H2FIRST Reference Station Design Task

Project Deliverable 2-2

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Danny Terlip, Chris Ainscough, Jennifer Kurtz
National Renewable Energy Laboratory

Amgad Elgowainy
Argonne National Laboratory

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Technical Report
NREL/TP-5400-64107
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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Sandia National Laboratories
Albuquerque, New Mexico 87185
Livermore, California 94550
www.sandia.gov

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The Hydrogen Fueling Infrastructure Research and Station Technology Project (H2FIRST) is a DOE project executed by Sandia National Laboratories and the National Renewable Energy Laboratory. The objective of H2FIRST is to ensure that fuel cell electric vehicle customers have a positive fueling experience relative to conventional gasoline/diesel stations as vehicles are introduced (2015–2017) and transition to advanced refueling technology beyond 2017.

DOE's Fuel Cell Technologies Office established H2FIRST directly in support of H2USA, a public-private partnership co-launched by DOE and industry in 2013 to address the key challenges of hydrogen infrastructure.

In addition to DOE, the team wishes to thank the H2USA Hydrogen Fueling Station Working Group, California Fuel Cell Partnership, and the California Air Resources Board for their input and support.

Nomenclature

AHJ	authority having jurisdiction
ANSI	American National Standards Institute
CARB	California Air Resources Board
BOM	bill of materials
CaFCP	California Fuel Cell Partnership
DOE	U.S. Department of Energy
FCEV	fuel cell electric vehicle
FMECA	failure modes effects and criticality analysis
HAZOP	hazard and operability study
H2FIRST	Hydrogen Fueling Infrastructure Research and Station Technology
HFSWG	H2USA Hydrogen Fueling Station Working Group
HRSAM	Hydrogen Refueling Station Analysis Model
HVAC	heating, ventilating, and air conditioning
ISA	International Society of Automation
NFPA	National Fire Protection Association
P&ID	piping and instrumentation diagram
PLC	programmable logic controller
ROI	return on investment

Executive Summary

Results

This report presents near-term station cost results and discusses cost trends of different station types. It compares various vehicle rollout scenarios and projects realistic near-term station utilization values using the station infrastructure rollout in California as an example. It describes near-term market demands and matches those to cost-effective station concepts. Finally, the report contains detailed designs for five selected stations, which include piping and instrumentation diagrams, bills of materials, and several site-specific layout studies that incorporate the setbacks required by NFPA 2, the National Fire Protection Association Hydrogen Technologies Code. This work identified those setbacks as a significant factor affecting the ability to site a hydrogen station, particularly liquid stations at existing gasoline stations. For all station types, utilization has a large influence on the financial viability of the station.

The station types and capacities are summarized in Table ES-1. Stand-alone drawing files and bills of materials are available for download on the site where this report is officially hosted.[1]

Table ES-1. Station Types Selected for Detailed Reference Design Development

Station Number	Hydrogen Delivery Method	Daily Capacity (kg)	Target Market	Site Type	Installed Capital Cost ($K)	Fuel Cost ($/kg)
1	Gaseous	300	High use	Gas station or greenfield	$1,265	$6.03
2	Gaseous	200	Low use		$1,179	$5.83
3	Gaseous	100	Intermittent		$1,098	$13.28
4	Liquid	300	High use	Greenfield	$2,007	[a]
5	Future liquid	300	High use		$1,551	$7.46

[a] This station type was not available in HRSAM as of this analysis and fuel cost could not be estimated. It will be included in a future version of the model.

Motivation

The goal of the H2FIRST Reference Station Design Task is to accelerate acceptance of hydrogen infrastructure build-out by exploring the advantages and disadvantages of various station designs. It is hoped that these reference designs will help reduce the cost and speed the deployment of hydrogen stations by providing a common baseline with which to start a design. These designs enable quick assessment of the suitability of a particular site for a hydrogen station, and they drive interchangeability of parts and manufacturing scale by employing uniformly-sized components. The station configurations evaluated in this report are not all inclusive. It is not intent to promote any specific station configuration or exclude any designs, but rather provide a rigorous analysis of a subset of likely near-term station configurations.

Approach

The H2FIRST team screened 160 possible station permutations using the Hydrogen Refueling Station Analysis Model developed by Argonne National Laboratory. The team developed input parameters and station configurations with feedback from the H2USA Hydrogen Fueling Station Working Group (HFSWG), California Fuel Cell Partnership (CaFCP), California Air Resources

[1] http://energy.gov/eere/fuelcells/h2first

Board (CARB), and industry. These station configurations were down selected by evaluating: (1) the station contribution to the cost of hydrogen, (2) station capital cost, and (3) time to positive return-on-investment (ROI). An approximate seven-year ROI was used for all stations; the team then selected stations with the lowest of the first two values. This narrowed the list to fifteen stations. From this set, the team selected stations to meet projected near-term market needs based on the station classification system described by CARB: high use commuter, low use commuter, and intermittent use profiles. This selection narrowed the list to the final set of five stations. The team then developed detailed designs for those final five stations.

Impact

The designs are intended to aid current and future station developers by providing a starting point for station designs for actual near-term station installations. The work addresses this intention by:

- Encouraging common component sizing and interchangeability for stations of the given target markets and capacities
- Providing station developers and local authorities a complete picture of the devices, components, and associated costs that make up a station, all the way down to individual valves and sensors
- Providing a tool that the H2USA financing and market support and acceleration working groups can use to develop station rollout scenarios
- Providing a detailed view of how these stations fit into greenfield and existing sites in relation to the NFPA 2 standard, 2011 edition.
- Helping station developers quickly evaluate the suitability of their sites for a particular station type and capacity.

Recommendations

In addition to producing the five specific station designs, this work identified four areas that need further improvement: component technology, station systems, codes and standards, and business practices. These areas have ample opportunity for improvement to help realize widespread rollout of cost-effective hydrogen stations.

1. **Component technology.** Designs are needed for off-the-shelf chillers, cryogenic pumps, evaporators, high capacity tube trailers, and underground storage.
2. **Station systems.** Work to reduce the need to chill hydrogen prior to dispensing, reduce boil off in liquid systems, and utilize more of the hydrogen in a gaseous tube trailer could all have significant impacts on the system cost.
3. **Codes and standards.** This work reinforced the need to use science-based methods to reduce the setbacks required for liquid stations. These setbacks are one of the largest hurdles to the placement of high-capacity liquid hydrogen stations in dense urban areas (where the customer base will be the highest).
4. **Business practices.** Utilization is the most important variable to impact the financial viability of a station. To the extent that hydrogen station networks can be optimized to maximize utilization, more of those stations will be self-sustaining and profitable.

Conclusion

This work presents the hydrogen community with a uniform, cost-optimal formula for designing and building hydrogen stations. The piping and instrumentation diagrams and bills of materials provided include a level of detail not previously reported publicly. Additionally, through this work the H2FIRST team has identified multiple areas where the design of stations and station networks can be further improved in the near term.

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1 Introduction

The Hydrogen Fueling Infrastructure Research and Station Technology Project (H2FIRST) is a U.S. Department of Energy (DOE) project executed by Sandia National Laboratories and the National Renewable Energy Laboratory. The objective of H2FIRST is to ensure that fuel cell electric vehicle customers have a positive fueling experience relative to conventional gasoline/diesel stations as vehicles are introduced (2015–2017) and transition to advanced refueling technology beyond 2017.

1.1 Motivation

The goal of the H2FIRST Reference Station Design Task is to guide hydrogen infrastructure development by understanding the advantages and disadvantages of multiple station designs. This task provides practical templates for technically feasible, economically optimized fueling station designs that utilize state-of-the-art components to serve the near-term U.S. hydrogen fueling market. It is hoped that these reference designs will help reduce the cost and speed the deployment of hydrogen stations by providing a common baseline with which to start a design, enable quick assessment of the suitability of a particular site for a hydrogen station, and drive interchangeability of parts and manufacturing scale by employing uniformly-sized components.

1.2 Approach

The H2FIRST team chose the stations to best fit near-term deployment plans. The H2USA Hydrogen Fueling Station Working Group (HFSWG), California Fuel Cell Partnership (CaFCP), California Air Resources Board (CARB), and industry members provided insight into current and anticipated stations including parameter value ranges, likely station types, and vehicle rollout scenarios.

The CARB June 2014 report[2] classifies stations based on the different demands they are meant to serve. The classifications—high use commuter, low use commuter, and intermittent—are defined by characteristics such as daily throughput and simultaneous and back-to-back fills. Task team members screened possible station permutations using the Hydrogen Refueling Station Analysis Model (HRSAM) developed by Argonne National Laboratory, and then matched the most economically viable station concepts resulting from HRSAM analysis with these CARB classifications. A summary of the values for characteristics of the selected stations is shown in Section 8 (Table 9). An exhaustive list of all of the analyzed station configurations along with the input parameters is included in Appendix A.

This work included four guiding principles: (1) decreasing the economic risk of a station by removing unknowns early in the design process, (2) reducing design costs by providing a detailed starting point for site-specific designs, (3) helping reduce permitting time and costs by presenting authorities having jurisdiction (AHJs) with known designs, and (4) driving economies of scale and component interchangeability through uniformly-sized components. The H2FIRST Reference Station Design Task addressed these principles through the following four-part approach linked to these guiding principles.

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[2] *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development*. Sacramento, CA: California Environmental Protection Agency Air Resources Board, June 2014. Accessed February 18, 2015: http://www.arb.ca.gov/msprog/zevprog/ab8/ab8_report_final_june2014.pdf.

First, the team addressed the economic risk associated with financing, building, and operating a station by pre-screening 160 possible permutations of station designs to arrive at the lowest cost stations. This economic screening considered input variables such as station capacity, cascade storage size, chiller cost, compressor size and cost, dispenser quantity and type, Lang factor, and utilization.

Second, the team addressed up-front conceptual design costs by producing design materials to help station developers quickly determine the suitability for a particular station design based on customer and site requirements. The team produced full station designs including piping and instrumentation diagrams (P&IDs), bills of materials (BOMs), and spatial layouts for several example sites, including both greenfield sites and those co-located with existing gasoline stations. Users of this report should not apply this information verbatim for construction or design, but rather use it as an advanced starting point to determine station siting requirements and actual costs. To complete designs for an actual station, the detailed engineering information herein must be coupled with an understanding of the specific site requirements. This step can only be completed by a team engaged with all of the stakeholders for a particular site.

Third, the team addressed the concerns of local AHJs. Reference stations can be particularly useful to local municipalities and those involved in permitting and code review in areas where hydrogen fueling stations are new and unfamiliar. Using these results to gain familiarity may help accelerate the acceptance and permitting process by providing a known design basis and philosophy to unfamiliar AHJs.

Fourth and finally, the team provided a common design philosophy for reference stations that may help drive cost reduction through economies of scale. This can lead to cost savings in both capital and maintenance costs by reducing logistical delay and parts inventory and increasing the pool of qualified technicians. Additionally, the reference designs can be used to support other analysis projects. For example this work could be an input to a station network model, which must account for station layout requirements, capacity, siting concerns, and costs.

1.3 Method Overview

The economic screening model used is the Hydrogen Refueling Station Analysis Model, or HRSAM, developed by Amgad Elgowainy at Argonne National Laboratory. HRSAM is a publicly-available model derived from H2A Delivery Scenario Analysis Model (HDSAM). HRSAM takes inputs such as station capacity, utilization, station type (delivered liquid or gas), and configuration and then uses a discounted cash flow calculation to find the cost contribution of a refueling station on the cost ($/kg) of hydrogen dispensed to vehicles. HRSAM focuses on near-term scenarios of delivered liquid or gas, whereas HDSAM considers the costs of hydrogen in a more mature market.[3]

The H2FIRST Reference Station Design Task consisted of the following six subtasks. The work flow is shown in Figure 1. The technical details and results from each step of the method are given in Appendix A.

[3] For more information on HDSAM, visit http://www.hydrogen.energy.gov/h2a_delivery.html.

1. Determine the parameters that are used to describe and design hydrogen fueling station performance and the parameter values of near-term relevance.
2. Compile near-term station component costs.
3. Propose station concepts that have different performance characteristics and require different components. Determine the economic implications of each station concept through modeling with the HRSAM tool, which incorporates cost-optimization routines for equipment sizing.
4. Use the economic results and screening for technical incompatibilities to down select to 15 near-term, high-priority station concepts.
5. Match the station concepts with near-term market needs to select stations for optimization and design.
6. Convert the desired station characteristics (from HRSAM analysis) of the selected stations to real-world designs by aligning the station equipment given by the model to currently available components.
7. Produce designs of the high-priority stations that include spatial layouts, P&IDs, and bills of materials, incorporating codified setback distances and current, low-volume component costs.

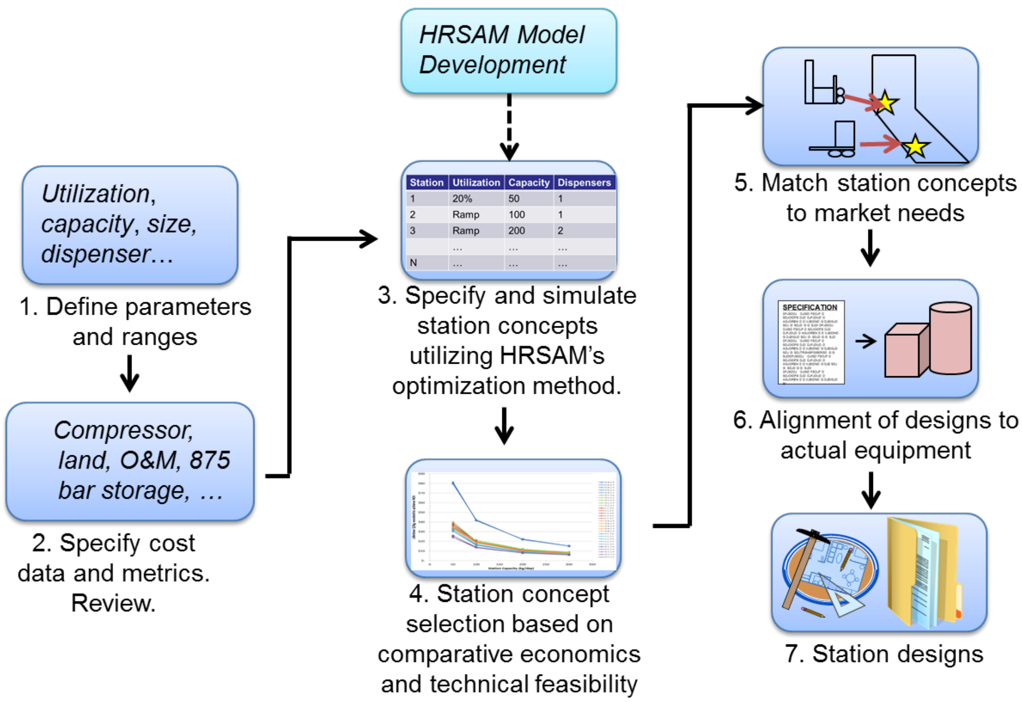

Figure 1. Subtasks and work flow of the Reference Station Design Task

2 Input Parameters

The HRSAM model has hundreds of input parameters. In general, these were kept at their default HDSAM Version 2.3 values; the HDSAM publications[4,5] describe what these values are along with the rationale and justification. The changed input values are summarized in Table 1. In some cases additional information is given in the subsections below the table.

Table 1. Changed Input Parameters in the HRSAM Model Used for Economic Screening
(all costs in 2009$ unless otherwise noted)

Parameter	Old (Default) Value[a]	New Value	Reason for Change
Real after-tax discount rate	10.0%	15.0%	Corresponds to changing return on investment period from ~10 years to ~7.5 years, in order to make investment more attractive in unknown market conditions
Cascade storage size	9.91 ft^3 (0.4 m outside diameter x 4.6 m long with 0.06 m wall thickness)	In addition to default, 1.98 ft^3 and 49.6 ft^3 (1/5x and 5x)	For storage size sensitivity analysis (on selected station concepts only)
Chiller cost	Function of refrigeration capacity (reference: 2 kg/min at -40°C from 40°C ambient = $72,107)	$113,500 per kg/min of capacity	Reflects current cost of 2 kg/min system at $227,000[b]
Low-to-high pressure compressor cost (for cascade fill systems	See Figure 2 “HDSAM, Cascade” data series	2.0 times the default	Reflects current cost of system[b] (see Section 2.1)
Low-to-medium pressure compressor cost (for booster fill systems)	See Figure 2 “HDSAM, Booster” data series	1.9 times the default	Reflects current cost of system[b] (see Section 2.1)
Medium-to-high pressure compressor (for booster fill systems)	$150,000 for 1 kg/min capacity	$260,000 for 1 kg/min capacity	Matches recent purchases[c]
Dispenser	$46,378 single hose	$57,500 per hose	Half the cost of a double-hose dispenser[b]
High-pressure storage (for cascade fill systems)	$2,500/kg	$1,190/kg	For Type II, 930-bar vessel[b]
Medium-pressure storage (for booster fill or 350-bar dispensing systems)	$1,500/kg	$822/kg	From recent quotes[d]

[4] See www.hydrogen.energy.gov/h2a_delivery.html for HDSAM models and user guides.

[5] Chen, T.-P. “Task 2: Evaluate Current and Future Efficiencies and Costs of Hydrogen Delivery Options.” *Final Report – Hydrogen Delivery Infrastructure Options Analysis*. Prepared by Nexant under DOE Award Number DE-FG36-05GO15032, May 2008.

Parameter	Old (Default) Value[a]	New Value	Reason for Change
Accumulator (small high-pressure storage for booster fill systems)	$2,500/kg	$985/kg	For Type IV, 950-bar vessel[b]
Low-pressure storage (for 20-bar supply systems)	$1,200/kg	$645/kg	For 250-bar vessel[b]
Installation factor—equipment	1.2 for compressor, dispenser, cryo storage, evaporator, and cryo pump; 1.3 for refrigeration and gas storage systems	1.3 for all	See Parks, et. al.[b]
Utilization	80%	Case 1: Ramp Case 2: 20%	See Section 6.2
Hourly use profile	Chevron profile	Chevron profile with one hour of specified number of consecutive fills	See Section 2.3

[a] See HDSAM documentation for reference and justification of default cost values.
[b] Parks, G.; Boyd, R.; Cornish, J.; Remick, R. *Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs*. NREL Technical Report NREL/BK-6A10-58564, May 2014.
[c] NREL quotation 2014.
[d] NREL quotation 2014.

2.1 Compressor Costs

The relationship between compressor flow rate and cost in the default model are shown in Figure 2 (noted in the legend as “HDSAM” or “H2A”). These costs represent long-term, volume production costs. Also shown in the figure are current-day, small quantity purchase prices (noted as “Actual”) determined from the Parks et al. report referenced in Table 1. It can be seen that for a given flow rate, the current-day prices are 1.9 and 2.0 times the long-term, volume production costs for medium-pressure and high-pressure compressors, respectively. The new compressor cost models used in this HRSAM economic analysis are also shown (noted as “New HRSAM”).

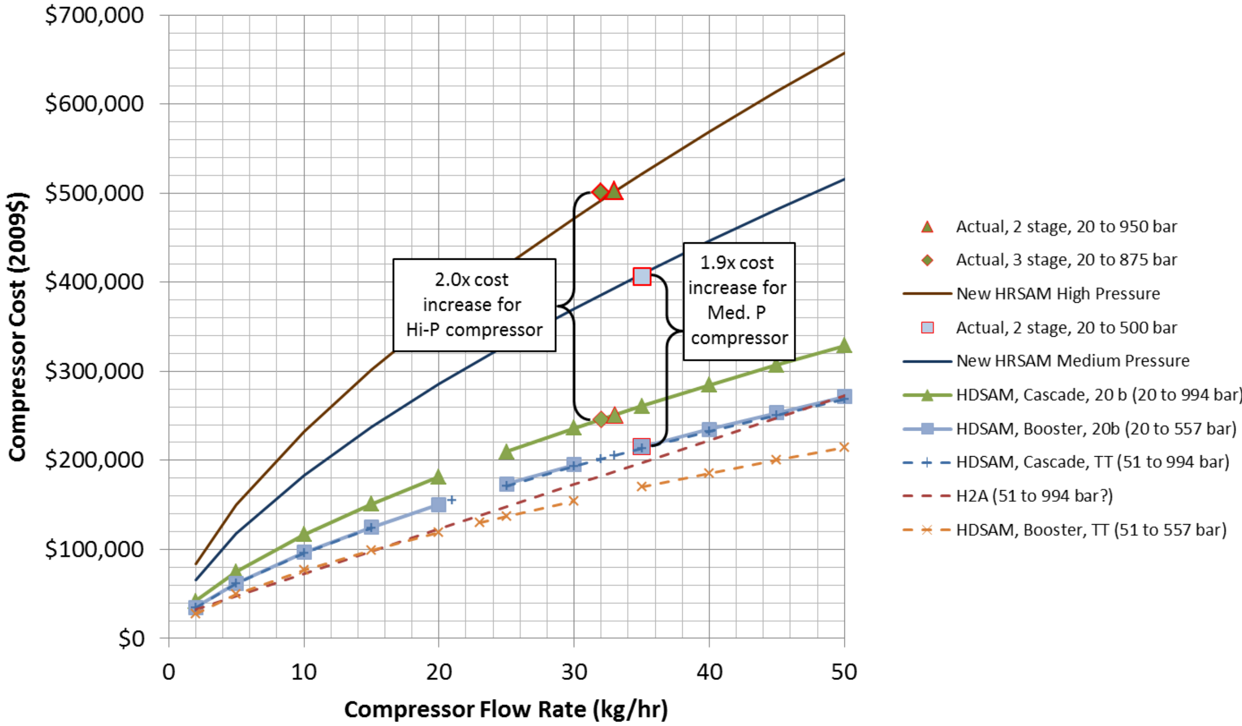

Figure 2. Comparison of compressor costs using HDSAM defaults ("HDSAM") and three current-cost data points ("Actual") with the scaled model to be used in this analysis ("New HRSAM"). Data sources are indicated in Table 1.

