demand from 50-100% of total production based on price.

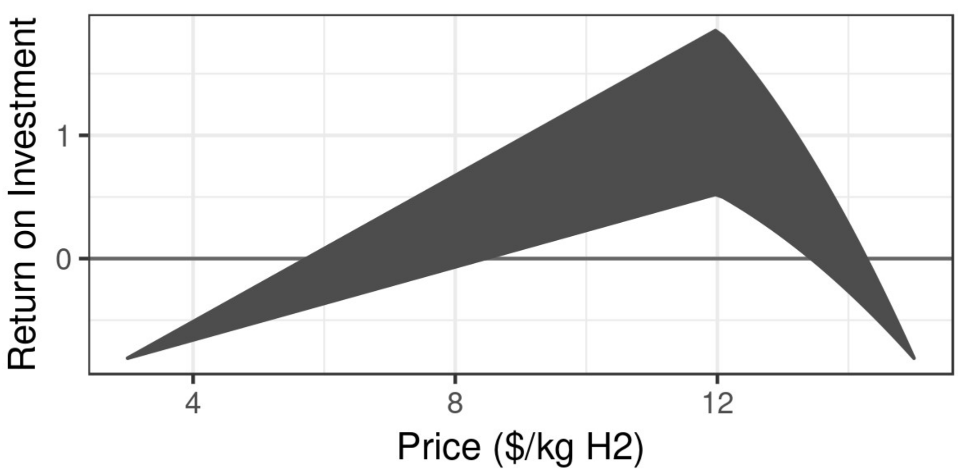


Figure 12: Return on investment with varying demand in response to price.

At 100% of estimated demand, ROI is positive for a price point between $5.67/kg and $14.27/kg. The sharp decrease in ROI above the $12/kg reflects rapidly declining demand as wholesalers obtain their hydrogen from elsewhere.

At 50% of estimated demand the pattern is similar, except that the P2G owner must charge at least $8.33/kg and less than $13.42/kg in order to earn a positive ROI. These two scenarios provide a range in which to consider prices in light of demand uncertainty. The minimum price should be between $5.67/kg and $8.33/kg and the maximum price should be between $13.42/kg and $14.27/kg based on the P2G owner's expectations of demand. Since price is maximized at $12/kg, the P2G owner can expect a positive ROI for even 50% of the initial estimate of demand.

Given the uncertainty involved in a nascent market and the paucity of data on current hydrogen prices, an alternative approach is to consider the price necessary to reach a certain ROI given a level of demand. Figure 15 shows the price necessary to achieve a specified ROI for a given demand level ranging from 0-100% of total hydrogen production.

To the extent that the estimate of the demand function is correct, namely that wholesalers will be willing to buy hydrogen at prices up to $12/kg, Figure 13 represents the matrix of price decision choices and the ROI that can be expected given a fixed level of demand. At a maximum price of $12/kg, ROI is positive for any level of demand above 29% of annual production. At $5.73/kg, a positive ROI is achieved if demand meets total production levels.