2.2 Utilization Model

Station utilization is defined as the ratio of actual hydrogen dispensed to the amount of hydrogen capable of being dispensed (capacity). In a network of multiple stations and vehicles, actual hydrogen dispensed depends on the *number of vehicles* on the road and the *amount of hydrogen consumed* by each vehicle, while network capacity depends on the *number of stations* and the *capacity of each station*.

To summarize, overall network utilization can be estimated by predicting the following:

- Vehicles in the network
- Hydrogen usage of the vehicles
- Number of hydrogen stations in the network
- Capacity of each hydrogen station in the network.

Each of these is described below with the utilization model shown in Section 2.2.4.

2.2.1 Vehicles in the Network

Figure 3 summarizes various vehicle scenario models and their predictions for the 10-year period from 2014 to 2023.

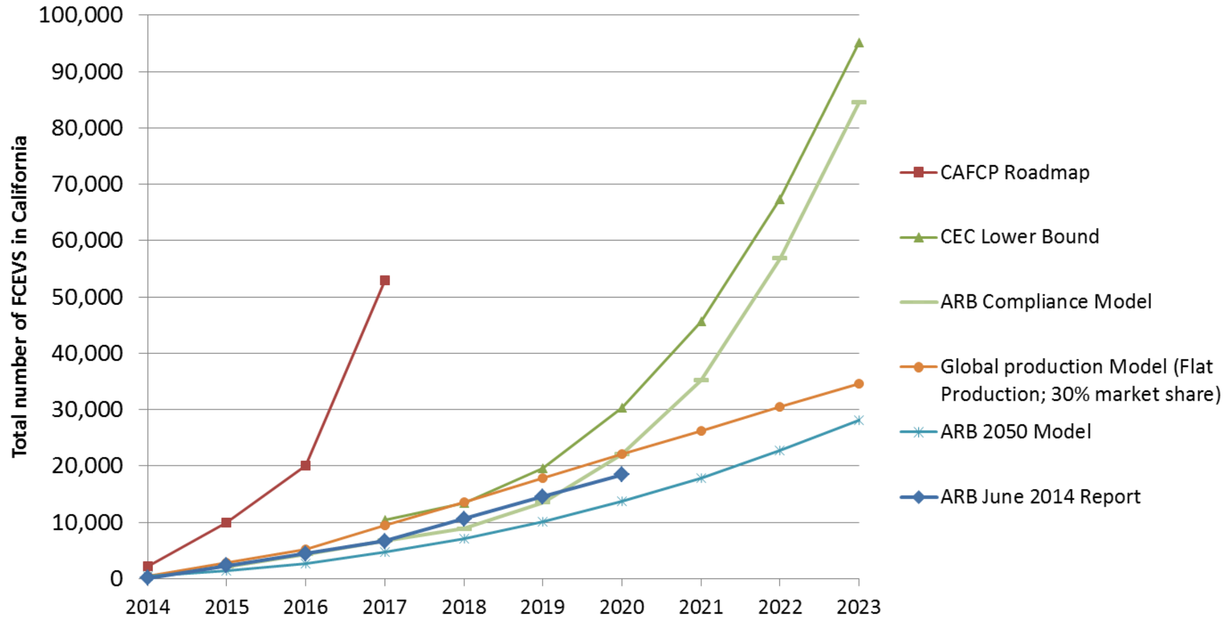

Figure 3. Network FCEV scenarios for California.
(See text for comments.)

The following comments relate to the models and predictions presented in Figure 3:

- The 2012 CaFCP Roadmap[6] model (shown in Figure 3) was based on infrastructure rollout assumptions that were not realized, and as a result was not used in this analysis. (Note that the 2014 update to the Roadmap [referred to as "2014 CaFCP Roadmap"[7]] did not forecast vehicle sales since those numbers were reflected elsewhere, in the ARB AB 8 June 2014 report.)
- The CARB Compliance Model is based on actual regulation for zero emissions vehicles, but it sets a split between fuel cell electric vehicle (FCEV) and battery electric vehicle to meet the compliance targets. The FCEV adoption ramp rate is dependent on fueling infrastructure deployment.
- The Global Production Model is based on estimates of FCEV production as part of the entire automaker manufacturing (14,000 FCEVs per year from 2017 onward) and then on estimates of California deployments as a part of worldwide deployments (30%). See Appendix D for more information.

[6] *A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles – Technical Version*. Sacramento, CA: CaFCP, June 2012.
[7] *A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles – 2014 Update: Hydrogen Progress, Priorities and Opportunities (HyPPO) Report*. Sacramento, CA: CaFCP, July 2014.

- The CARB June 2014 Report[8] numbers are based on those provided by surveys to auto manufacturers, with 125 vehicles identified in 2014, 6,650 in 2017 and 18,465 in 2020. CARB calculations project exponentially decaying FCEV fleets of a given model/model year to reflect attrition (e.g. from accidents, vehicle returns/swaps, vehicles leaving the state) as well as decaying miles traveled per vehicle based on age. All of these calculations were made in accordance with the rates and assumptions utilized in the CARB model of the State's vehicle fleet and emissions rates, which is in accordance with CARB's approach. These results are represented in Figure 15 (Section 6.2).

2.2.2 Hydrogen Usage of Vehicles

For this analysis, it is assumed that each vehicle uses 4 kg of hydrogen per week, which is based on Federal Highway Administration mileage survey data. The exception to this is the data presented from the CARB June 2014 Report, The CARB report's method calculation calculated populations of all known vehicle models. Every model was assigned its OEM-provided fuel economy and this was utilized in the calculation of the full fleet's hydrogen consumption within a designated geography. To translate from this detailed model to a number of stations required, the CARB report made a number of assumptions that resulted, in one instance, in vehicular usage of roughly 0.7 kg/day (4.9 kg/week). See Figure 13 of that report.

2.2.3 Number and Capacity of Hydrogen Stations in the Network

The number of hydrogen stations in California is projected by the 2014 CaFCP Roadmap and by the CARB June 2014 Report. Both predictions are summarized in Table 2.

Table 2. Predicted Total End-of-Year Number of Hydrogen Fueling Stations in California

Year	CaFCP (2014)	CARB (2014)
2014	23	
2015	51	51
2016	59	
2017	67	73
2018	77	
2019	87	
2020	99	100
2021	111	
2022	123	

The CaFCP 2014 and CARB 2014 predictions match well. Figure 4 shows the CARB predictions (dashed lines) of stations and the overall state hydrogen supply capacity based on 180 kg/day average per station. The figure also shows the model used in this work to extrapolate hydrogen capacity through 2023 (solid lines); the number of stations increases by 11 each year after 2020, in agreement with the CARB predicted growth trend. This growth rate is less than the 14.6 per

[8] *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development*. Sacramento, CA: California Environmental Protection Agency Air Resources Board, June 2014. Accessed February 18, 2015: http://www.arb.ca.gov/msprog/zevprog/ab8/ab8_report_final_june2014.pdf.

year estimated by Melaina and Penev,[9] but this is expected because that work also uses the aggressive 2012 CaFCP Roadmap estimates for vehicle rollouts.

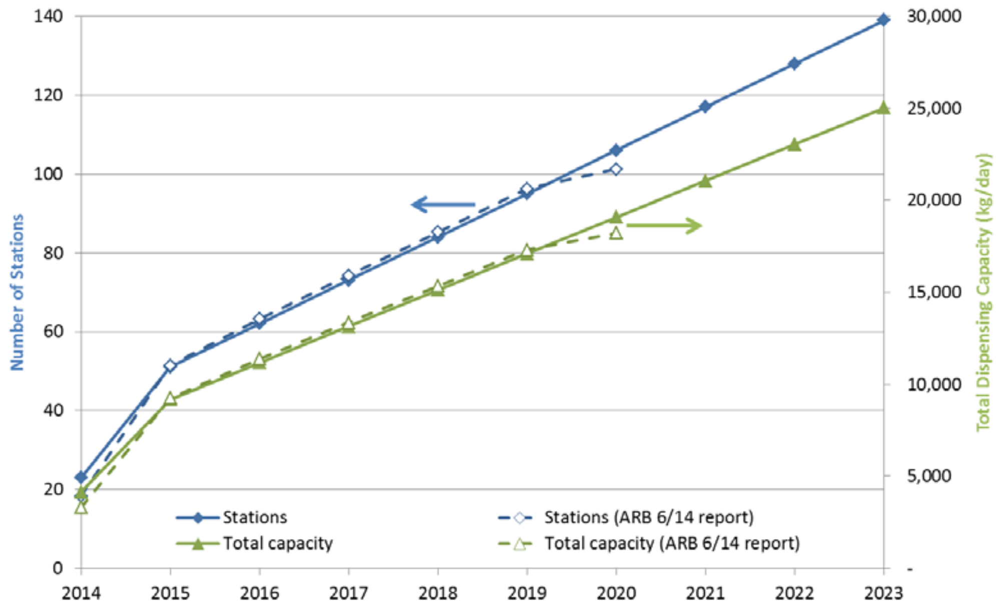

Figure 4. Station growth and network capacity for California.
Dashed lines represent predictions in the CARB June 2014 Report. Solid lines represent the model used in this work to predict utilization in other vehicle rollout scenarios (presented in Figure 5).

2.2.4 Utilization Model

Combining the vehicle scenarios from Figure 3 with the station modeling shown in Figure 4 results in the corresponding utilization scenarios shown in Figure 5. While this clearly represents network utilization, the assumption here is to assign this value to each individual station for modeling purposes.

[9] Melaina, M.; Penev, M. *Hydrogen Station Cost Estimates: Comparing Hydrogen Station Cost Calculator Results with other Recent Estimates*. NREL Technical Report TP-5400-56412. Golden, CO: National Renewable Energy Laboratory, September 2013.

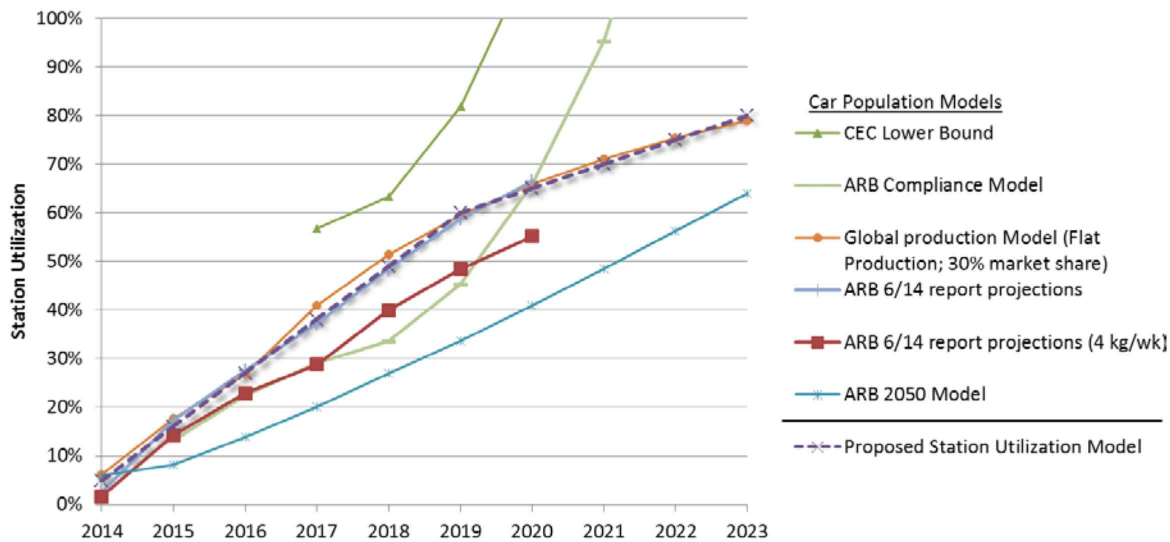

Figure 5. Predicted overall network utilization for the California vehicle and station growth scenarios shown above

The proposed utilization model for this initial effort is based on the CARB June 2014 Report projections to 2020 and extrapolated to 2023. Initially, the station utilization growth rate is 11% per year from 2014 to 2019, then it slows to 5% per year until 2023 (see Table 3). This lower growth rate is chosen for two reasons. First, the final utilization (in 2023) is 80%, which falls between the suggestions for maximum utilization of initial hydrogen stations of 70% in the 2012 CaFCP Roadmap and 90% by Brown et al.[10] and matches that of the 2014 CaFCP Roadmap. Second, the CARB Model matches well with the Global Production Model for the years 2014–2020, so the Global Production Model is used as a surrogate for the CARB Model for 2021–2023.

Table 3. Proposed Utilization Model

Year	Utilization
1	5%
2	16%
3	27%
4	38%
5	49%
6	60%
7	65%
8	70%
9	75%
10	80%

If vehicle demand increases more than predicted, it is assumed that either more stations will be added to keep up with demand or average station size will increase, but overall utilization will remain similar.

[10] Brown, T.; Schell, L.; Stephens-Romero, S.; and Samuelsen, S. "Economic analysis of near-term California hydrogen infrastructure." *International Journal of Hydrogen Energy* (38), 2013; pp. 3846-3857.

2.3 Daily Demand Profile

The HDSAM default model uses the so-called Chevron profile (described in the HDSAM User Manual). It can be seen as the open circles in Figure 6. As noted, one of the parameters used to define a station concept is the number of consecutive fills it can meet. To do this, the Chevron profile was modified so that during a single hour of the day, this number of consecutive fills is specified while still maintaining a resemblance of the Chevron profile in the other hours of the day. This was done by specifying the percentage for the peak hour, then scaling the Chevron profile percentages in all other hours by the following equation:

$$New\ \% = Original\ \% * (1 - New\ Peak\ \%) / (1 - Original\ Peak\ \%)$$

Examples of the effect of this scaling can also be seen in Figure 6 with 10%, 30%, 50%, and 70% of station capacity being dispensed during the peak hour in the form of consecutive fills.

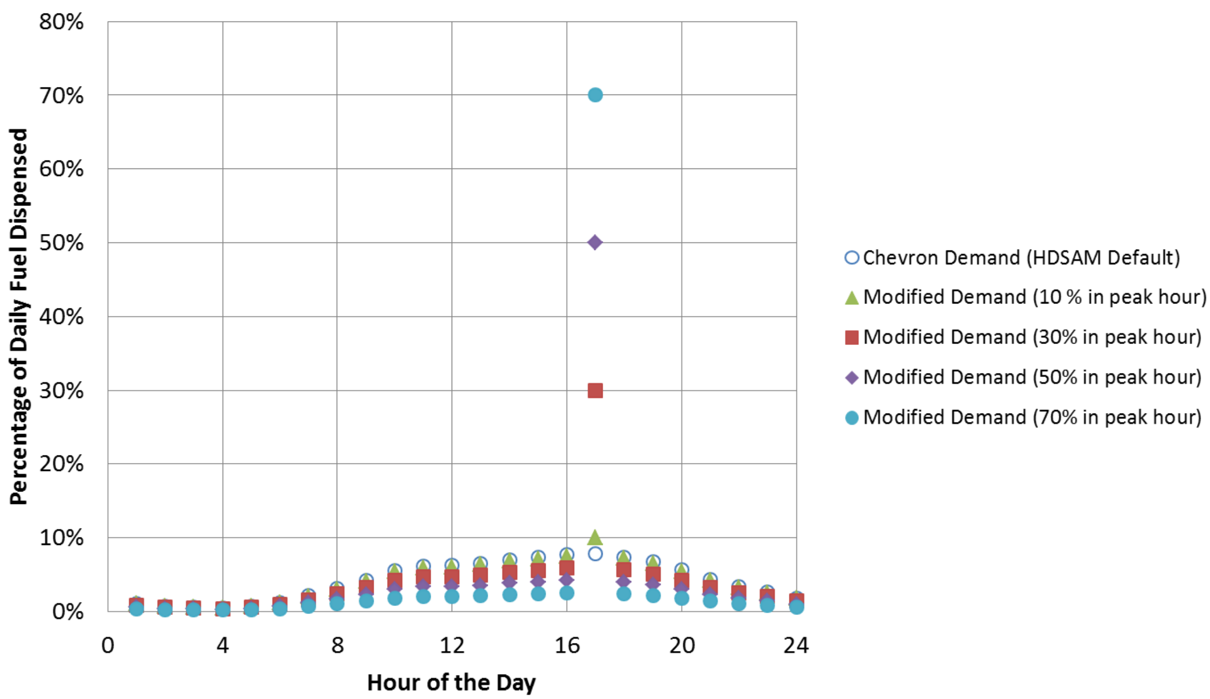

Figure 6. Daily demand profile, showing the default "Chevron Demand Profile" and the modified versions used in the economic screening with HRSAM

3 Station Configurations

After defining the input parameters, the team applied them to HRSAM. HRSAM can simulate five different station configurations:

1. Gas (tube trailer) delivery, 700-bar cascade fill
2. Gas (tube trailer) delivery, 700-bar booster compressor fill
3. Liquid trailer delivery, 700-bar cascade fill
4. Pipeline delivery or on-site production, 700-bar cascade fill
5. Pipeline delivery or on-site production, 700-bar booster compressor fill.

Figure 7 to Figure 11 present schematics for each of these configurations. Configurations 1–3 were studied in this work. Multiple hoses are allowed in each configuration. The cleanup system necessary for on-site production is not specifically shown in these schematics, but is assumed to be present.

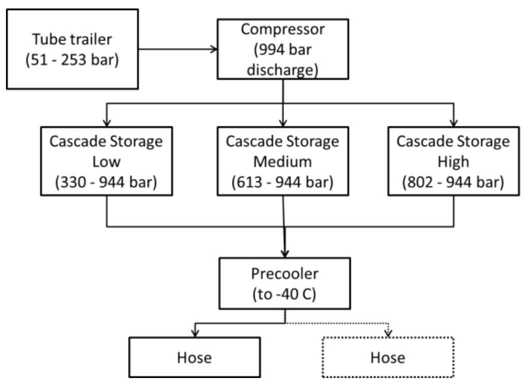

Figure 7. System schematic for configuration 1: gas (tube trailer) delivery, 700-bar cascade fill

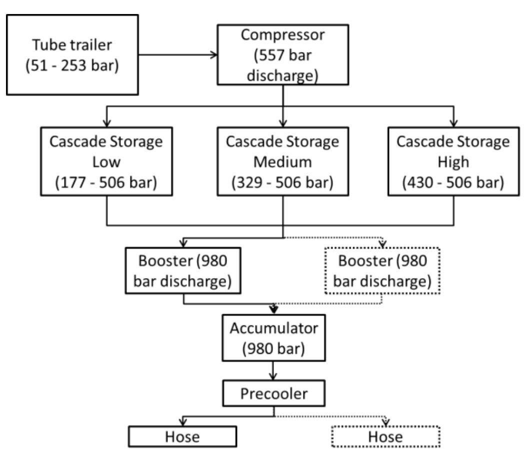

Figure 8. System schematic for configuration 2: gas (tube trailer) delivery, 700-bar booster compressor fill

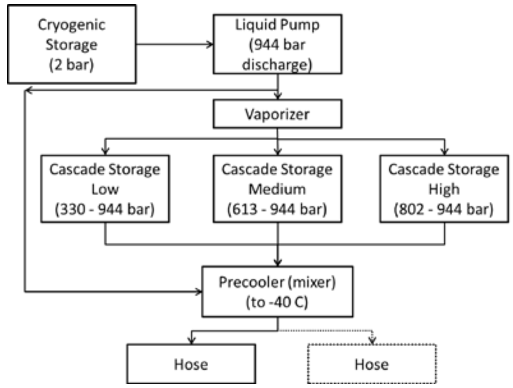

Figure 9. System schematic for configuration 3: liquid trailer delivery, 700-bar cascade fill

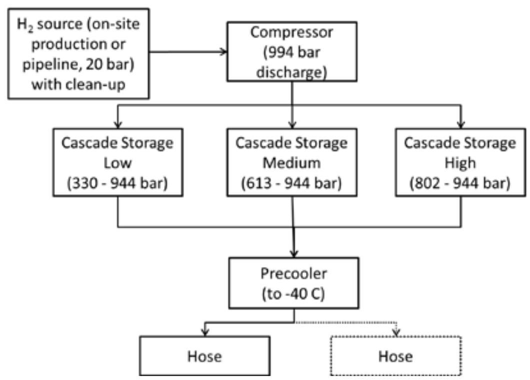

Figure 10. System schematic for configuration 4: pipeline delivery or on-site production, 700-bar cascade fill

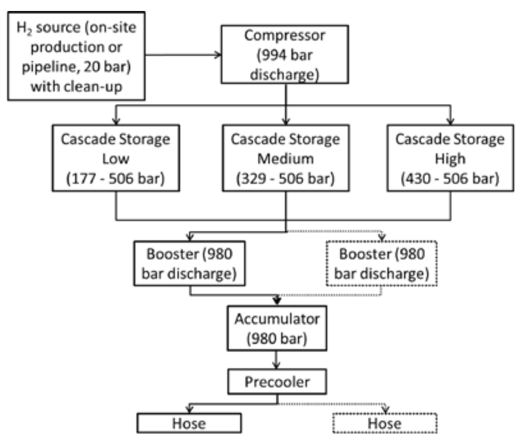

Figure 11. System schematic for configuration 5: pipeline delivery or on-site production, 700-bar booster compressor fill

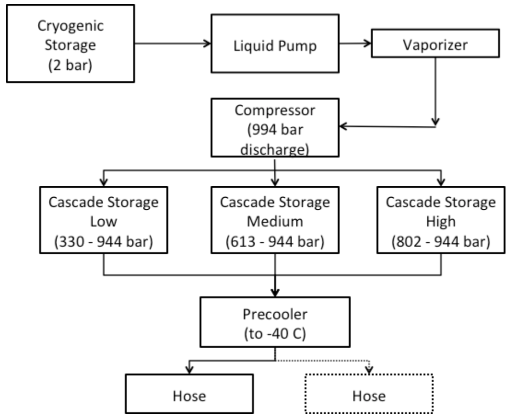

Figure 12. System schematic for current liquid station. This configuration will be added to a future version of HRSAM

4 Station Concepts

The team began the economic screening task by defining station concepts through combinations of the following five parameters:

1. Design capacity: Total kilograms per day that the station is capable of dispensing, assuming full storage immediately following hydrogen delivery.
2. Peak performance: Maximum number of 5-kg consecutive fills per hose before the station can no longer fuel to its specified fueling type according to SAE J2601. In modeling, the time period for simulating consecutive fills is limited to one hour. This limits the number of consecutive fills to eight per hose when 5-minute fill and 2-minute lingering times are used.
3. Number of hoses: A hose is defined as a fueling position, i.e., a single-hose dispenser and hose can be used interchangeably.
4. Fill configuration: The primary method of obtaining full pressure in the vehicle tank, i.e., cascade from higher pressure reservoir, or compress from lower pressure reservoir.
5. Hydrogen delivery method: How hydrogen gets delivered to or made on the site.

Discrete values chosen for each parameter are shown in Table 4. The H2FIRST team chose the selected parameters, definitions, and range values through detailed conversations with members of the H2USA HFSWG, U.S. Department of Energy (DOE) headquarters personnel, and Argonne National Laboratory personnel in the spring of 2014, and vetted them with the entire H2USA HFSWG membership during a web meeting and email exchange at the end of July 2014. These conversations focused on (1) obtaining station designs of near-term (0–2 years) practicality and (2) data for current cost of equipment to support this near-term build-out.

Table 4. Parameters and Values Used to Define Station Concepts for the FY14 Economic Screening Task

Performance Parameter	Values Used for Screening
Design capacity (kg/day)	50, 100, 200, 300
Peak performance	2, 3, 4, 5, 6 consecutive fills per hose
Number of hoses	1, 2
Fill configuration	Cascade, booster compressor
Hydrogen delivery method	Gas (tube trailer), liquid trailer

Table A-1 in Appendix A lists the 160 possible station concepts that arise from combinations of these parameter values. As noted in Section 3 and shown in the station configuration schematics, there is no provision in the current version of HRSAM to simulate a station with a booster compressor refueling method when that station is supplied by liquid hydrogen. The high capacity of available liquid pumps (100–200 kg/h) is too large for near-term hydrogen stations. Therefore, this station configuration is not currently included in HRSAM. The liquid station configuration that is included in HRSAM includes a high-pressure evaporator, cryopump, and mixing heat exchanger. These components have the potential to reduce station cost by eliminating the compressor and chiller, but so far they have not been deployed in a commercial station in the United States. For these reasons the last 40 stations in the list are greyed out, leaving 120 stations to simulate.

5 Output Parameters

This model outputs three key economic indicators:

1. Station contribution to the cost of hydrogen ($/kg)
2. Station capital cost ($)
3. Time to positive return on investment (ROI) (years).

It must be emphasized that the hydrogen cost results do not include the cost of the hydrogen itself or the delivery cost; it is only the portion of the hydrogen cost that is attributed to the cost of owning and operating the station. During the process of vetting this method, the input parameters, and the economic indicators, stakeholders identified a need to quantify economic risk as it pertains to station utilization. In other words, recognizing that station utilization largely determines the price of hydrogen required to achieve a given time to positive ROI, stakeholders want to know which station concepts are able to better absorb lower-than-expected utilizations while still maintaining reasonable ROI. For this reason, two utilization values are also simulated for each station concept:

1. Projected utilization ramp for a near-term station network (from 15% to 82.5% in 10 years as described in section 2.2.4)
2. Constant 20% utilization for 10 years.

The percentage change in required hydrogen cost to achieve a given ROI period as a result of the two different utilization scenarios will be used to quantify the economic tolerance of a station to lower-than-expected utilizations.

6 Initial Economic Screening

The team used HRSAM to simulate the 120 station concepts listed in Table A-1 using the parameters, costs, and ranges from Chapter 2 and Chapter 4, the ramped utilization model in Section 2.2.4, and the daily demand profile from Section 2.3. These simulations generated the output parameters described in Section 5, and the team performed a comparative analysis to select the most cost-effective, near-term station designs for further analysis and design. In addition, all stations were re-simulated using a constant 20% utilization for 10 years in order to compare the effect of low utilization on station economics and identify station designs that may be more economically robust than others to lower-than-expected utilizations.

6.1 Overall Results

Figure 13 shows the levelized station contribution to the cost of hydrogen with a specified 15% discount rate for all station configurations.

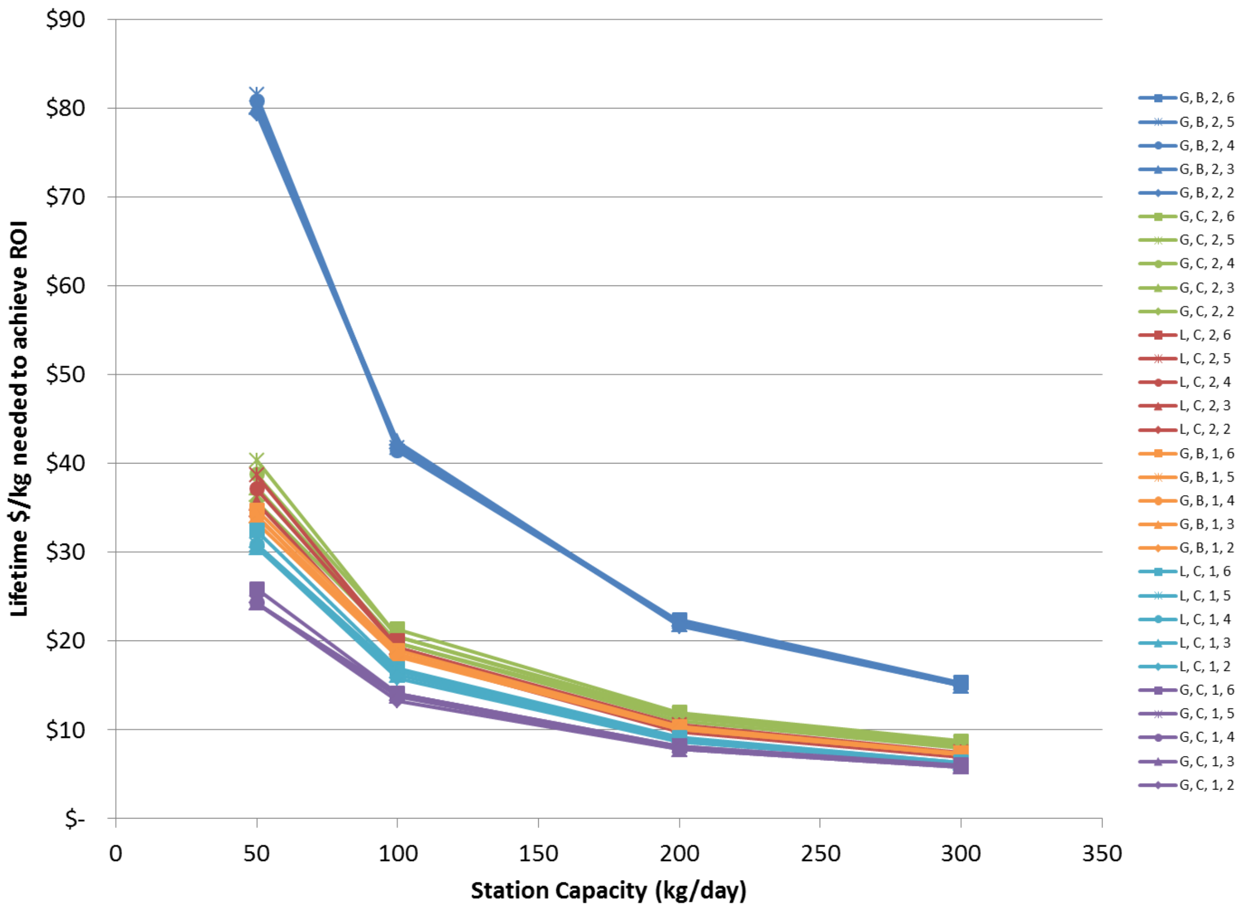

Figure 13. Levelized station contribution to the cost of hydrogen with a specified 15% discount rate for all station configurations.

In the legend, the letters and numbers (from left to right) refer to the type of hydrogen supply (G=gaseous or L=liquid), the type of fill (C=cascade or B=booster compressor), the number of hoses (1 or 2), and the number of consecutive fills (2–6).

Several trends can be seen from the figure:

- The lowest levelized station contribution to the cost of hydrogen is \$5.83/kg, which can be achieved with a 300 kg/day gas-supplied, cascade fill, single hose station design with two or three consecutive fills.
- Larger station capacities have lower levelized costs, but there is a diminishing return with increased station capacity. The magnitude reduction in cost achieved by larger stations is largest when going from 50 kg/day to 100 kg/day (0.93% average cost reduction per kg increased capacity), medium when going from 100 kg/day to 200 kg/day (0.45% average cost reduction per kg increased capacity), and smallest when going from 200 kg/day to 300 kg/day (0.29% average cost reduction per kg increased capacity). This trend is similar regardless of station type or configuration.
- For a given number of hoses and station capacity, gas delivery cascade systems have the lowest cost, followed by liquid delivery cascade systems, followed by gas delivery booster systems, which are the most expensive.
- The cost of an additional hose (going from one hose to two hoses) is considerably more expensive for booster fill systems than for either cascade system (liquid or gas supplied).
- For 200 kg/day stations, the increase in the levelized station contribution to the hydrogen cost due to increasing the number of hoses from one to two averages \$1.36/kg for liquid supply systems, \$3.47/kg for gas supply cascade systems, and \$11.86/kg for gas supply booster systems. In deciding between one or two hoses, a station developer should weigh customer preference between the potential inconvenience of having to wait for a hose to become available and the hydrogen purchase price savings.
- Note that the liquid stations analyzed here assume a configuration with a high pressure liquid pump and evaporator, eliminating the need for a chiller, which is the reason why multiple-hose liquid delivery stations appear to have more favorable economics than multiple-hose gaseous delivery stations. Unfortunately this kind of equipment is not currently available as standard technology except for very large stations (>1,000 kg/day). Therefore the advantage that liquid delivery stations have in this regard does not exist in actual near-term station designs, and the dual-hose designs of the liquid stations will have higher costs than are shown here (i.e., the red lines for the dual-hose liquid delivery stations in Figure 13 and Figure 14 will likely be close to or higher than the green lines for the dual-hose gaseous delivery stations).
- The consecutive fill requirement is not as important as station size or number of hoses. It has the largest impact at smaller station capacities.

Figure 14 shows the capital cost trends of the stations studied. From this figure it can be seen that:

- The systems with the lowest capital cost are the delivered gas, cascade fill, 50 kg/day, single hose, 2–5 consecutive fill configurations, which all have the same capital cost of \$910,477.

- At the highest station capacity (300 kg/day), the liquid-supplied cascade system has the lowest capital cost regardless of the number of consecutive fills or hoses. At a 200 kg/day capacity, the capital costs of single-hose liquid and gas cascade fill stations are nearly identical (within 1.5%).
- For a single-hose system the capital cost of a gas-supplied cascade system is typically lower than that of a liquid-supplied cascade system, but for a dual-hose system the increase in capital cost for the gas-supplied system is much more than for the liquid-supplied system. However, as noted above, this only applies to a liquid system configuration with technology that is not readily available. This advantage disappears when considering current liquid station designs.
- The capital cost of an additional hose (going from one hose to two hoses) is considerably more expensive for booster fill systems than for either cascade system (liquid or gas supplied).

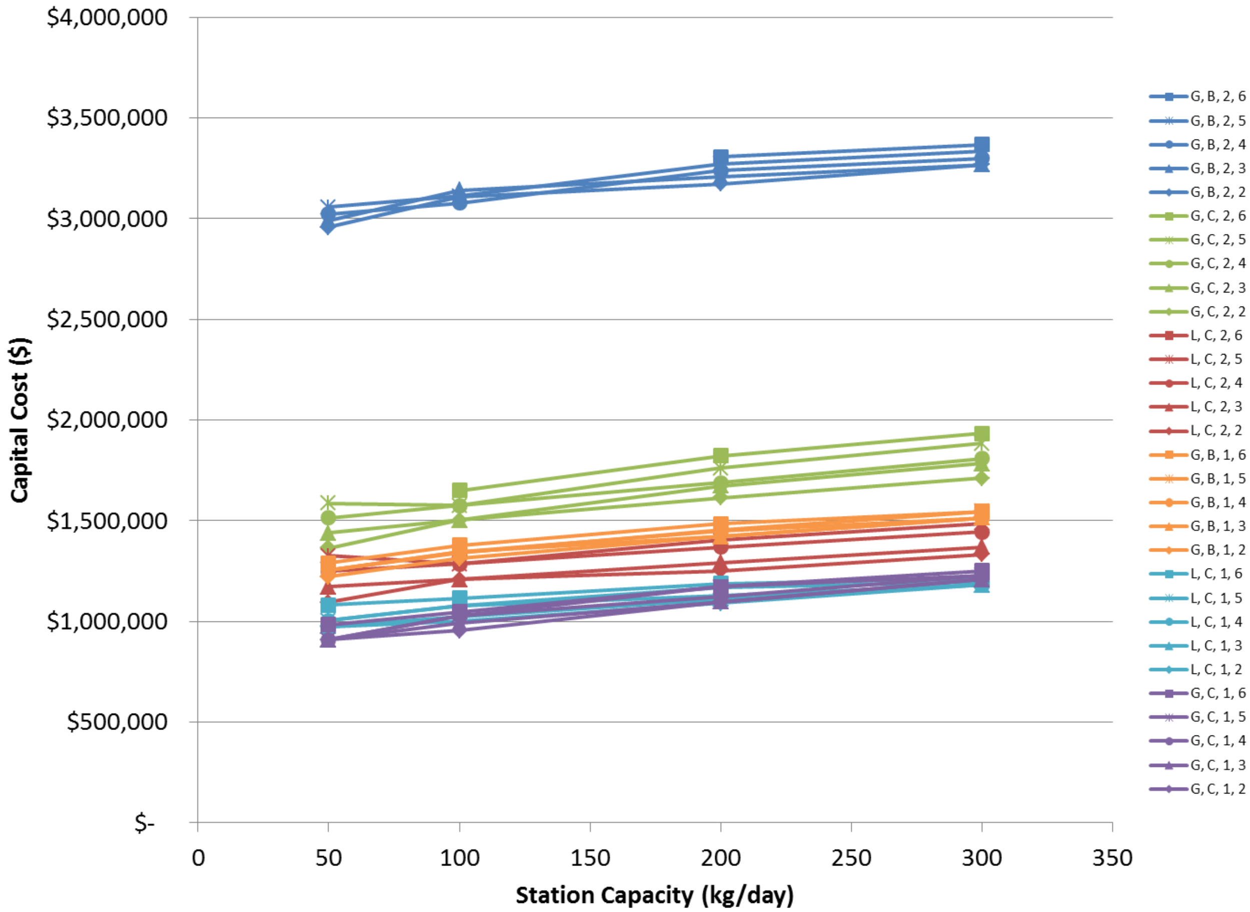

Figure 14. Station capital cost.

In the legend, the letters and numbers (from left to right) refer to the type of hydrogen supply (G=gaseous or L=liquid), the type of fill (C=cascade or B=booster compressor), the number of hoses (1 or 2), and the number of consecutive fills (2–6).

Three broad trends are apparent when considering both Figure 13 and Figure 14:

- While the smallest capacity stations have the lowest capital cost, the levelized station contribution to the cost of hydrogen is the highest.
- For each station capacity (50, 100, 200, and 300 kg/day), the station concept that has the lowest capital cost also has the lowest levelized station contribution to the cost of hydrogen.
- The consecutive fill requirement has more of an impact on capital cost than on levelized station contribution to the cost of hydrogen.

The ROI period is not plotted because, due to the forcing of a 15% discount rate, all stations have very similar ROI (the top 50 station concepts have an average ROI period of 7.47 years with a standard deviation of 0.10).

6.2 Utilization Effects

As described in Section 2.2, the utilization model assumed will significantly affect the economics of a station concept. The team evaluated the sensitivity of fuel cost and capital costs to lower-than-expected utilizations by simulating each station with a constant 20% utilization for its lifetime. From the results shown in Figure 15, it is clear that all stations are nearly equally affected by the low utilization. In other words, there is no particular station design that is better than another in withstanding a lower-than-expected utilization.