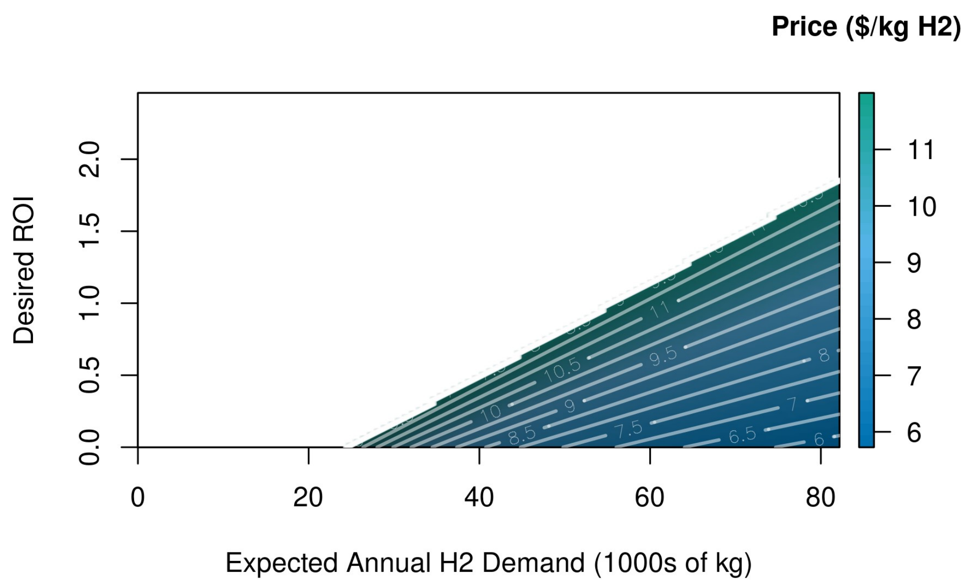


Figure 13: Price needed to reach a specified return on investment given stable non-price dependent demand.

5. SAFETY ANALYSIS & CODES AND STANDARDS

All components in the system are required to abide by city, state and federal codes and regulations.

5.1 FMEA

The system is analyzed for possible subsystem failures through a process known as Failure Mode and Effect Analysis (FMEA). The purpose of FMEA is to reduce, if not completely resolve, all failures in a system. Understanding each key component's function as well as what their vulnerabilities are such as potential power loss, vandalism, or human error, plays as important a step in system design for improvement. This method has been a highly effective avenue of analysis since the 1950s and is still heavily practiced to this day.

FMEA, again, ranks potential failures in a system and does so by calculating the Risk Priority Number (RPN). The RPN is the value assigned to a component to measure the its importance when considering failure; the greater the value of the RPN, the greater the need to develop the appropriate precautions to mitigate its failure. RPN is calculated by taking the product of three assessed actions: Severity, Occurrence, and Detection.

Severity (SEV) measures the impact, not only on the component itself but, on the surrounding components/environment. SEV is scaled, typically, from 1 to 10, 10 being the most hazardous the outcome, should failure become a reality. Occurrence (OCC) measures a systems probability of failure within certain periods of time. Whether the component will likely fail within a week's time, requiring extra preventive measures, or is likely to fail within a year. OCC is scaled from 1 to 10, 10 being the most probable to fail within a small period of time. Detection (DET) measures the likelihood of noticing failure once it has occurred. This is also scaled from 1 to 10, 10 being practically impossible to detect the failure. Figure 14 provides brief explanations of the criteria used to determine each rank. Typically, FMEA's categorize the scale with color: 1-2 (Green), 3-7 (Yellow), and 7-10 (Red).

Severity (SEV)			Occurrence (OCC)				Detection (DET)		
Effect	Criteria	Ranking	Probability of Failure	Time Period	Percentage	Ranking	Detection	Criteria	Ranking
Hazardous: No Warning	Injury	10	Almost Certain	More than once per day	> 30%	10	Almost Impossible	Very Unlikely	10
Hazardous: Warning	Risk Safety	9	Very High	Once every 3-4 days	< 30%	9	Very Remote	Detectable on Yearly Inspections	9
Very High	Damage System Integrity	8	High	Once per week	< 5%	8	Remote	Detectable on Monthly Inspections	8
High	Damage Equipment	7	Moderately High	Once per Month	< 1%	7	Very Low	Detectable on Weekly Inspections	7
Moderate	Rendering Useless	6	Moderate	Once every 3 Months	< 0.03%	6	Low	Easily Detectable via Manual Inspection	6
Low	Loss in Performance: Severe	5	Low	Once every 6 Months	< 1 per 10,000	5	Moderate	Detected via Daily System Checks	5
Very Low	Loss in Performance: Minor	4	Very Low	Once per Year	< 6 per 100,000	4	High	Detected via Remote Operator	4
Minor	Inconvenience	3	Remote	Once every 1-3 Years	< 1 per 500,000	3	Very High	Detected via Operator w/ Error Message	3
Very Minor	Detected without Performance Loss	2	Very Remote	Once every 3-7 Years	< 1 per 1 Million	2	Almost Certain	Detected Immediately w/out Warning	2
None	Unnoticed, No Performance Loss	1	Almost Impossible	Once every 7-10 Years	< 1 per 10 Million	1	Certain	Detected Immediately and Warning	1