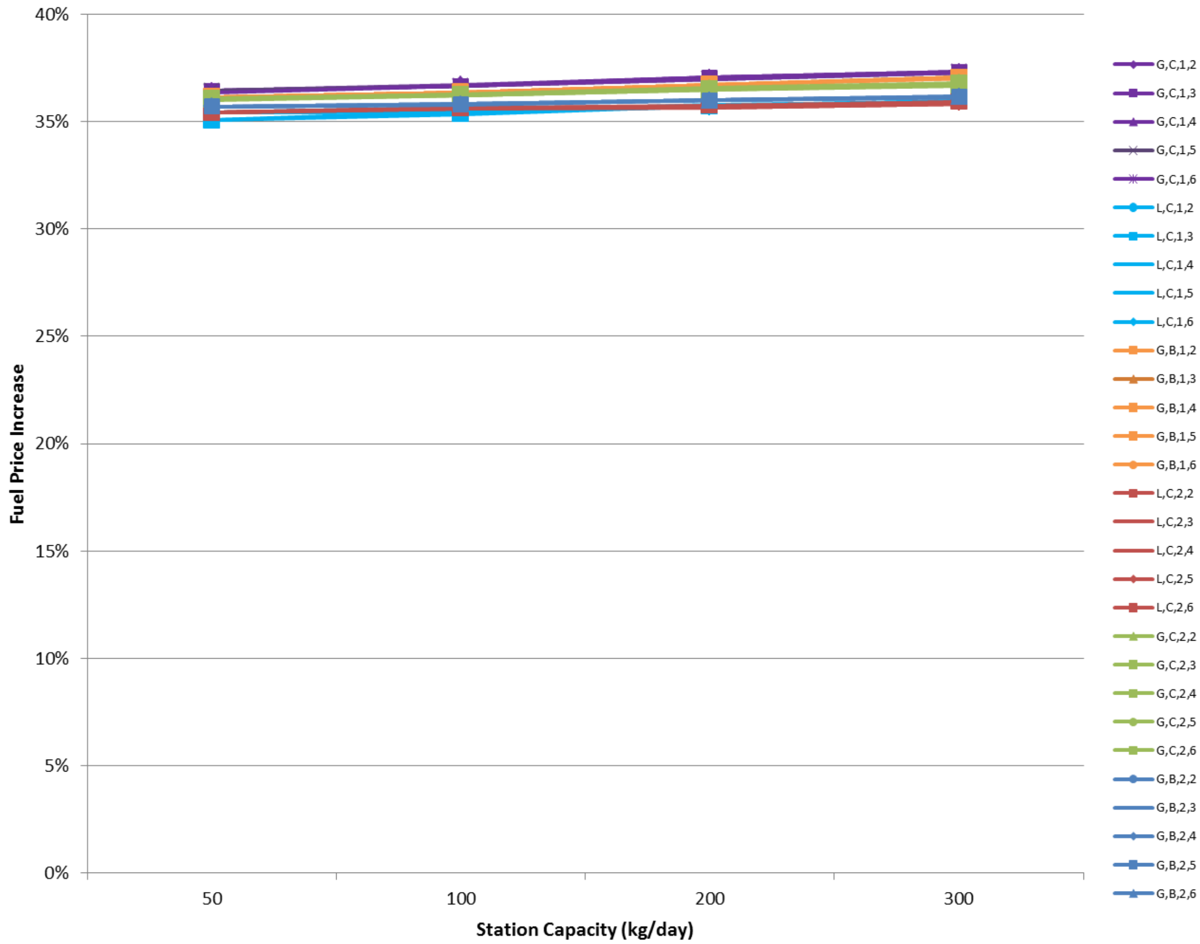

Figure 15. Increase in levelized station contribution to the hydrogen cost due to a constant utilization of 20% for the station's lifetime

6.3 Comparative Analysis

The team developed a method for comparing the overall economic attractiveness of each station. As mentioned above, the lowest station capital cost is $910,477 and the lowest levelized station contribution to the cost of hydrogen is $5.83/kg. The methodology involves calculating the relative change in capital cost and fuel cost for each station with respect to the cheapest capital cost and fuel cost.

$$M_{capital} = \frac{(C_S - C_0)}{C_0} * 100\% \qquad M_{fuel\ cost} = \frac{(F_S - F_0)}{F_0} * 100\%$$

Where

$M_{capital}$ = Relative capital cost from the minimum
$M_{fuel\ cost}$ = Relative fuel cost from the minimum
C_s = Current station capital cost
C_0 = Lowest station capital cost
F_s = Current station fuel cost
F_0 = Lowest station fuel cost

The team then ranked all stations according to their combined percentage increase from these two metrics. The results for each station are given in Figure 16. These results are broken down into the three figures that follow it, which show the top 20 stations in terms of lowest increase in levelized station contribution to hydrogen cost (Figure 17), lowest increase in capital cost (Figure 18), and lowest overall combination of the two (Figure 19). These charts are meant to enable readers to immediately identify the preferred station concept to meet their financial needs, whether it is minimization of capital cost, hydrogen cost, or both combined.

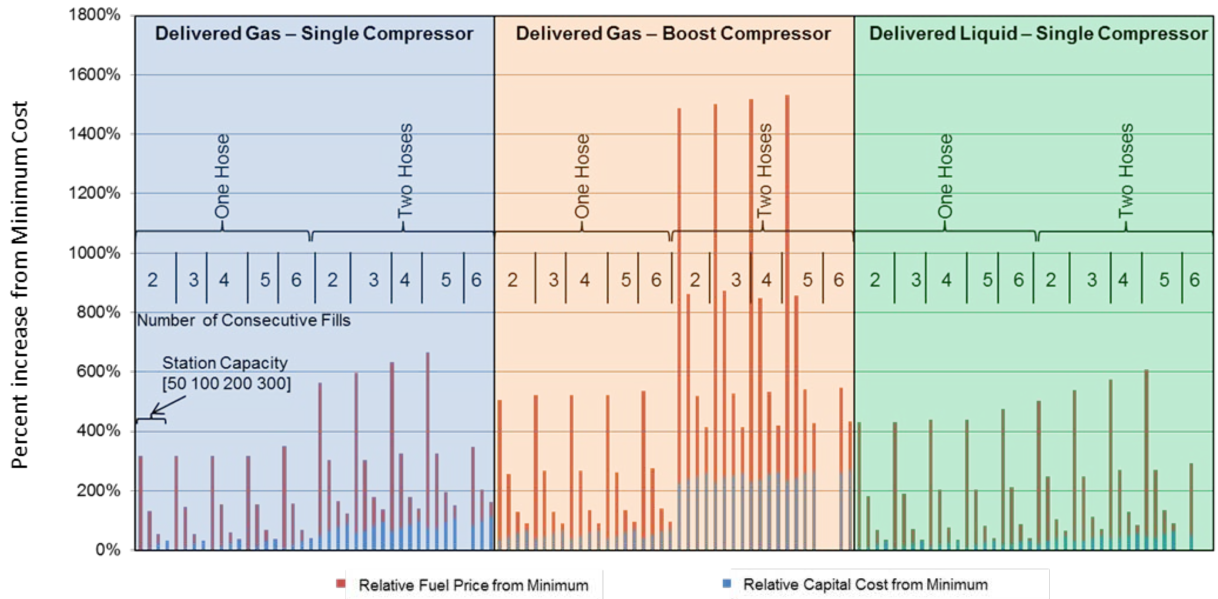

Figure 16. Overall comparison of station capital and hydrogen costs to the lowest costs in the study.
The blue portions of the columns are the percent increase in capital cost above the minimum and the red portions of the columns are the percent increase in hydrogen cost above the minimum. The station concepts presented are in a repeating pattern as shown in the figure.

Figure 17 shows the top 20 station concepts in terms of lowest increase in levelized station contribution to the cost of hydrogen from the minimum ($5.83/kg) (red portion of the columns). Similar to what was shown in Figure 13, the largest stations, regardless of the number of consecutive fills or hoses, are able to charge the lowest price for hydrogen and still maintain a real after-tax discount rate of 15%.

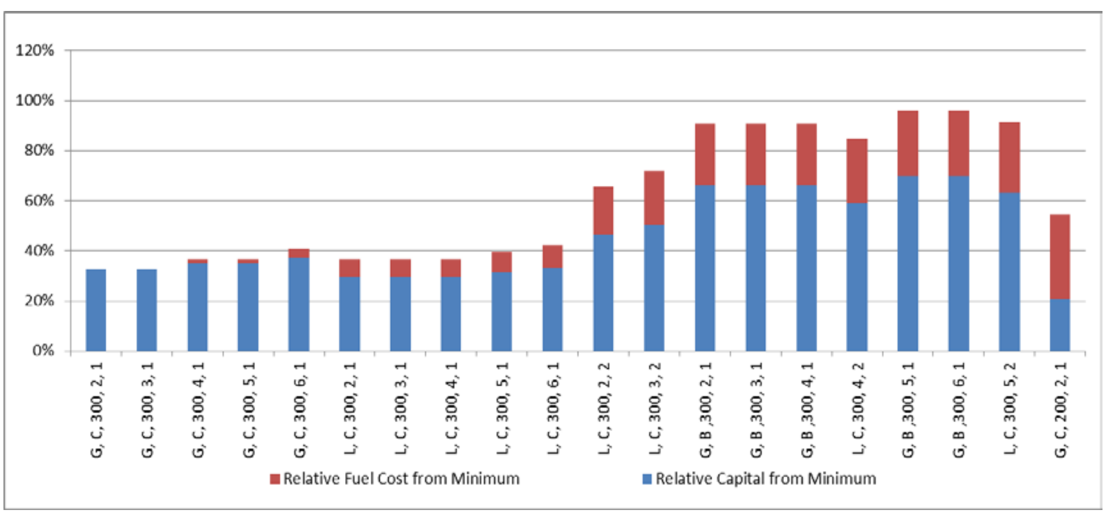

Figure 17. Top 20 station concepts in terms of lowest increase in levelized station contribution to the hydrogen cost from the minimum (red portion of the columns)

Figure 18 shows the top 20 station concepts in terms of lowest increase in capital cost from the minimum ($910,477) (blue portion of the columns). It can be seen that the smallest stations require the least capital. It is interesting to note that the 100 kg/day gaseous delivery, cascade fill station with two consecutive fills is less capital intensive than the 50 kg/day liquid cascade stations. Additionally, the requirement for more consecutive fills eventually causes the smaller liquid stations to become more capital intensive than the next size larger liquid station with only two consecutive fills required.

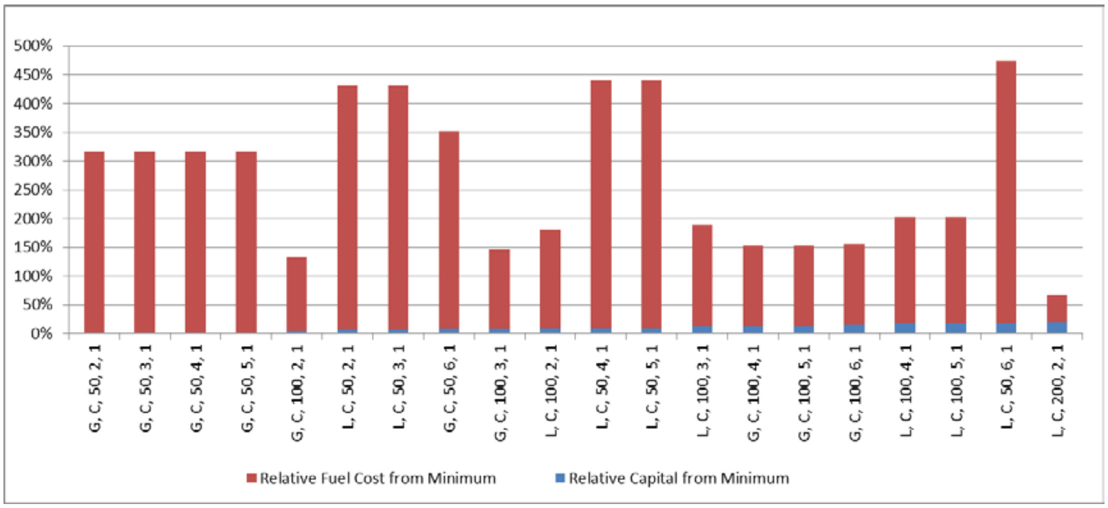

Figure 18. Top 20 station concepts in terms of lowest increase in capital cost from the minimum (blue portion of the columns)

Figure 19 shows the top 20 station concepts in terms of the lowest combined increase in levelized station contribution to the hydrogen cost and capital cost from their respective minimums. One trend that is evident is that the stations with the lowest overall cost (toward the left of the figure) have relatively higher capital costs but lower levelized station contribution to the hydrogen costs than the stations with the higher overall cost (to the right of the figure). That is, fuel cost can be considered a larger driver in the overall economic viability of a station than capital cost, and the most economically viable stations are ranked so largely due to their ability to charge a cheaper fuel price. This seems to indicate that, in general, it is more favorable to invest more on the capital side of a station in order to achieve the lower hydrogen cost associated with the economy of scale.

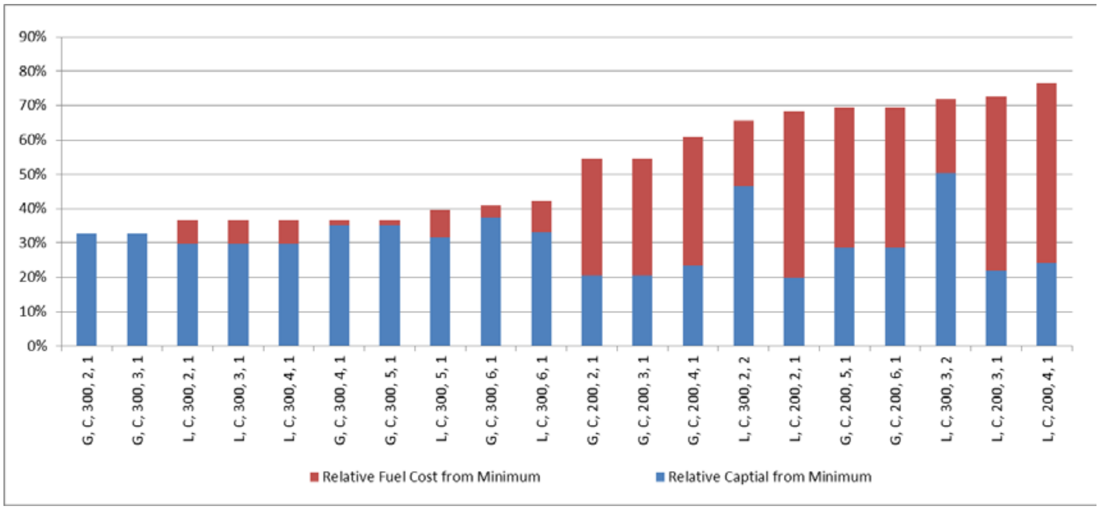

Figure 19. Top 20 station concepts in terms of lowest combined increase in capital cost (blue) and levelized station contribution to the hydrogen cost (red) from the respective minimums

Table 5 summarizes the top 20 station concepts in each economic category (overall, fuel cost, and capital cost). When station concepts were found to have the same cost number regardless of the number of consecutive fills they were included at the same rank.

Table 5. Ranking of Station Concepts in Terms of Lowest Capital Cost, Lowest Fuel Cost, and Lowest Overall Combination of the Two

	Rank Order of Capital Cost			Station Contribution to Fuel Cost			Overall		
	Station ID[a]	$M_{capital}$	M_{fuel}	Station ID[a]	$M_{capital}$	M_{fuel}	Station ID[a]	$M_{capital}$	M_{fuel}
1	G, C, 50, 2, 1 G, C, 50, 3, 1 G, C, 50, 4, 1 G, C, 50, 5, 1	0%	316%	G, C, 300, 2, 1 G, C, 300, 3, 1	33%	0%	G, C, 300, 2, 1 G, C, 300, 3, 1	33%	0%
2	G, C, 100, 2, 1	5%	128%	G, C, 300, 4, 1 G, C, 300, 5, 1	35%	2%	L, C, 300, 2, 1 L, C, 300, 3, 1 L, C, 300, 4, 1	30%	7%
3	L, C, 50, 2, 1 L, C, 50, 3, 1	7%	424%	G, C, 300, 6, 1	37%	3%	G, C, 300, 4, 1 G, C, 300, 5, 1	35%	2%
4	G, C, 50, 6, 1	8%	343%	L, C, 300, 2, 1 L, C, 300, 3, 1 L, C, 300, 4, 1	30%	7%	L, C, 300, 5, 1	31%	8%
5	G, C, 100, 3, 1	9%	136%	L, C, 300, 5, 1	31%	8%	G, C, 300, 6, 1	37%	3%
6	L, C, 100, 2, 1	10%	172%	L, C, 300, 6, 1	33%	9%	L, C, 300, 6, 1	33%	9%
7	L, C, 50, 4, 1 L, C, 50, 5, 1	10%	430%	L, C, 300, 2, 2	46%	19%	G, C, 200, 2, 1 G, C, 200, 3, 1	21%	34%
8	L, C, 100, 3, 1	13%	177%	L, C, 300, 3, 2	50%	22%	G, C, 200, 4, 1	24%	37%
9	G, C, 100, 4, 1 G, C, 100, 5, 1	13%	141%	G, B ,300, 2, 1 G, B ,300, 3, 1 G, B ,300, 4, 1	66%	24%	L, C, 300, 2, 2	46%	19%
10	G, C, 100, 6, 1	15%	141%	L, C, 300, 4, 2	59%	26%	L, C, 200, 2, 1	20%	48%

	Rank Order of Capital Cost			Station Contribution to Fuel Cost			Overall		
	Station ID[a]	$M_{capital}$	M_{fuel}	Station ID[a]	$M_{capital}$	M_{fuel}	Station ID[a]	$M_{capital}$	M_{fuel}
11	L, C, 100, 4, 1 L, C, 100, 5, 1	18%	185%	G, B ,300, 5, 1 G, B ,300, 6, 1	70%	26%	G, C, 200, 5, 1 G, C, 200, 6, 1	29%	41%
12	L, C, 50, 6, 1	19%	456%	L, C, 300, 5, 2	63%	28%	L, C, 300, 3, 2	50%	22%
13	L, C, 200, 2, 1	20%	48%	G, C, 200, 2, 1 G, C, 200, 3, 1	21%	34%	L, C, 200, 3, 1	22%	51%
14	L, C, 50, 2, 2	20%	484%	G, C, 300, 2, 2	88%	37%	L, C, 200, 4, 1	24%	53%
15	G, C, 200, 2, 1 G, C, 200, 3, 1	21%	34%	G, C, 200, 4, 1	24%	37%	L, C, 200, 5, 1	28%	55%
16	L, C, 200, 3, 1	22%	51%	G, C, 200, 5, 1 G, C, 200, 6, 1	29%	41%	L, C, 300, 4, 2	59%	26%
17	L, C, 100, 6, 1	23%	190%	G, C, 300, 3, 2	96%	41%	L, C, 200, 6, 1	30%	57%
18	G, C, 200, 4, 1	24%	37%	G, C, 300, 4, 2	99%	42%	G, B ,300, 2, 1 G, B ,300, 3, 1 G, B ,300, 4, 1	66%	24%
19	L, C, 200, 4, 1	24%	53%	G, C, 300, 5, 2	107%	46%	L, C, 300, 5, 2	63%	28%
20	L, C, 200, 5, 1	28%	55%	L, C, 200, 2, 1	20%	48%	G, B ,300, 5, 1 G, B ,300, 6, 1	70%	26%

[a] In the Station ID the letters and numbers (from left to right) refer to the type of hydrogen supply (G=gaseous or L=liquid), the type of fill (C=cascade or B=booster compressor), the kg/day station capacity (50, 100, 200, or 300), the number of consecutive fills (2–6), and the number of hoses (1 or 2).

Table 6 lists the 15 designs selected from the economic screening to proceed to the next phase of analysis. The team selected the stations by choosing the top 10 from the "Overall" category, the top five from the "Station contribution to fuel cost" category, and the top five from the "Capital cost" category. If multiple station concepts achieved the same ranking, and all characteristics of the station except number of consecutive fills were the same, only the station with the highest number of consecutive fills was chosen. Because the top five from the "Station contribution to fuel cost" category all appear in the "Overall" top 10, the resulting list only contains 15 station concepts.

Table 6. The Final 15 Station Concepts Selected Based on the Preliminary Economic Results

No.	Station ID	Supply Type	Fill Type	Capacity (kg/day)	Consecutive Fills	Hoses	$M_{capital}$	M_{fuel}
1	G, C, 300, 3, 1	Gas	Cascade	300	3	1	33%	0%
2	L, C, 300, 4, 1	Liquid	Cascade	300	4	1	30%	7%
3	G, C, 300, 5, 1	Gas	Cascade	300	5	1	35%	2%
4	L, C, 300, 5, 1	Liquid	Cascade	300	5	1	31%	8%
5	G, C, 300, 6, 1	Gas	Cascade	300	6	1	37%	3%
6	L, C, 300, 6, 1	Liquid	Cascade	300	6	1	33%	9%
7	G, C, 200, 2, 1	Gas	Cascade	200	2	1	21%	34%
8	G, C, 200, 4, 1	Gas	Cascade	200	4	1	24%	37%
9	L, C, 300, 2, 2	Liquid	Cascade	300	2	1	46%	19%
10	L, C, 200, 2, 1	Liquid	Cascade	200	2	1	20%	48%
11	G, C, 50, 5, 1	Gas	Cascade	50	5	1	0%	316%
12	G, C, 100, 2, 1	Gas	Cascade	100	2	1	5%	128%
13	L, C, 50, 3, 1	Liquid	Cascade	50	3	1	7%	424%
14	G, C, 50, 6, 1	Gas	Cascade	50	6	1	8%	343%
15	G, C, 100, 3, 1	Gas	Cascade	100	3	1	9%	136%

7 Final Screening and Down Select

The initial economic screening results presented in Section 6 help to identify preferred station concepts based on economics alone. They present a variety of economically viable station concepts independent of intended use or market need. Selecting the three most useful near-term relevant station concepts now requires an analysis of the market need and technical and regulatory requirements, and a matching of those to the station concepts. This section examines the market need and recommends reference stations for further development.