Figure 14: Explanation of Ranking Criteria for all components for an FMEA

Understandably, the dispensing system has the highest RPN, primarily because of the fact that the dispenser is relatively dependent upon all other subsystems. Without the electrolyser, the nozzle would still dispense to the extent of the buffer tanks remaining contents. However, once this buffer tank emptied, the system would not be able to dispense. Without the compressor active, the system would be able to dispense, but never to fill a tube tank entirely. These are only a few examples towards the point that the dispensing system has the greatest risk of failing. Provided the dispensing nozzle is damaged during fueling, the monitoring system would signal the automated flow valve to close. The second highest RPN resides with the monitoring system. Disabling this component would prohibit the ability of remotely deactivate the systems safety measures. The monitoring system is key because it controls the entirety of the facility. The primary way this would fail would be through power loss. The third and final RPN is the electrolyser. This component is intended to be constantly running at full capacity for long periods of time. Failure of the electrolyser is more of an inconvenience than a serious safety concern.

These three high RPN subsystems have the potential to bring about inconveniences. To avoid failure of any of the components listed, check-ups and daily monitoring are advised with the suggested time intervals provided in Figure 15 under the Prevention column.

Subsystem	Potential Failure Mode	Potential Failure Effect(s)	SEV	Potential Failure Cause(s)	OCC	Prevention of potentional failure cause(s)	Detection of Potential Failure occurrence	DET	RPN
Electrolyzer	Power loss, loss of water flow, pressure backflow	Loss of hydrogen fueling capability, loss of injection	8	power loss, poor maintainance, vandalism	2	Supervising, daily monitoring, regular system checks	PLC detection, continuous maintenance	2	32
Water Pump	Malfunction, power loss, damage to turbine	Unable to deliver water to electrolyzer	3	wear, power loss, faulty seals	1	Routine check ups, maintenance	Fluid flow will cease	1	3
Gas Compressor	Malfunction, power loss, damage to turbine	Loss of hydrogen tanker fueling capability	2	power loss, wear, faulty or damage seals	4	Back up power system, routine check ups	Visible detection, physical handling of the device	1	8
Buffer Tank	Pressurization outside of specifications	Tank Ruptures, Loss of gas to atmosphere	7	pressure relief valve failure	1	Daily valve checking, pressure instruments	Sensor readings recognize over pressurzation	2	14
Monitoring System (PLC)	Loss of power, computer or sensor failure	Unable to prevent system failures or issue maintainance	6	loss of power, vandalism, faulty sensors	3	Monthly inspections, daily system monitoring	Remote operator loses connection, back up system alert	2	36
Fire Suppression	Power loss, loss of communication with PLC	Unable to prevent spread of fire	2	Power loss, unintentional system activation	1	Surveillance systems, routine maintenance	System alerts the proper authorities and operator	1	2
Cellular Uplink	Power loss, loss of communication with PLC	Unable to alert Avista employees of system issues	2	Power loss, service provider down, physical	2	Back up system automated connection	Internet disconnected	2	8
Dispensing System	Nozzle connection or leak, power loss	Unable to dispense	6	Power loss, wear, compressor failure	4	Weekly inspections, breakway nozzle	Monitoring system, leak detection	2	48

Figure 15: FMEA for Power to Gas Subsystem

6. REGULATIONS, CODES AND STANDARDS

Development of a power-to-gas system must adhere to numerous regulations from a variety of local and national regulatory agencies. Table 6 below describes said regulations that were employed and how they are applicable to a power-to-gas system in a public space. Any exemptions for hydrogen are reported in Table 7.

Table 6: Applicable regulations used in the development of the P2G station.

Application	Prevention Strategy	Applicable Regulations
Setback distances	The System will be placed within acceptable range of any street, river or building that complies with regulatory codes.	WAC 296-24-31503, NFPA 55, OSHA Standard 1910.103
Fire-resistant materials	Interior fire-resistant materials will line the interior of the system, preventing catastrophic failure due to fire.	ASTM E84, ASTM E136, NFPA 55, UL 454
Hydrogen Dispensing	The tube trailers and nozzles will comply with the appropriate pressure class to avoid overpressurization or leakage.	SAE J2600, SAE TIR J2799
Tanks and piping	All tanks and piping will comply and be rated to gaseous hydrogen.	NFPA 2, NFPA 704, OSHA Standard 1910.103, WAC 296-24-31503, ANSI B31.1-1967, ANSI 31.3-1966
Signage	Applicable signage will be posted on and around the system to inform the public.	NFPA 55, NFPA 704, OSHA Standard 1910.103, WAC 296-24-31503
Electrical equipment	The electrical systems will communicate with monitoring to ensure continued nominal operation.	NFPA 55, OSHA Standard 1910.103, NEC Article 840, 800.173, 800.93-A, and 514
Safety equipment	The sub-systems will be outfitted with correct sensors and valves to mitigate any overpressurization or failure.	NFPA 55, NFPA 68, WAC 296-24-31503
Exposure limits	Hydrogen is a non-toxic substance, making exposure a non-issue.	Non-applicable under OSHA Standard 1910.103

Table 7: P2G station regulation exemptions

Regulation	Explanation
Emergency Planning and Community Right-to-Know Act (EPCRA), 40 CFR	Gaseous hydrogen is not a toxic material and is exempted from reporting requirements under Section 3012 of EPCRA.

7. OPERATION & MAINTENANCE

For a P2G station, it is common practice that the subsystems run autonomously for as long as possible. Good practice does include an operation team nearby or onsite to monitor a systems function. P2G systems are expected to operate for long periods of times and are simple to maintain or repair. The necessity of this is to optimize the limit of operational downtime

7.1 OPERATION

The Power to Gas system is designed to run autonomously, with the functionality to switch between tube tanker dispensing, and injection into the natural gas grid. This two-state system involves running the electrolyser continuously, while the remaining components are controlled by the monitoring system.

The electrolyser includes an onboard PLC, whose schematic is shown below in Figure 16. It has been designed with autonomy in mind, with the ability to manage all input and outputs of the system, and will feed information back to the monitoring system. In addition, it can shut the electrolyze down in the event of a critical failure, and send an alert to the monitoring system.

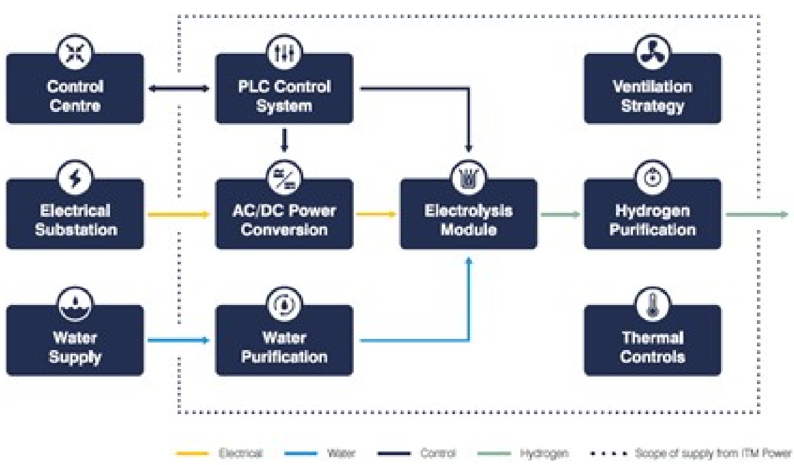


Figure 16: An onboard PLC schematic

The remaining system is controlled by the monitoring system. It is designed such that when hydrogen is being drawn by the dispensing station, the flow intended for blending into the gas line will be shut off, shifting flow into the compressor. The compressor will then be kicked on, and the tube trailer filled. When the tanker is filled, a pressure sensor will report back to the monitoring system, and the above procedure will be reversed.

The minimum operational state of the system will be when hydrogen is no longer being dispensed to a tube tanker. In this phase, the compressor will be offline, extending the life of the unit through the reduction of wear. The hydrogen flow will not be curtailed, and will be mixed into the natural gas line at the same pressure as the 20 bar electrolyser outputs.
At peak output, all components will be use the entirety of the available power from the turbine. Peak operation will be functioning just over a day in length, which is the estimated fill time of a tube truck. In this state, the pump is expected to need replacement every 4 years, while the electrolyser and compressor are 20 years. The buffer tank, piping, and all valves have lifetimes near to or more than the electrolyser and compressor, and are expected to outlive the proposed installation.