7.1 Market Need

It is generally recognized that the types of fueling stations needed in the early stages of infrastructure development will be different than what would exist in a well-established infrastructure such as the gasoline station network. The "cluster strategy" for rollout of hydrogen infrastructure as described in Ogden and Nicholas,[11] for example, seems to be the prevailing favored method for early infrastructure development. In this strategy station rollouts are centered on areas most likely to be early adopters of FCEVs. According to the findings of that work, "[a] cluster strategy provides good convenience and reliability with a small number of strategically placed stations, reducing infrastructure costs." The cluster strategy classifies stations as being either local or regional; the latter are referred to as "connector" stations.

The CARB June 2014 report went a step further and defined three "station classifications" shown here in Table 7.[12] The report connects these classifications to the cluster strategy by defining them as follows:

[11] Ogden, J.; Nicholas, M. "Analysis of a 'cluster' strategy for introducing hydrogen vehicles in Southern California." *Energy Policy* (39), 2011; pp. 1923-1938.
[12] *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development*. Sacramento, CA: California Environmental Protection Agency Air Resources Board, June 2014. Accessed February 18, 2015: http://www.arb.ca.gov/msprog/zevprog/ab8/ab8_report_final_june2014.pdf.

- High Use Commuter (500+ kg/day) stations are local stations within clusters.
- Low Use Commuter stations are local stations outside of clusters; they serve the same types of customers, just with fewer vehicle visits.
- Intermittent stations are regional stations outside of clusters that serve occasional vehicles traveling a long distance between clusters, but they have a chance for high demand at special times (e.g., weekends and holidays).

Table 7. Recommended Station Classifications Based on Customer Habits
(copied from Table 2 of the CARB June 2014 Report)

Classification	Daily Throughput	Hourly Peak Throughput	Dispensers	Technical Capabilities
High Use Commuter	High	High	More than 2	Back-to-back, simultaneous fills
Low Use Commuter	Low–intermediate	Low	2	Simultaneous fills
Intermittent	Low, intermittent	Low	1–2	Limited fuel capabilities

The report further suggests that the next stations funded by the state should have the capability to achieve five consecutive fills per hour and have at least two 70 MPa dispensers ("hoses" in our terminology). The average station size currently being installed under CEC PON-13-607, a California program that awarded funding for hydrogen fueling infrastructure, is 180 kg/day.

7.2 Technical and Regulatory Requirements

Interestingly, the CARB report does not address the issue of the hydrogen delivery or production method. In this work, the delivery method (liquid or gas) is an important distinctive parameter (future iterations of this task could also consider on-site generation and pipeline delivery). To help understand whether or not hydrogen delivery type and station classification are related, it is useful to consider the impact of the choice between liquid and gas.

It is well known that, because of the extremely cold temperature of liquid hydrogen storage, natural heating and vaporization causes boil-off from liquid storage tanks over time. In addition, whenever liquid hydrogen flows through warmer process equipment such as piping, pumps, and heat exchangers, the initial liquid to contact the equipment will vaporize and is typically vented. This occurs until the equipment reaches the temperature of the liquid. Both of these phenomena can be mitigated through constant use, where liquid flows out of the tank faster than it can naturally boil off, and equipment stays cold because it is in continuous contact with the liquid. Connecting this to station classifications, it seems clear that liquid delivery is best suited for the highest-use stations. The previous section about economics showed that liquid delivery is the economically-preferred option for the largest stations, especially when there is more than one hose. Of course, liquid delivery can always be used in any application, but for stations with intermittent use, the boil-off issues will not allow the station to achieve the economics described in Section 6 (which assumes minimal boil-off for all cases). Considering all of this, liquid delivery should not be considered for the Intermittent station classification; it is best suited for the High Use Commuter station classification.

In addition to the boil-off issue, another factor that can influence the choice between liquid and gas delivery is the available site area. This is because the codified setback distances adopted for liquid storage tanks are much larger than those required for gas storage tanks. This is illustrated in the report by Harris et al., which shows that a station design with 100 kg of storage in the form of high pressure (12,500 psi) gas has a footprint of 493 m^2 when using NFPA 2 setback distances. If the storage is in the form of liquid, the footprint increases by nearly a factor of three to 1,406 m^2.[13] This area is important because it affects the potential siting of a hydrogen station. In the report, Harris et al. showed that there were no existing gasoline stations within the areas identified by the California Energy Commission that could accommodate an add-on liquid-delivery hydrogen station, but that between 18% and 44% of the existing gasoline stations studied could potentially accommodate an add-on gas-delivery hydrogen station, while 20% are "H2 ready". The areas studied included a mix of highly urban (e.g., downtown San Francisco) as well as suburban (e.g., Dublin/Pleasanton) locations. Although liquid stations may be sited at "greenfield" sites (available land without any structures), these greenfield sites are difficult to find in urban areas. Even if they are available, siting a liquid hydrogen station there may be subject to more public scrutiny as exemplified by the resistance in Japan to site any liquid delivery hydrogen stations within urban areas due to safety concerns.[14] Therefore, because clusters are centered on urban areas, it seems unlikely that liquid delivery stations can be practically sited within clusters.

7.3 Mapping Needs and Requirements to Station Classifications

In light of the above analyses, the following mapping of station characteristics to station classifications begins to take shape:

- High Use Commuter: Greenfield or existing gasoline station, high daily capacity, multiple hoses, 5+ consecutive fills per hour per hose
- Low Use Commuter: Greenfield or existing gasoline station, compressed gas or liquid supply, medium daily capacity, single or multiple hoses, several consecutive fills per hour
- Intermittent: Greenfield, compressed gas supply, low daily capacity, single hose, ability to meet multiple consecutive fills per hour when called for.

From here, the most economically-viable station concepts determined by economic screening in the previous chapter can be selected to fulfill each of these three classifications.

7.4 Selecting the Best Combination

The final screening and down select process combined economic, performance, and regulatory information from external authorities with modeling results from the previous section. The team chose the resulting stations from the top 15 (Table 6) to fit the CARB[15] High Use Commuter, Low Use Commuter, and Intermittent station categories for near-term station implementation.

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[13] Harris, A.; Dedrick, D.; LaFleur, C.; San Marchi, C. *Safety, Codes and Standards for Hydrogen Installations: Hydrogen Fueling System Footprint Metric Development*. SAND2014-3416. Livermore, CA: Sandia National Laboratories, 2014.
[14] Greene, D.; Duleep, G. Status and Prospects of the Global Automotive Fuel Cell Industry and Plans for Deployment of Fuel Cell Vehicles and Hydrogen Refueling Infrastructure. ORNL/TM-2013/222. Oak Ridge, TN: Oak Ridge National Laboratory, 2013.
[15] *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development*. Sacramento CA: California Environmental Protection Agency Air Resources Board, June 2014.

Only delivered hydrogen was considered in the station analysis. Hydrogen delivered in a liquid state is much denser than gas so much larger quantities can be delivered at a time, which may result in a lower overall hydrogen cost than delivered gaseous hydrogen. The stations that will be further optimized and designed are provided in Table 8.

Table 8. Stations Selected for Final Design

Profile	Site Type	Delivery	Capacity (kg/day)	Consecutive Fills	Hoses	Station Contribution to Hydrogen Cost ($/kg)	Capital Cost (2009$)
High Use Commuter	Gas station or greenfield	Gaseous	300	6	1	$6.03	$1,251,270
High Use Commuter	Greenfield	Liquid	300	5	2	$7.46	$1,486,557
Low Use Commuter	Gas station or greenfield	Gaseous	200	3	1	$5.83	$1,207,663
Intermittent	Gas station or greenfield	Gaseous	100	2	1	$13.28	$954,799

7.4.1 High Use Commuter

The team chose the gaseous delivery, 300 kg/day station for the High Use Commuter profile because it is best suited to be integrated into existing gasoline stations in an urban environment where utilization will likely be very high and back-to-back fills will be required. Additionally, the station ranks fifth in the overall economic analysis. The station requires only 4% more capital investment than the highest ranking station while maintaining one of the lowest fuel costs and doubling the consecutive fills capacity. The CARB High Use Commuter profile calls for multiple hoses for simultaneous fueling. However, adding a second hose to this station to allow for simultaneous filling with the same consecutive fill capability would increase the capital costs by 50% and fuel costs by 45%. A capacity of 300 kg/day was chosen because, while smaller station capacities require less capital investment, they significantly increase the fuel cost ($/kg) while providing little savings on footprint.

The efficiency of delivered liquid hydrogen and operational requirements of a liquid station make it the best choice for the High Use Commuter profile. Unfortunately the required setback distances for liquid storage currently make the urban gasoline station integration unrealistic and greenfield installation the most likely. If setback distances are changed in the future through code revisions, if acceptable designs can be certified through the Performance-Based Option (Section 5 of NFPA 2), or if innovative concepts such as underground storage tanks can be used, a liquid station will be the best fit for the High Use Commuter station. Because of this attractiveness, the liquid delivery, 300 kg/day station with a single fueling hose is anticipated to be attractive in the near-term market and is also selected for further analysis.

7.4.2 Low Use Commuter

The Low Use Commuter profile offers more flexibility in terms of location and thus makes a liquid station more attractive. Low utilization is still a concern for liquid stations, but if this station is assumed to be located near a main pathway to an urban center, it will likely see spikes in demand for short windows of time as commuters travel to or from the urban center. A liquid station would benefit from condensed demand because the piping would not heat up between fills. In spite of this acceptability of liquid stations, a gaseous station is recommended because it does not suffer from the boil-off and temperature change losses that liquid stations do under consistent low utilization, and it has the best economics overall and offers fuel at the cheapest price of all the stations modeled. Therefore, a gaseous delivery 200 kg/day station is selected for the Low Use Commuter profile.

7.4.3 Intermittent

CARB's Intermittent station profile is expected to have very low average utilization and thus a low capacity gaseous delivery station is the most appropriate. Requiring only two consecutive fills minimizes the capital cost and the required for fuel cost to meet an ROI of 7.5 years for stations of this size. The very low capital cost (second lowest) of the 100 kg/day station offers an opportunity for investors to enter the hydrogen market without a large burden.

One probable application for an Intermittent station is to connect two urban centers or vacation destinations (e.g. Lake Tahoe). FCEV drivers would depend on this station to refuel on long trips. It is possible that the on-site storage will run out during periods of abnormally high demand (i.e., during the holidays); however, this can be mitigated by designing a station with enough space to allow two delivery trailers to be parked side by side. In addition, CARB has indicated that a mobile refueling unit could be parked at the station during these anticipated peak times to supplement capacity, and that strategy is assumed here instead of building a larger and very underutilized station. Another strategy to avoid underutilization of a large station used as a connector is to identify a local fuel cell vehicle or bus fleet that it could also support.

8 Selected Reference Stations

8.1 Station Overview

The H2FIRST team defined characteristics for each station concept that specified whether hydrogen is produced locally or remotely and delivered, the daily dispensing capacity of a station, the number of hoses available for independent fills, back-to-back fill capacity, and the fill configuration. The team developed parameter ranges for each characteristic and a matrix of station concepts consisting of 160 different stations, modeled all of the stations using HRSAM software, and selected five station concepts for further development. This work accomplishes station optimization and design (Subtasks 6 and 7 from Figure 1) by developing P&IDs and bills of materials for each of the station concepts. The team also developed spatial layouts for greenfield and select existing gasoline station sites as well. The station designs and analyses highlight the advantages and disadvantages of configuration, layout, and spatial requirements for each of the station concepts.

The liquid station configurations currently available in HRSAM include options with a high pressure evaporator and cryogenic liquid pump. As this equipment is not currently available in the near term, the team added a fifth station that is consistent with currently deployed liquid stations, coupled to the compressed gas equipment of the 300 kg/day gaseous station.

The H2FIRST team chose the stations to best fit near-term deployment plans. The H2USA HFSWG, CaFCP, CARB, and industry members provided insight into current and anticipated stations including parameter value ranges, likely station types, and vehicle rollout scenarios.

The CARB June 2014 report[16] gives station classifications meant to serve different demands. The classifications—High Use Commuter, Low Use Commuter, and Intermittent—are defined by characteristics such as daily throughput and simultaneous and back-to-back fills. The team matched the most economically viable station concepts resulting from HRSAM analysis with these classifications. A summary of the values for design parameters of the selected stations from Subtask 4 is shown in Table 9.

Table 9. Parameter Values for the Selected Station Concepts

Station Number	Delivery Method	Daily Capacity (kg/day)	Number of Hoses	Back-to-Back Fill Capacity	Fill Configuration
1	Gaseous	300	1	6	Cascade
2	Gaseous	200	1	3	Cascade
3	Gaseous	100	1	2	Cascade
4	Near-term liquid	300	2	5	Cascade
5	Future liquid	300	2	5	Cascade

Current-day cost breakdowns of the four near-term stations are shown in Figure 20. These costs differ slightly from those shown in the modeling results section (Table 8) because these use actual equipment costs ("Uninstalled Equipment") determined from the stations' Bills of Materials in the following chapter. This figure shows that for the same capacity (300 kg/day), gaseous delivery is the lower-cost option with both reduced capital and installation expenses relative to a liquid station. This fact, coupled with the reduced setbacks required of gaseous stations, may make this option favorable for existing gasoline station installations in urban environments. The capital and installation costs for all three of the gaseous options are within $200,000 of each other. Despite this small marginal cost for up to three times the capacity, it must be remembered that utilization is critically important to the finances of a station and users are cautioned against oversizing a station for the needs of the local market. The Near-term liquid station was not able to be simulated using the current version of HRSAM and the installation costs from the Future liquid station were used as a substitute. The drastic increase in uninstalled equipment cost for the near-term liquid station is primarily due the addition of a low-pressure cryopump and cryogenic storage to what effectively is otherwise a gaseous delivery station. The future liquid station does not have such an increase because it is able to leverage a high pressure cryopump and mixing chamber and can therefore eliminate the high pressure compressor and chiller. However, as noted in Section 6.1, a high pressure cryopump in the flow rate range for this station does not currently exist and it is likely that the model underestimates the near-term cost of such a pump were it to be developed.

[16] *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development*. Sacramento, CA: California Environmental Protection Agency Air Resources Board, June 2014.

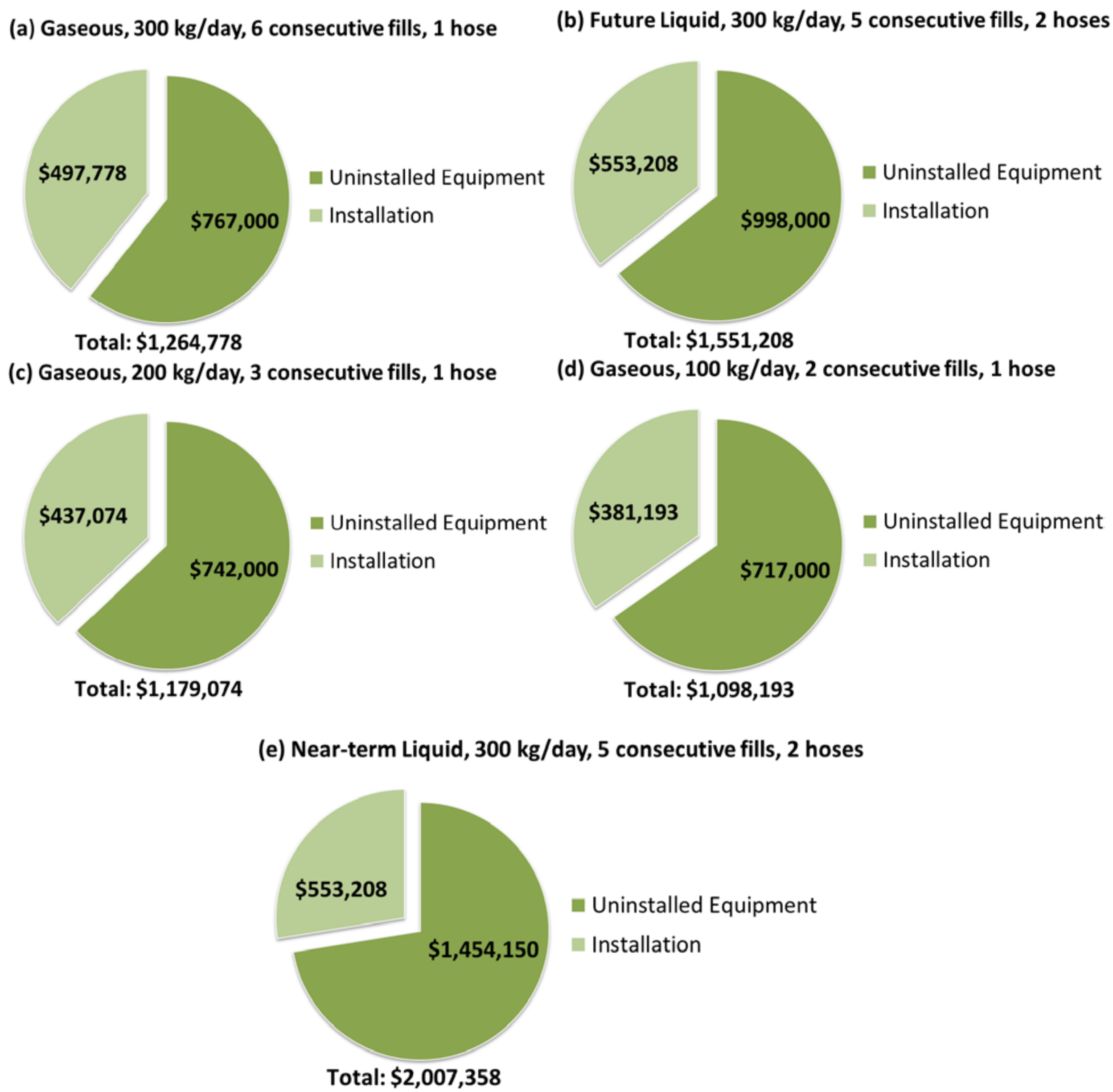

Figure 20. (a)–(d): Breakdown of capital cost of the selected stations

The final station selection process and justifications are documented in detail in Section 7.4. In general, large-capacity stations, such as Station 1 and Station 4, could serve an urban market with high demand and fit the High Use Commuter classification. Small-capacity stations, such as Station 2 or Station 3, may be used to connect large city centers where there is demand and fit the Low Use Commuter or Intermittent station classifications. These applications are just an example. Many other factors such as market projections, traffic patterns, the socio-economic status of the surrounding community, fleet opportunities, land use and zoning laws in addition to the requirements of NFPA 2, should be considered when determining which station is the most appropriate for a location.

All selected stations rely on delivered hydrogen in either gaseous or liquid form because centralized production and truck delivery is the most common near-term method. The number of hoses and back-to-back fills represents the station's ability to handle multiple customers in a short window of time. Fill configurations impact fueling times, storage capacities, and compressor operation.

Converting the desired station characteristics to designs involved aligning the station equipment given in the model with currently available components. The team researched costs, footprints, and operating specifications for major station equipment, such as compressors, storage tanks, dispensers, and evaporators. Costs of other equipment, such as tubing, valves, and fittings, were estimated based on experience from the team and input from industry members.

The team designed each station by synthesizing what is assumed in HRSAM with known current station configurations from the industry and national laboratories. The three gaseous delivery stations (Stations 1–3) have similar configurations and bills of materials but different component sizes.

Station scaling is primarily based on the size of the hydrogen compressor. Based on HRSAM, compressors are the only piece of major equipment to scale with the throughput of the stations. This decision allows the reference stations, including the near-term delivered liquid station, to utilize the largest set of common components possible. This should reduce the overall cost by driving commonality of parts and economies of manufacturing scale. The compressor costs range from approximately $100,000 to $150,000 in the 100 to 300 kg/day size ranges.

The benefits of this approach are tangible. Common parts will help minimize maintenance inventory, drive economies of scale, allow for simplified training of technicians, and reduce the number of station permutations. Simplicity will allow operators to identify and find solutions for reliability issues that will occur.

Liquid stations are less common so it was more challenging to match designs to current stations. Most liquid stations operating today do not operate with the high-pressure evaporator and cryopump configuration modeled in HRSAM. Through conversations with industry members and equipment manufacturers, the team determined that this equipment is produced in very low volume and at times is custom-made. Two designs are presented for liquid stations to show both current stations and the HRSAM concept of future liquid stations.