7.2 MAINTENANCE

This system will have a monthly maintenance schedule, where the system is shut down for 1-2 days, dependent on if seals, fittings, or other easily replaceable components are required. This monthly servicing will involve employees of Avista performing inspections of the compressor, electrolyser, pump, and dispensing station. Components which are to be entirely serviced by Avista are the buffer tank, fittings, valves, and the dispensing station. In the event of the monitoring system detecting a pressing problem, an inspection regime will be implemented immediately so that repairs can be completed.

From time to time, maintenance will be required on the critical electrolyser and compressor systems. A maintenance cycle on the compressor and electrolyser system will be dictated by the chosen compressor and electrolyser models, and the type of service contract taken out by Avista.

8. ENVIRONMENTAL ANALYSIS

Because the proposed system operates using only water and electricity collected from existing turbines in the Spokane River, there will be no carbon emissions from the production of hydrogen. The only outputs will be hydrogen gas and oxygen gas from the electrolyser, however emissions from the tube trailers used to transport the hydrogen will also be considered. There will also be emissions associated with the development of the needed infrastructure, such as power, natural gas, and water lines, as well as expanding the nearby parking lot to accommodate tube trailer parking. Also discussed is the noise impact the system will have on the nearby surroundings. Because the site is in a public park, it is important it does not have an adverse impact on the residential population, while meeting all codes and regulations set by the city of Spokane and the state of Washington. In this section, the resources, emissions, and noise associated with the system's operation will be further discussed.

8.1 RESOURCE ANALYSIS

The only resources that will be consumed during the operation of the system are water, by the electrolyser, and electricity, used to power the pump, electrolyser, and compressor. The water will be provided through piping connecting the system to main water lines just to the east. The electricity will be routed to the facility from power lines just to the south of the site, which are fed by the electrical grid. The extra electricity produced by the turbines is currently curtailed and can be readily connected to the P2G system. Through its utilization, the P2G system will turn waste electricity into a clean fuel source for the city. The electrolyser and compressor consume a total of 580 kW of electricity nominally, which can be reduced to 576 kW by slightly reducing the performance of the electrolyser in order to be fully fueled by the extra electricity. The natural gas in the city's lines are being omitted as a resource as it is produced and upheld by Avista. The tube trailers that are being filled will be provided by a third party and were not included in the resource analysis, however their emissions will be considered.

8.2 EMISSION ANALYSIS

With the P2G system utilizing a net-zero emission turbine, and only producing oxygen and hydrogen first hand, there are virtually no carbon emissions resulting from the facility itself. The produced hydrogen is collected and ultimately purchased by third parties, for purposes such as manufacturing, chemical production, or use as a fuel source. Hydrogen will also be injected into a natural gas line at up to 20%-volume of the total gas feed to supply homes and businesses throughout the city. Because hydrogen produces only water when combusted, the overall carbon emissions associated with burning the natural gas blend over pure natural gas is reduced by about 8%, while increasing energy output [5]. As a result, residents will be burning cleaner, more efficient natural gas in their homes and businesses. The oxygen is non-polluting and will be vented directly into the atmosphere as it is produced, at a rate of 1800 kg of O2 per day.

The hydrogen tube trailers used for transportation will be owned and operated by an industrial gas supplier. Typical tube trailers get an average of 6.5 miles per gallon of diesel and the resulting greenhouse gas emissions are summarized in Figure 17, depending on the average speed of the tube trailer [1].