The near-term liquid station mirrors the design of many of the liquid stations deployed in the United States. The team developed the design by reviewing actual station process flow diagrams for stations built within the last five years and adopting commonalities between them into the final near-term liquid station design.

Physical layouts—derived from the P&IDs and bills of materials—account for equipment size, setback distances mandated by NFPA 2 (2011 version), and delivery truck space requirements. The layouts highlight the different aspects of greenfield sites and existing gasoline stations.

9 Station Designs

This section describes the development of layouts, P&IDs, and bills of materials for the selected station concepts.

9.1 Layouts

The H2FIRST Reference Station Design Task produced three layouts:

1. Gaseous-delivered hydrogen on greenfield site
2. Liquid-delivered hydrogen on greenfield site
3. Gaseous-delivered hydrogen on existing gasoline station (brownfield) site.

As noted in the analysis results in Section 6 and Section 7, siting liquid stations on existing gasoline stations is not preferred due to the fact that the setback distances (see Table B-1) result in unmanageable station sizes in dense urban areas. While there may be opportunities to site liquid stations at gasoline stations in suburban or rural areas, these stations will likely suffer from low utilization (and the high cost of lost product due to frequent boil-off) and thus they are not as economically attractive as gaseous-delivered stations in those areas.

The H2FIRST team formed the layouts using the setback distances given in NFPA 2[17] (Section 7 for gaseous systems, Section 8 for liquid storage, and Section 10 for dispensing equipment) and used the tubing size and pressure ratings from the P&IDs to customize the gaseous piping and equipment separation distances based on the formulas for alternative pipe or tube internal diameters. For the gaseous stations, refer to Table B-3 and Table B-4 in Appendix B for the NFPA 2 setback distances, excerpted from NFPA 2 Table 7.3.2.3.1.1 and 7.3.2.3.1.2. For the liquid stations, refer to Table B-1, adapted from NFPA-2 Table 8.3.2.4.5.1.

A hydrogen station will have to meet all of the requirements in NFPA 2 plus the regular zoning ordinances and construction codes of the municipality. These can impose additional requirements on the station developer that are unrelated to hydrogen. For example, some developers have had to include aesthetic elements such as art, while others were required to plant four trees for each tree removed from the site to make way for the station. For these reference stations, the team chose a middle lot layout instead of a corner lot because some municipalities have minimum allowable distances between the first driveway and the roadway intersection, which could be up to 100 feet. Implementing this requirement would extend the width of the lot and result in more unused space. These designs also include a 15-foot offset from the building to the property line, which may also be required by municipal code. Correspondingly, it is uncertain whether the wall placed around the hydrogen equipment will need to be more than 2 feet from the property line. If so, it may increase the required overall footprint. Finally, this design assumes the municipality will require driveways at least 25 feet wide; if this can be reduced it may decrease the lot size as well. In general, there are many lot design factors that depend on the local municipal code that may result in smaller or larger overall lots than are shown here.

[17] National Fire Protection Association 2: Hydrogen Technologies Code, 2011. Also see NFPA 55.

9.2 Station P&IDs

The team developed detailed P&IDs for each reference station. These P&IDs provide sufficient detail as a beginning basis for a site-specific design. Use of these designs does not absolve the user of the responsibility to perform site-specific engineering for a station including, but not limited to the following: equipment sizing, pressure ratings, location and types of instruments, safety analysis such as a hazard and operability study or failure modes and effects analysis, NFPA 2 setback analysis, and production of design drawings by a licensed Professional Engineer. The P&IDs are provided in Appendix D.

9.2.1 Gaseous Stations

The design philosophy behind the reference stations relies on reuse of the same components wherever possible in order to help drive economies of scale, ease of maintenance, and interchangeability of parts. The only piece of equipment that varies between the three gaseous stations (100, 200, and 300 kg/day) is the compressor.

Tag identification is adapted from ANSI/ISA 5.1, with customizations for hydrogen equipment. The standard provides a flexible framework for setting P&ID tags that succinctly describe the measured variable, readout, and function of an instrument or piece of process equipment. For example, a position switch on a valve is tagged ZSO or ZSC for position switch open or closed, respectively. See Table 10 for details.

Table 10. P&ID Tag Scheme Adapted From ANSI/ISA 5.1

	Measured Variable	Readout of Function	Output Function
A	Air	Alarm	
B	Burner	Storage	Users choice
C	Compressor		
D	Dispenser		
E	Electrolyzer	Sensor (primary element)	
F	Flow	Filter	
G	Chiller	Glass, viewing	
H	Hand		
I	Current	Indicator	
J	Power		
K	Time		Control station
L	Level	Light	
M	Conductivity		
N	Users choice	Users choice	Hydrogen
O	Water	Orifice, restriction	Air
P	Pressure		
Q	Quantity		
R	Radiation	Record, reduce	
S	Speed, frequency		Switch
T	Temperature		Transmit
U	Multivariate	Multifunction	Multifunction
V	Vibration		Valve
W	Weight	Well	Water
X	Unclassified	Unclassified	Unclassified
Y	State		Relay
Z	Position		Actuator

The P&ID is divided into zones loosely based on the pressure of the hydrogen or the type of equipment present in the zone. These designations are merely for convenience and were selected arbitrarily to modularize the P&ID. Dividing the P&ID into zones allows one to very quickly correlate the physical location of a particular piece of equipment with its tag number. This is handy for alarm signaling; for instance an operator will immediately know that an alarm on equipment tagged with a 9XX tag is from the dispenser. P&ID tags are coded with a three-digit number beginning with the equipment zone. For instance, a hand valve in Zone 100 may be tagged HV-100. See Table 11 for a description of the zones and their corresponding numbers (Zones 500–700 are reserved for future use).

Table 11. P&ID Zone Numbers and Descriptions

Zone	Description
100–200	Tube trailer delivered pressure
300	Compressor output
400	High-pressure storage
800	Compressor cooling
900	Dispensing

Selecting Air-Operated Valves

Air-operated valves are used as a standard in all reference station designs. The valves are all configured with open and closed position switches and visual indication. Air-operated valves are appropriate for Class 1 Division 2 Group B locations, such as a hydrogen station. All valves are configured with a spring return actuator to return to a closed or open position in the event of a power or air loss.

The safety benefits far outweigh the additional cost. It is not sufficient to assume the position of a valve based on the command signal to it. The control system must command a valve to move and then receive confirmation from the limit switches that the desired position has been reached before making further decisions.

The team made the decision to use a small air compressor/receiver and dryer for reasons of reliability and operating cost. According to data published by the National Renewable Energy Laboratory, stations that use nitrogen dewars for supply control gas experience downtime if the dewar level is not monitored and actively maintained. The control gas system accounts for 8% of maintenance at early market material handling stations.[18]

Zones 100 and 200

Zones 100 and 200 include the interface to the tube trailer (in the case of gaseous stations) or the liquid tanker (for liquid stations). In addition to any flow and pressure controls on the trailer itself (not shown due to the many variations likely to be encountered), the station design includes a manual shut-off valve (HV-100) and an air-operated valve (FV-101) controlled by the station programmable logic controller (PLC). See above for a discussion on the rationale for selecting air-operated valves.

[18] "Infrastructure Maintenance by Equipment Type." National Renewable Energy Laboratory, April 2014. Accessed February 19, 2015: http://www.nrel.gov/hydrogen/cfm/images/cdp_mhe_18.jpg.

Upstream and downstream of FV-101 are indicating pressure transmitters (PI/PT-101/102), each connected to the system with a block and bleed valve to allow for easy maintenance with minimal disruption to the system.

Zone 100 also includes a path to bypass the compressor through FV-101 and feed gas directly to the high-pressure storage tanks. This path may be utilized any time PT-201/202 are lower than any of the tank pressures (PT-401/402/403). This method of operation will result in faster tank filling and lower compressor power consumption.

Zones 300 and 800

Zone 300 is the compressor zone. Zone 800 is the compressor cooling system. These reference stations assume the use of a multi-stage piston-type compressor that can accept pressure up to 250 bar on its inlet. The compressor is cooled by a closed-loop cooling system that may be mounted on the compressor skid or remotely, based on the individual manufacturer's design. Although not shown, all compressors will use some sort of inter-stage cooling in order to maximize efficiency by increasing gas density on the inlet of subsequent stages. Additionally, the compressor may be fitted with a heater system for cold locations to ensure the hydraulic fluid has a low enough viscosity to allow for safe startup in cold conditions.

The compressor motor sizes for the gaseous stations are given in Table 12.

Table 12. Compressor Motor Scaling

Station Throughput (kg/day)	Motor Size (kW)
100	25
200	50
300	60

Zone 400

Zone 400 is the high-pressure storage zone comprising three 13-kg Type II composite wrapped steel hydrogen tanks. Each of the three tanks is individually addressable with separate fill valves, FV-401/402/403.

This arrangement allows for maximum flexibility and control of the system for the operator. The tanks will be used in a cascade arrangement, filling vehicles from the lowest-pressure tank first until it equalizes with the vehicle tank, then moving to the next-highest-pressure tank until the vehicle is full or the highest-pressure tank is equalized with the vehicle.

While this arrangement allows direct compressor-to-vehicle filling, it is not recommended by automakers because the pulsatile flow of the compressor can accelerate wear of the check valves in the vehicle fuel train.

All fuel flow may be shut off by FV-400 as an additional safety and control device.

Pressure Safety Valves

Pressure safety valves are not used in Zone 400 on the high-pressure tanks because pressure safety valves on hydrogen tanks can fail and be a net safety risk rather than a benefit. This design choice may be controversial, but it has a sound basis in making the system as safe as possible.

Pressure safety valves are common failure points and can lead to high profile incidents and fire such as the failure of a relief valve at the AC Transit station in Emeryville, California.[19] This approach is non-standard but is allowed under the current ASME Section VIII boiler and pressure vessel code. Sub-section UG-140 of the code allows for overpressure protection by design, if the pressure in the vessels is self limiting (e.g., fed by a compressor). This requires a detailed HAZOP or FMECA analysis to show that the coincident pressure and temperature in the vessel does not exceed MAWP.

The standard practice of including pressure relief valves on the tanks is also an option that may save some time in the approval stage of the project. However, there are other ways to mitigate the threats traditionally controlled with a pressure relief valve, namely vessel rupture due to an engulfing fire.

The compressor will always have an internal series of relief valves to prevent overpressure on the output of the stages. These much smaller relief valves will prevent overfilling of the tanks, even in the event of a control system failure. As long as appropriate safety measures are in place to prevent an engulfing fire around the hydrogen tanks, the need for pressure safety valves on the vessels is obviated. These controls can include bollards to prevent intrusion by vehicles, non-flammable landscaping, concrete barriers, and others. If users of these reference station designs wish to adopt this approach, they must complete their own safety analysis, particular to their design.

Zone 900

Zone 900 is the dispenser zone. The work scope of this task called for the inclusion of dual pressure dispensing for 350-bar or 700-bar fills. Although 350-bar filling is not a priority for light-duty vehicles, it is the pressure level of choice for buses and other industrial medium-duty vehicles.

The physical interfaces of the nozzles are one-way incompatible to prevent a 700-bar fill into a vehicle equipped with 350-bar tanks. However, a 700-bar vehicle could fill at a 350-bar nozzle.

The cost and footprint required for installing a separate 350-bar storage cascade are impractical. Instead 350-bar filling, which does not require the use of a chiller in most instances, will be accomplished by the use of a forward pressure regulator in the dispenser. There is an efficiency penalty for this approach; however, the number of 350-bar fills is likely to be small in comparison to the 700-bar fills and the compromise is made to the benefit of efficient 700-bar filling.

Controls

The controls for the reference stations are accomplished through the use of an industrial-quality PLC. The PLC will control the air solenoid valves (ZVO) in the gas control cabinet, which will in turn control the air operators (ZZO) on the flow valves (FV).

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[19] Harris, A.P.; San Marchi, C.W. *Investigation of the Hydrogen Release Incident at the AC Transit Emeryville Facility (Revised)*. SAND2012-8642. Livermore, CA: Sandia National Laboratories, 2012. http://prod.sandia.gov/techlib/access-control.cgi/2012/128642.pdf.

The system will also need to have a fire panel or similar safety system that will receive signals from the emergency stops (EPO) and the infrared flame detectors (RAH-100/900). Infrared flame detectors typically have a visible radius of 90 degrees and must be positioned to oversee areas of leaks. In the P&IDs they are shown overlooking the bulk storage and the dispenser, as these are the most critical station elements.

9.2.2 Liquid Stations

Liquid stations are divided into two types: (1) a near-term station and (2) a future station with a high-pressure evaporator, which could eliminate the need for a chiller and compressor. Although this technology exists at an experimental station in Europe, it is not commercially available.

The near-term station uses a cryogenic liquid storage tank and ambient air evaporator to supply hydrogen to the compressor. Beyond these differences, the station design is the same as that of the gaseous stations. NFPA 2 does require different (generally larger) setbacks for liquid stations than for gaseous stations. Refer to Table B-1, adapted from NFPA 2 Table 8.3.2.4.5.1, for these setback distances.

The future liquid station makes use of a high-pressure forced-draft evaporator and cryogenic liquid pump to autogenously pressurize up to the 900-bar level for high-pressure storage. This removes the compressor from the design. This design also uses a mixing heat exchanger at the dispenser to mix a small amount of liquid hydrogen in with the high-pressure gas in order to eliminate the chiller. This system could potentially simplify and reduce the cost of a liquid-based station. In reality, this design is difficult to build due to the highly custom nature of the required evaporator, pump, and heat exchanger components.

9.3 Bills of Materials

Bills of materials are developed for each station type as shown in Section 10. The cost data used for the bills of materials is the uninstalled capital cost for the equipment. Cost estimates come from a variety of sources including direct quotes, actual purchase orders for equipment, and, failing those, estimates based on similar equipment. Summary equipment costs for the five station types are shown in Table 13.

Table 13. Approximate Uninstalled Equipment Costs for Five Stations

Station	Approximate Uninstalled Equipment Cost ($K)
100 kg/day gas	$717
200 kg/day gas	$742
300 kg/day gas	$767
300 kg/day liquid	$1,454
Future liquid	$998

10 Detailed Design

This section presents detailed P&IDs and bills of materials for all five selected stations:

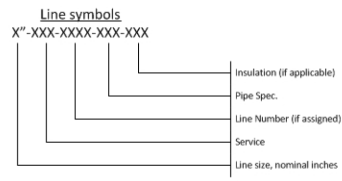
1. 100 kg/day gaseous station
2. 200 kg/day gaseous station
3. 300 kg/day gaseous station
4. 300 kg/day near-term liquid station
5. 300 kg/day future liquid station.

Section 10.1 includes layouts for a gaseous station on a green field site and on an existing gasoline station, and Section 10.4 includes a layout for a liquid station on a greenfield site.

10.1 Design for the 100 kg/day Gaseous Station

P&ID

	Measured Variable	Readout of function	Output Function	Modifier
A	Air	Alarm		
B	Burner	Storage	Users Choice	Users Choice
C	Compressor			Closed
D	Dispenser			
E	Electrolyzer	Sensor (primary Element)		
F	Flow	Filter		
G	Chiller	Glass, viewing		
H	Hand			High
I	Current	Indicator		
J	Power			
K	Time		Control Station	
L	Level	Light		Low
M	Conductivity			Middle
N	Users Choice	Users Choice	Hydrogen	Users Choice
O	Water	Orifice, restriction	Air	Open
P	Pressure			
Q	Quantity			
R	Radiation	Record, Reduce		
S	Speed, Frequency		Switch	
T	Temperature		Transmit	
U	Multivariate	Multifunction	Multifunction	Multifunction
V	Vibration		Valve	
W	Weight	Well	Water	
X	Unclassified	Unclassified	Unclassified	Unclassified
Y	State		Relay	
Z	Position		Actuator	



Line Service Identification codes
CCA-CLEAN COMPRESSED AIR
CHW-CHILLED WATER
H-HYDROGEN
N-NITROGEN

Insulation codes
F1- Soda-lime silicate glass (FOAMGLAS) 1" wall thickness
F2- Buna N Foam 3/8" thick

Pipe Specification Details

3000PSI	Min. pressure rating of 3,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
6500PSI	Min. pressure rating of 6,500 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
15000PSI	Min. pressure rating of 15,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
POLY	Polyamide (Nylon) pneumatic tubing, light and heat stabilized.
0.032CU	0.032" wall copper alloy 122 seamless tubing
SCH40	Schedule 40 iron pipe

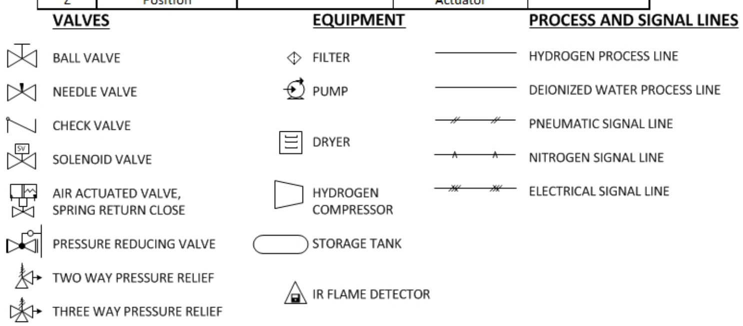


Figure 21. P&ID legend: 100 kg/day gaseous station

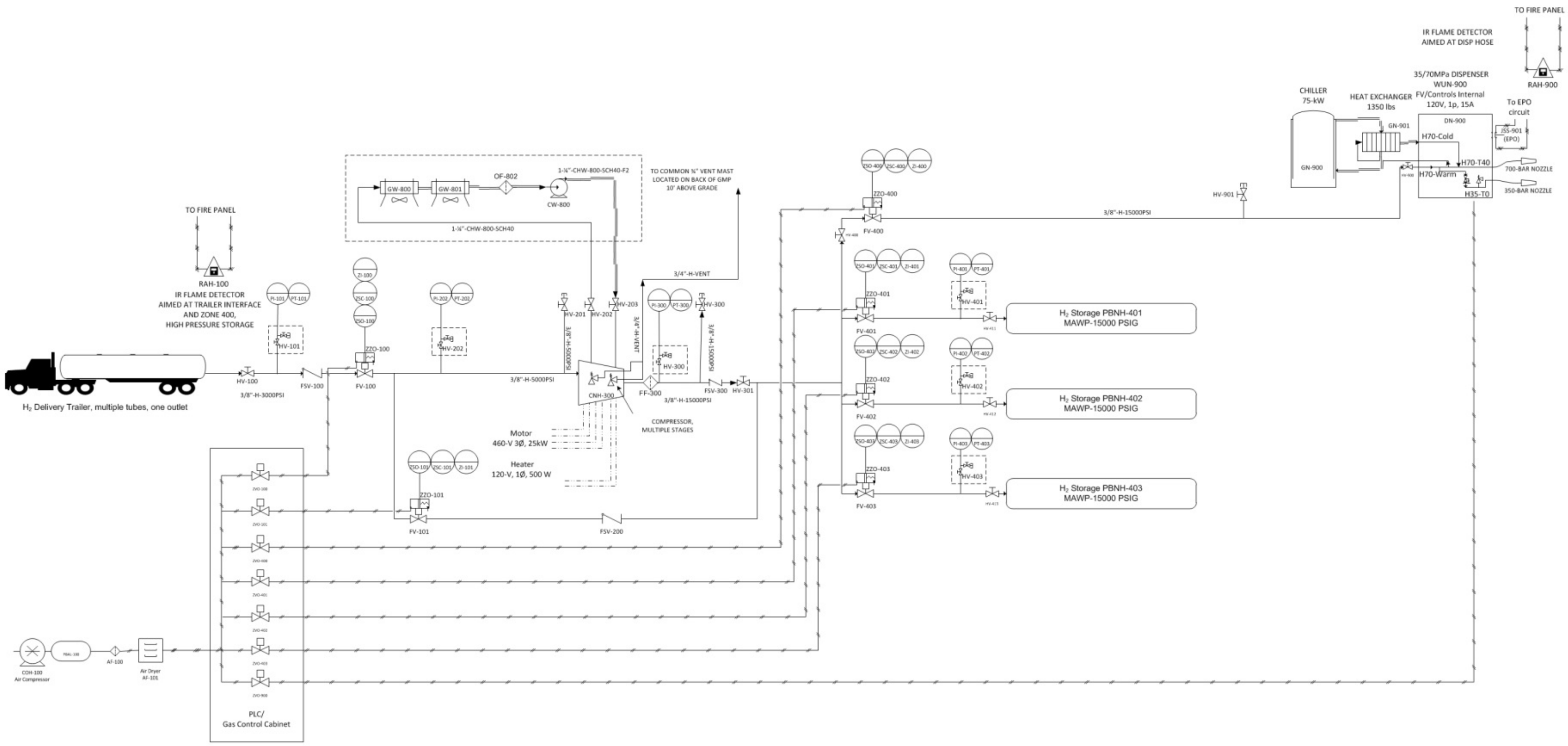


Figure 22. P&ID for the 100 kg/day gaseous station

Layout

Figure 23 shows a middle lot layout with the hydrogen equipment in a walled cluster in the vicinity of the dispenser and includes an attendant's building/shop and parking area. The wall around the hydrogen equipment allows many of the separation distances to be reduced so that the largest lot line separation distance is 17.5 feet from the cascade storage system. Of the non-hydrogen equipment (air compressor, dryer, and cooling water equipment), the air compressor or its inlet must be placed 45 feet away from the hydrogen trailers (this separation distance is not reduced by the wall). The other non-hydrogen equipment could be placed directly outside the wall to reduce cost because the classified electrical zone (Class 1, Division 2, Group B) ends at the wall and this equipment will not need to be classified. However, this equipment is small and it is located along with the air compressor in another equipment cluster for convenience. An option would be to locate this equipment just outside the wall and pipe the air compressor inlet 45 feet away; this decision should be made while considering actual site conditions. The wall also does not allow the heating, ventilating, and air conditioning (HVAC) and air inlet separation distance to be reduced, which necessitates locating the building at least 45 feet away from the hydrogen trailers and 35 feet away from the cascade storage. Furthermore, because of the need to deliver hydrogen trailers within the walled area, there is no wall on the delivery side. This open side means that the full separation distance—which is 45 feet from the hydrogen trailer to the lot line and building openings—must be adhered to in this direction. This, combined with the need to easily back in a hydrogen trailer, dictates that the wall opening face an unoccupied space within the station. Space is most effectively utilized if it also faces a driveway to the street. Refer to Table B-3 and Table B-4 in Appendix B for the NFPA 2 setback distances for this station and the other two gaseous stations (excerpted from NFPA 2 Table 7.3.2.3.1.1 and 7.3.2.3.1.2).

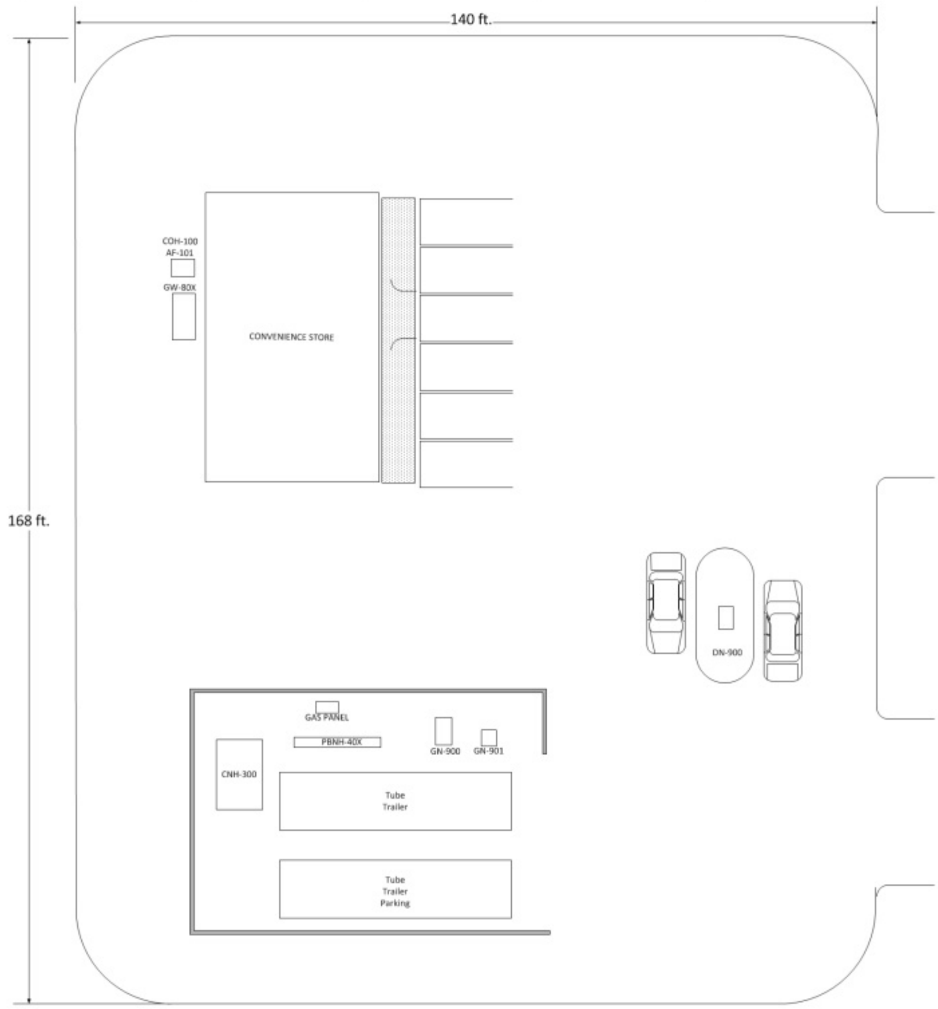


Figure 23. Layout of gaseous hydrogen station on greenfield site

To determine the requirements for siting the hydrogen station at an existing gas station, the team selected a gasoline station previously identified as "ready" for hydrogen infrastructure co-location in a report by Harris et al.[20] that examined urban gasoline stations within California Energy Commission target areas for suitability for add-on hydrogen infrastructure. An overhead image of the "Torrance 6" station is shown in Figure 24, and a hydrogen infrastructure layout that would fit and meet all codified setback distances within this station is shown in Figure 25. This hydrogen equipment is identical to that of the greenfield site (Figure 23) and uses the same separation distances. The only modification needed to the site, besides installation of the hydrogen infrastructure, is relocation of a driveway about 25 feet to the north.

[20] Harris, A.; Dedrick, D.; LaFleur, C.; San Marchi, C. *Safety, Codes and Standards for Hydrogen Installations: Hydrogen Fueling System Footprint Metric Development*. SAND2014-3416. Livermore, CA: Sandia National Laboratories, 2014.

Figure 24. Overhead image of the “Torrance 6” gasoline station located at 3401 Torrance Blvd., Torrance, CA 90503

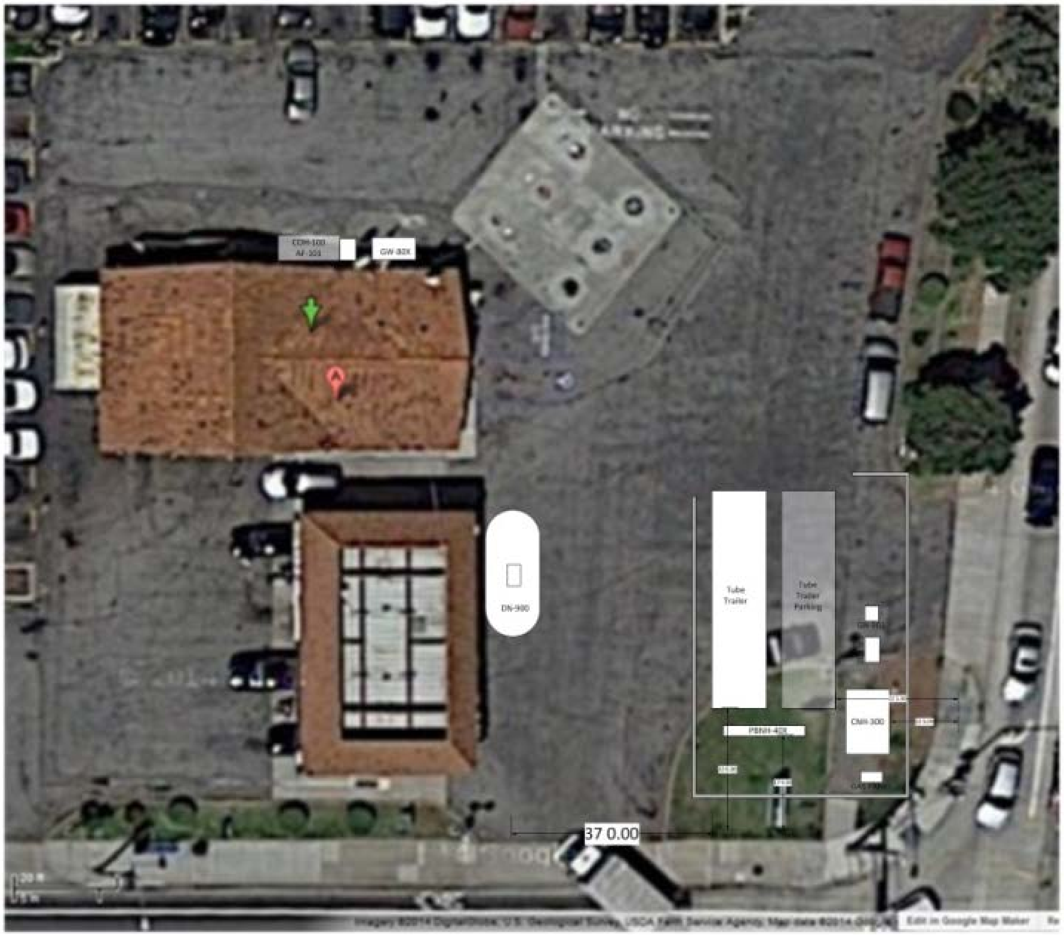


Figure 25. Layout of the hydrogen station add-on to the "Torrance 6" gasoline station shown in Figure 24

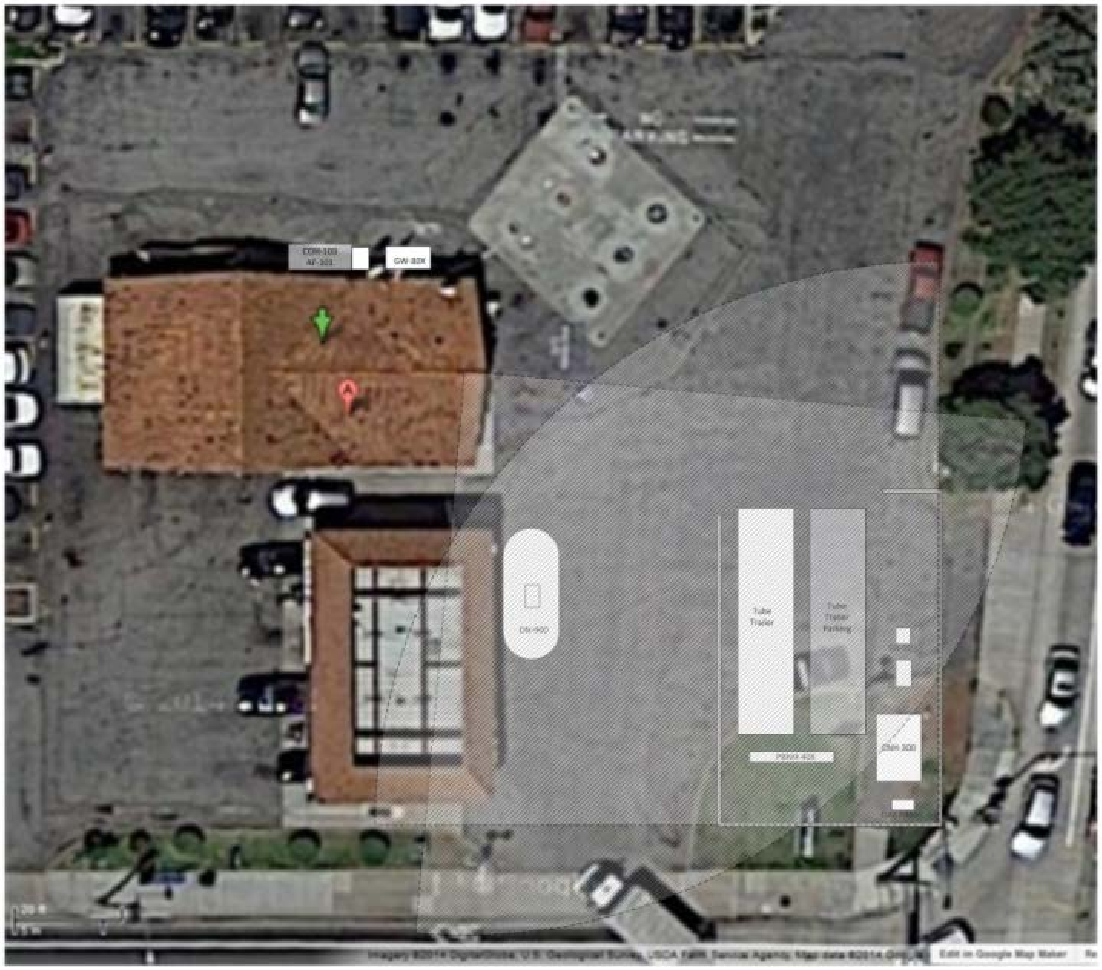


Figure 26. Torrance Station fire eye coverage

As indicated in the Harris et al. report, there are very few existing gasoline stations with sufficient open area to accommodate an add-on hydrogen station meeting all prescribed NFPA 2 separation distances. An alternative described in NFPA 2 Section 5 is the use of the Performance-Based Option, which has the potential to effectively reduce the separation distances and allow AHJ acceptance of more compact designs, enabling add-on hydrogen station infrastructure at more existing gasoline stations. An example of such a design is shown in Appendix C.

Bill of Materials

Table 14. Bill of Materials for the 100 kg/day Gaseous Station

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Hydrogen tank 401	PBNH-401	1	$40,000	$40,000
Hydrogen tank 402	PBNH-402	1	$40,000	$40,000
Hydrogen tank 403	PBNH-403	1	$40,000	$40,000
Pressure transmitter w/ indicator	PT-101	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-202	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-300	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-401	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-402	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-403	1	$1,000	$1,000
Block and bleed valve	HV-101	1	$500	$500
Block and bleed valve	HV-202	1	$500	$500
Block and bleed valve	HV-300	1	$500	$500
Block and bleed valve	HV-401	1	$500	$500
Block and bleed valve	HV-402	1	$500	$500
Block and bleed valve	HV-403	1	$500	$500
Position switch open	ZSO-100	1	incl w/ valve	$-
Position switch closed	ZSC-100	1	incl w/ valve	$-
Position indicator	ZI-100	1	incl w/ valve	$-
Air operator	ZZO-100	1	incl w/ valve	$-
Air operated valve	FV-100	1	$2,000	$2,000
Position switch open	ZSO-101	1	incl w/ valve	$-
Position switch closed	ZSC-101	1	incl w/ valve	$-
Position indicator	ZI-101	1	incl w/ valve	$-
Air operator	ZZO-101	1	incl w/ valve	$-
Air operated valve	FV-101	1	$2,000	$2,000
Position switch open	ZSO-400	1	incl w/ valve	$-
Position switch closed	ZSC-400	1	incl w/ valve	$-
Position indicator	ZI-400	1	incl w/ valve	$-
Air operator	ZZO-400	1	incl w/ valve	$-
Air operated valve	FV-400	1	$2,000	$2,000
Position switch open	ZSO-401	1	incl w/ valve	$-
Position switch closed	ZSC-401	1	incl w/ valve	$-
Position indicator	ZI-401	1	incl w/ valve	$-
Air operator	ZZO-401	1	incl w/ valve	$-
Air operated valve	FV-401	1	$2,000	$2,000
Position switch open	ZSO-402	1	incl w/ valve	$-
Position switch closed	ZSC-402	1	incl w/ valve	$-
Position indicator	ZI-402	1	incl w/ valve	$-
Air operator	ZZO-402	1	incl w/ valve	$-
Air operated valve	FV-402	1	$2,000	$2,000
Position switch open	ZSO-403	1	incl w/ valve	$-

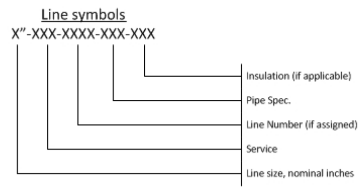
Description	Tag Number	Quantity	Approx Cost	Ext Cost
Position switch closed	ZSC-403	1	incl w/ valve	$-
Position indicator	ZI-403	1	incl w/ valve	$-
Air operated valve	FV-403	1	$2,000	$2,000
Air operator	ZZO-403	1	incl w/ valve	$-
Isolation hand valve	HV-100	1	$500	$500
Isolation hand valve	HV-201	1	$500	$500
Isolation hand valve	HV-202	1	$500	$500
Isolation hand valve	HV-203	1	$500	$500
Isolation hand valve	HV-300	1	$500	$500
Isolation hand valve	HV-301	1	$500	$500
Isolation hand valve	HV-411	1	$500	$500
Isolation hand valve	HV-412	1	$500	$500
Isolation hand valve	HV-413	1	$500	$500
Isolation hand valve	HV-400	1	$500	$500
Isolation hand valve	HV-901	1	$500	$500
Isolation hand valve	HV-900	1	$500	$500
Check valve	FSV-100	1	$400	$400
Check valve	FSV-200	1	$400	$400
Check valve	FSV-300	1	$400	$400
Coolant pump	CW-800	1	$1,200	$1,200
Air-cooled water chiller	GW-800	1	$4,000	$4,000
Air-cooled water chiller	GW-801	1	$4,000	$4,000
Coolant filter	OF-802	1	$50	$50
Instrument air compressor	COH-100	1	$1,000	$1,000
Instrument air receiver	PBAL-100	1	-	$-
Instrument air filter	AF-100	1	$50	$50
Instrument air dryer	AF-101	1	$2,500	$2,500
Pilot solenoid valve	ZVO-100	1	$50	$50
Pilot solenoid valve	ZVO-101	1	$50	$50
Pilot solenoid valve	ZVO-400	1	$50	$50
Pilot solenoid valve	ZVO-401	1	$50	$50
Pilot solenoid valve	ZVO-402	1	$50	$50
Pilot solenoid valve	ZVO-403	1	$50	$50
Pilot solenoid valve	ZVO-900	1	$50	$50
Hydrogen compressor	CNH-300	1	$100,000	$100,000
Hydrogen chiller	GN-900	1	$350,000	$350,000
Hydrogen cooling block	GN-901	1	-	$-
Hydrogen dispenser	WUN-900	1	-	$-
IR flame detector	RAH-100	1	$1,500	$1,500
IR flame detector	RAH-900	1	$1,500	$1,500
Hydrogen filter	FF-300	1	$2,500	$2,500
PLC		1	$5,000	$5,000
Tubing		1	$20,000	$20,000

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Fittings		1	$15,000	$15,000
Electrical upgrades		1	$50,000	$50,000
Fencing		1	$5,000	$5,000
Bollards		1	$5,000	$5,000

10.2 Design for the 200 kg/day Gaseous Station

P&ID

	Measured Variable	Readout of function	Output Function	Modifier
A	Air	Alarm		
B	Burner	Storage	Users Choice	Users Choice
C	Compressor			Closed
D	Dispenser			
E	Electrolyzer	Sensor (primary Element)		
F	Flow	Filter		
G	Chiller	Glass, viewing		
H	Hand			High
I	Current	Indicator		
J	Power			
K	Time		Control Station	
L	Level	Light		Low
M	Conductivity			Middle
N	Users Choice	Users Choice	Hydrogen	Users Choice
O	Water	Orifice, restriction	Air	Open
P	Pressure			
Q	Quantity			
R	Radiation	Record, Reduce		
S	Speed, Frequency		Switch	
T	Temperature		Transmit	
U	Multivariate	Multifunction	Multifunction	Multifunction
V	Vibration		Valve	
W	Weight	Well	Water	
X	Unclassified	Unclassified	Unclassified	Unclassified
Y	State		Relay	
Z	Position		Actuator	



Line Service Identification codes
CCA-CLEAN COMPRESSED AIR
CHW-CHILLED WATER
H-HYDROGEN
N-NITROGEN

Insulation codes
F1- Soda-lime silicate glass (FOAMGLAS) 1" wall thickness
F2- Buna N Foam 3/8" thick

Pipe Specification Details

3000PSI	Min. pressure rating of 3,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
6500PSI	Min. pressure rating of 6,500 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
15000PSI	Min. pressure rating of 15,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
POLY	Polyamide (Nylon) pneumatic tubing, light and heat stabilized.
0.032CU	0.032" wall copper alloy 122 seamless tubing
SCH40	Schedule 40 iron pipe