Speed Range (mph)	CO_2	N_2O	CH_4	Units
0 (Idle)	4640	0.037	0.183	g/hr
1 - 5	3842	0.015	0.785	g/mile
6 - 10	3489	0.015	0.606	g/mile
11 - 15	2865	0.015	0.318	g/mile
16 - 20	2351	0.015	0.145	g/mile
21 - 25	2109	0.015	0.102	g/mile
26 - 30	1979	0.015	0.082	g/mile
31 - 35	1872	0.015	0.066	g/mile
36 - 40	1786	0.015	0.056	g/mile
41 - 45	1723	0.015	0.05	g/mile
46 - 50	1682	0.015	0.049	g/mile
51 - 55	1662	0.015	0.053	g/mile
56 - 60	1665	0.015	0.062	g/mile
61 - 65	1690	0.015	0.075	g/mile
66 - 70	1737	0.015	0.094	g/mile

Figure 17: The greenhouse gas emissions of tube trailers at speeds from 0-70 mph

8.3 NOISE ANALYSIS

The only appreciable noise generated by the P2G system will be from the operation of the electrolyser and compressor, with the compressor being the loudest component. The noise provided by the electrolyser and compressor in tandem is estimated to be about 70 decibels within 10 meters of the system. To mitigate this, several steps will be taken to cancel out as much of the noise as possible. The electrolyser and compressor are both shipped in steel containers, which when closed will dampen the majority of the noise. Also, noise canceling foam will be used to line the steel containers along with the operation of a white noise machine. As a result, the noise released to the environment will be minimal, and will meet all of Spokane City's noise regulations and codes set by WAC 173-60-040 [12]. This system falls under class B regulations which state it must remain under 65 decibels to stay within the maximum permissible environmental noise levels. Riverfront Park is closed from the public between midnight and 5 AM so there is no concern of disturbance during these hours. The necessary steps have been taken to ensure the welfare of the Riverfront Park public in Spokane in order to maximize their comfort.

A PROMISING FUTURE FOR WASHINGTON STATE

This project would increase Washington's potential to be a leader in the hydrogen fueling world. Currently most of the hydrogen produced is not used for fueling vehicles and much of Washington's hydrogen is provided by the state of California. With the movement towards clean energy this will put Spokane ahead of the curve and will catalyze the adoption of clean energy technologies within Washington and possibly around the United States. This project has the potential to offset 2005 metric tons/ year of carbon dioxide which is equivalent to the emissions of 430 gasoline powered passenger vehicles.

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APPENDIX

Policy and Regulatory Analysis & 1 Pager for Policy Maker

The technology of power-to-gas (P2G) involves splitting water into its constituents, hydrogen and oxygen gas, utilizing electricity. This is known as electrolysis and is completed by an electrolyser. The oxygen gas can be used for various industries, including cancer and wastewater treatment. The hydrogen can be used for rocket fuel, superconductivity research, but more importantly, hydrogen fuel-cell vehicles (FCV). These vehicles produce no CO2 emissions, and their only by-product is water. The average range of FCVs is around 300 miles per tank fill [6].

Strict codes slow the installation of hydrogen production systems and they are provided by the National Fire Protection Agency (NFPA), Occupational Safety and Health Administration (OSHA) and the Compressed Gas Association (CGA). Many of the impedances can be mitigated by streamlining the permitting process for implementation of hydrogen production systems.

Another issue preventing large-scale adoption of P2G stations is the expensive cost of installing the system. On average, the electrolyser alone is over one million dollars. This does not include the storage, compression for fueling and any associated electronics to run the system which can exceed $500,000. This pricing alone is for systems that provide relatively low amounts of hydrogen gas. Investment into Washington's Clean Energy Fund is a clear solution to advancing the development, demonstration and deployment of clean energy technologies. In 2013, Washington State Legislature approved $76 million for the fund. In 2016, they approved over $100 million in funds to invest in clean energy. The grants available to electric utilities sums to an invested $14.3 million since 2013 in smart grid projects alone. This represents more than $35 million in total investment by Washington State's largest electric utilities [4].

Washington Legislature will match funds from an industry partner, making this an ideal solution for local utility companies such as Avista. This for example, could translate to the state paying for half of a proposed P2G station, cutting the return on investment for a system in half. Furthermore, currently in-committee is House Bill 1646 (HB 1646) which states that it will "promote an equitable clean energy economy by creating a carbon tax that allows clean investment in clean energy, clean air, healthy forests, and Washington's communities" [9]. Supporting HB 1646, as well as increasing the budget of the Clean Energy Fund has the potentiality of creating a much larger commercial market for hydrogen and clean energy within the State of Washington.