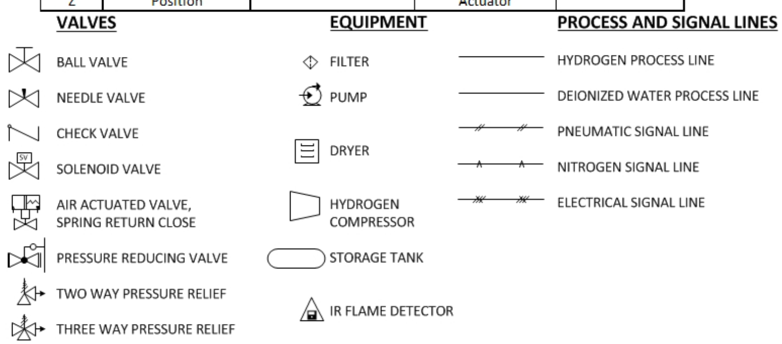


Figure 27. P&ID legend: 200 kg/day gaseous station

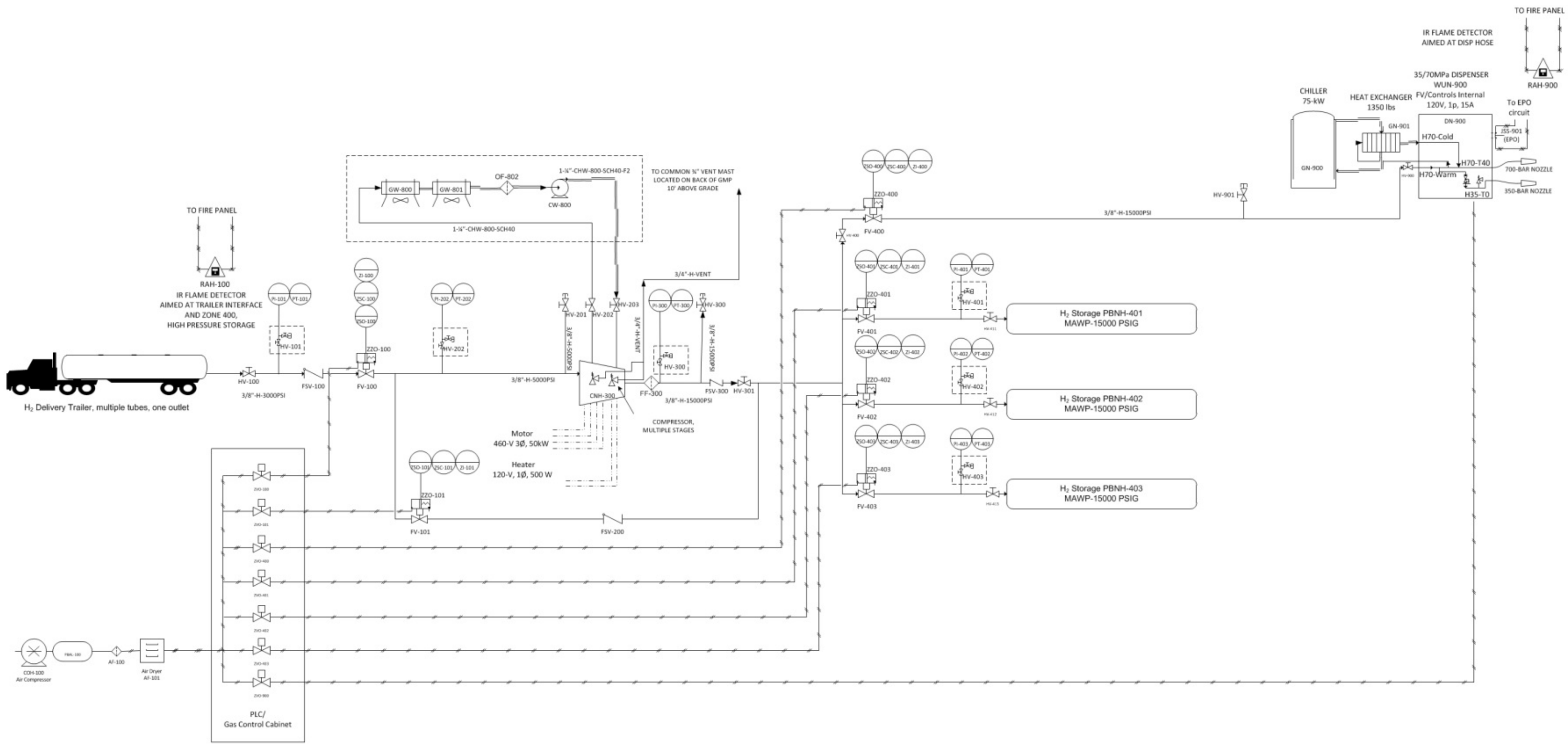


Figure 28. P&ID for the 200 kg/day gaseous station

Bill of Materials

Table 15. Bill of Materials for 200 kg/day Gaseous Station

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Hydrogen tank 401	PBNH-401	1	$40,000	$40,000
Hydrogen tank 402	PBNH-402	1	$40,000	$40,000
Hydrogen tank 403	PBNH-403	1	$40,000	$40,000
Pressure transmitter w/ indicator	PT-101	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-202	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-300	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-401	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-402	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-403	1	$1,000	$1,000
Block and bleed valve	HV-101	1	$500	$500
Block and bleed valve	HV-202	1	$500	$500
Block and bleed valve	HV-300	1	$500	$500
Block and bleed valve	HV-401	1	$500	$500
Block and bleed valve	HV-402	1	$500	$500
Block and bleed valve	HV-403	1	$500	$500
Position switch open	ZSO-100	1	incl w/ valve	$-
Position switch closed	ZSC-100	1	incl w/ valve	$-
Position indicator	ZI-100	1	incl w/ valve	$-
Air operator	ZZO-100	1	incl w/ valve	$-
Air operated valve	FV-100	1	$2,000	$2,000
Position switch open	ZSO-101	1	incl w/ valve	$-
Position switch closed	ZSC-101	1	incl w/ valve	$-
Position indicator	ZI-101	1	incl w/ valve	$-
Air operator	ZZO-101	1	incl w/ valve	$-
Air operated valve	FV-101	1	$2,000	$2,000
Position switch open	ZSO-400	1	incl w/ valve	$-
Position switch closed	ZSC-400	1	incl w/ valve	$-
Position indicator	ZI-400	1	incl w/ valve	$-
Air operator	ZZO-400	1	incl w/ valve	$-
Air operated valve	FV-400	1	$2,000	$2,000
Position switch open	ZSO-401	1	incl w/ valve	$-
Position switch closed	ZSC-401	1	incl w/ valve	$-
Position indicator	ZI-401	1	incl w/ valve	$-
Air operator	ZZO-401	1	incl w/ valve	$-
Air operated valve	FV-401	1	$2,000	$2,000
Position switch open	ZSO-402	1	incl w/ valve	$-
Position switch closed	ZSC-402	1	incl w/ valve	$-
Position indicator	ZI-402	1	incl w/ valve	$-
Air operator	ZZO-402	1	incl w/ valve	$-
Air operated valve	FV-402	1	$2,000	$2,000
Position switch open	ZSO-403	1	incl w/ valve	$-

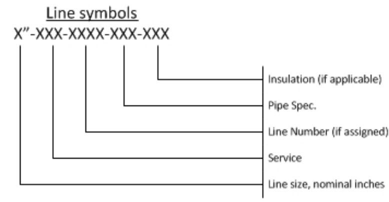
Description	Tag Number	Quantity	Approx Cost	Ext Cost
Position switch closed	ZSC-403	1	incl w/ valve	$-
Position indicator	ZI-403	1	incl w/ valve	$-
Air operated valve	FV-403	1	$2,000	$2,000
Air operator	ZZO-403	1	incl w/ valve	$-
Isolation hand valve	HV-100	1	$500	$500
Isolation hand valve	HV-201	1	$500	$500
Isolation hand valve	HV-202	1	$500	$500
Isolation hand valve	HV-203	1	$500	$500
Isolation hand valve	HV-300	1	$500	$500
Isolation hand valve	HV-301	1	$500	$500
Isolation hand valve	HV-411	1	$500	$500
Isolation hand valve	HV-412	1	$500	$500
Isolation hand valve	HV-413	1	$500	$500
Isolation hand valve	HV-400	1	$500	$500
Isolation hand valve	HV-901	1	$500	$500
Isolation hand valve	HV-900	1	$500	$500
Check valve	FSV-100	1	$400	$400
Check valve	FSV-200	1	$400	$400
Check valve	FSV-300	1	$400	$400
Coolant pump	CW-800	1	$1,200	$1,200
Air-cooled water chiller	GW-800	1	$4,000	$4,000
Air-cooled water chiller	GW-801	1	$4,000	$4,000
Coolant filter	OF-802	1	$50	$50
Instrument air compressor	COH-100	1	$1,000	$1,000
Instrument air receiver	PBAL-100	1	-	$-
Instrument air filter	AF-100	1	$50	$50
Instrument air dryer	AF-101	1	$2,500	$2,500
Pilot solenoid valve	ZVO-100	1	$50	$50
Pilot solenoid valve	ZVO-101	1	$50	$50
Pilot solenoid valve	ZVO-400	1	$50	$50
Pilot solenoid valve	ZVO-401	1	$50	$50
Pilot solenoid valve	ZVO-402	1	$50	$50
Pilot solenoid valve	ZVO-403	1	$50	$50
Pilot solenoid valve	ZVO-900	1	$50	$50
Hydrogen compressor	CNH-300	1	$125,000	$125,000
Hydrogen chiller	GN-900	1	$350,000	$350,000
Hydrogen cooling block	GN-901	1	-	$-
Hydrogen dispenser	WUN-900	1	-	$-
IR flame detector	RAH-100	1	$1,500	$1,500
IR flame detector	RAH-900	1	$1,500	$1,500
Hydrogen filter	FF-300	1	$2,500	$2,500
PLC		1	$5,000	$5,000
Tubing		1	$20,000	$20,000

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Fittings		1	$15,000	$15,000
Electrical upgrades		1	$50,000	$50,000
Fencing		1	$5,000	$5,000
Bollards		1	$5,000	$5,000

10.3 Design for the 300 kg/day Gaseous Station

P&ID

	Measured Variable	Readout of function	Output Function	Modifier
A	Air	Alarm		
B	Burner	Storage	Users Choice	Users Choice
C	Compressor			Closed
D	Dispenser			
E	Electrolyzer	Sensor (primary Element)		
F	Flow	Filter		
G	Chiller	Glass, viewing		
H	Hand			High
I	Current	Indicator		
J	Power			
K	Time		Control Station	
L	Level	Light		Low
M	Conductivity			Middle
N	Users Choice	Users Choice	Hydrogen	Users Choice
O	Water	Orifice, restriction	Air	Open
P	Pressure			
Q	Quantity			
R	Radiation	Record, Reduce		
S	Speed, Frequency		Switch	
T	Temperature		Transmit	
U	Multivariate	Multifunction	Multifunction	Multifunction
V	Vibration		Valve	
W	Weight	Well	Water	
X	Unclassified	Unclassified	Unclassified	Unclassified
Y	State		Relay	
Z	Position		Actuator	



Line Service Identification codes
CCA-CLEAN COMPRESSED AIR
CHW-CHILLED WATER
H-HYDROGEN
N-NITROGEN

Insulation codes
F1- Soda-lime silicate glass (FOAMGLAS) 1" wall thickness
F2- Buna N Foam 3/8" thick

Pipe Specification Details

3000PSI	Min. pressure rating of 3,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
6500PSI	Min. pressure rating of 6,500 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
15000PSI	Min. pressure rating of 15,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
POLY	Polyamide (Nylon) pneumatic tubing, light and heat stabilized.
0.032CU	0.032" wall copper alloy 122 seamless tubing
SCH40	Schedule 40 iron pipe

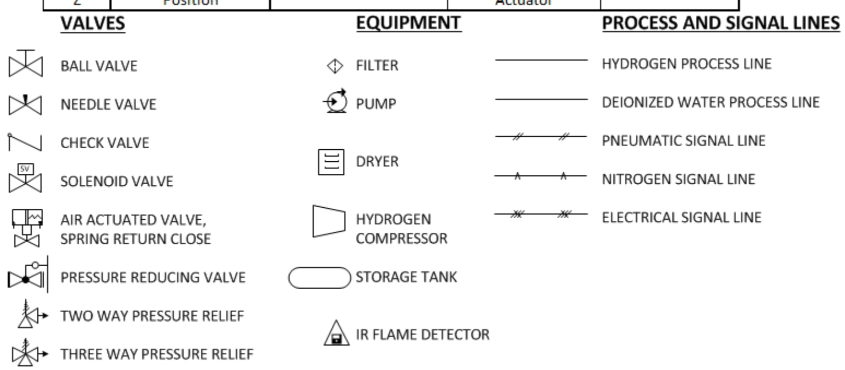


Figure 29. P&ID legend: 300 kg/day gaseous station

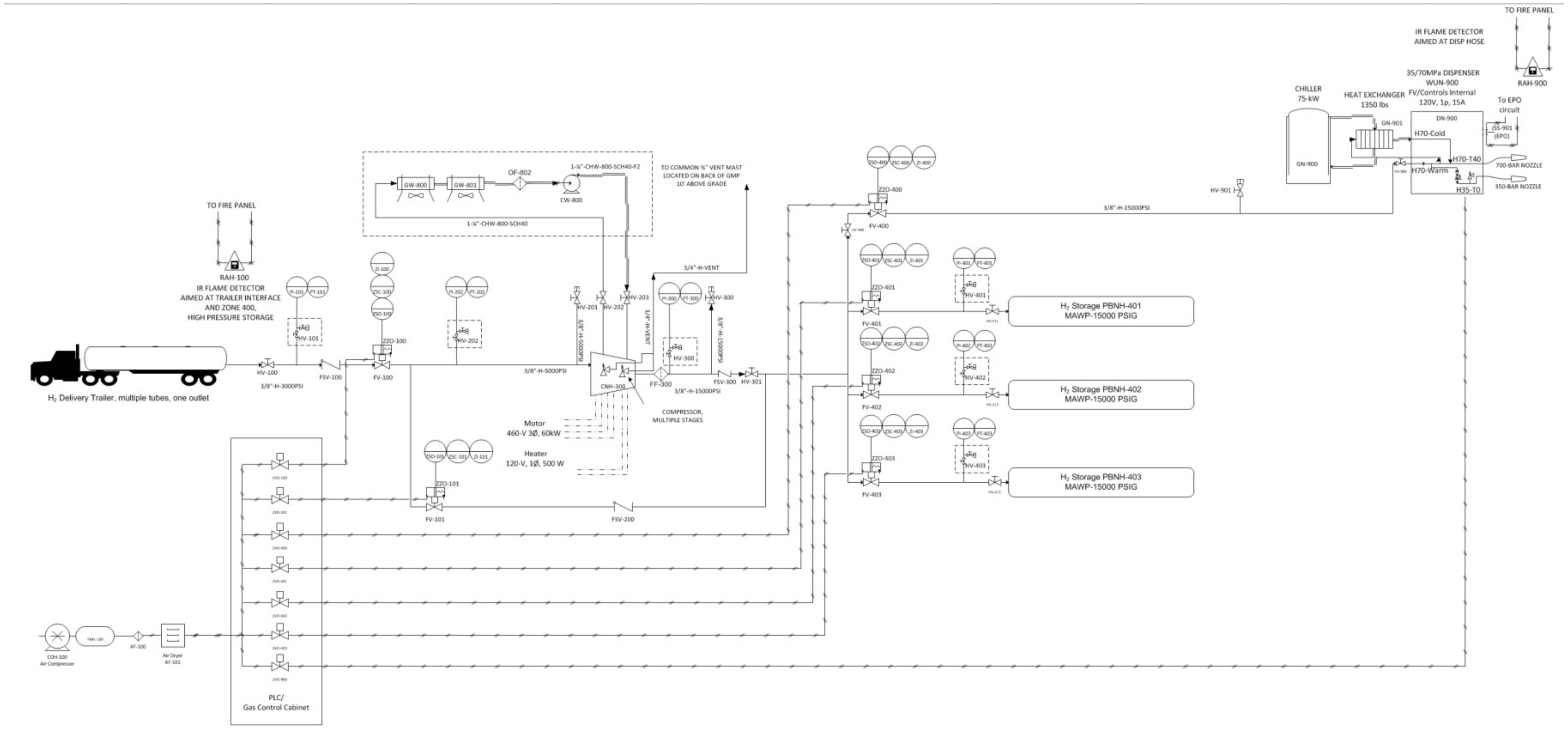


Figure 30. P&ID for the 300 kg/day gaseous station

Bill of Materials

Table 16. Bill of Materials for 300 kg/day Gaseous Station

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Hydrogen tank 401	PBNH-401	1	$40,000	$40,000
Hydrogen tank 402	PBNH-402	1	$40,000	$40,000
Hydrogen tank 403	PBNH-403	1	$40,000	$40,000
Pressure transmitter w/ indicator	PT-101	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-202	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-300	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-401	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-402	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-403	1	$1,000	$1,000
Block and bleed valve	HV-101	1	$500	$500
Block and bleed valve	HV-202	1	$500	$500
Block and bleed valve	HV-300	1	$500	$500
Block and bleed valve	HV-401	1	$500	$500
Block and bleed valve	HV-402	1	$500	$500
Block and bleed valve	HV-403	1	$500	$500
Position switch open	ZSO-100	1	incl w/ valve	$-
Position switch closed	ZSC-100	1	incl w/ valve	$-
Position indicator	ZI-100	1	incl w/ valve	$-
Air operator	ZZO-100	1	incl w/ valve	$-
Air operated valve	FV-100	1	$2,000	$2,000
Position switch open	ZSO-101	1	incl w/ valve	$-
Position switch closed	ZSC-101	1	incl w/ valve	$-
Position indicator	ZI-101	1	incl w/ valve	$-
Air operator	ZZO-101	1	incl w/ valve	$-
Air operated valve	FV-101	1	$2,000	$2,000
Position switch open	ZSO-400	1	incl w/ valve	$-
Position switch closed	ZSC-400	1	incl w/ valve	$-
Position indicator	ZI-400	1	incl w/ valve	$-
Air operator	ZZO-400	1	incl w/ valve	$-
Air operated valve	FV-400	1	$2,000	$2,000
Position switch open	ZSO-401	1	incl w/ valve	$-
Position switch closed	ZSC-401	1	incl w/ valve	$-
Position indicator	ZI-401	1	incl w/ valve	$-
Air operator	ZZO-401	1	incl w/ valve	$-
Air operated valve	FV-401	1	$2,000	$2,000
Position switch open	ZSO-402	1	incl w/ valve	$-
Position switch closed	ZSC-402	1	incl w/ valve	$-
Position indicator	ZI-402	1	incl w/ valve	$-
Air operator	ZZO-402	1	incl w/ valve	$-
Air operated valve	FV-402	1	$2,000	$2,000
Position switch open	ZSO-403	1	incl w/ valve	$-

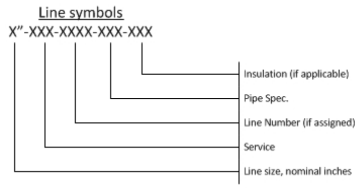
Description	Tag Number	Quantity	Approx Cost	Ext Cost
Position switch closed	ZSC-403	1	incl w/ valve	$-
Position indicator	ZI-403	1	incl w/ valve	$-
Air operated valve	FV-403	1	$2,000	$2,000
Air operator	ZZO-403	1	incl w/ valve	$-
Isolation hand valve	HV-100	1	$500	$500
Isolation hand valve	HV-201	1	$500	$500
Isolation hand valve	HV-202	1	$500	$500
Isolation hand valve	HV-203	1	$500	$500
Isolation hand valve	HV-300	1	$500	$500
Isolation hand valve	HV-301	1	$500	$500
Isolation hand valve	HV-411	1	$500	$500
Isolation hand valve	HV-412	1	$500	$500
Isolation hand valve	HV-413	1	$500	$500
Isolation hand valve	HV-400	1	$500	$500
Isolation hand valve	HV-901	1	$500	$500
Isolation hand valve	HV-900	1	$500	$500
Check valve	FSV-100	1	$400	$400
Check valve	FSV-200	1	$400	$400
Check valve	FSV-300	1	$400	$400
Coolant pump	CW-800	1	$1,200	$1,200
Air-cooled water chiller	GW-800	1	$4,000	$4,000
Air-cooled water chiller	GW-801	1	$4,000	$4,000
Coolant filter	OF-802	1	$50	$50
Instrument air compressor	COH-100	1	$1,000	$1,000
Instrument air receiver	PBAL-100	1	-	$-
Instrument air filter	AF-100	1	$50	$50
Instrument air dryer	AF-101	1	$2,500	$2,500
Pilot solenoid valve	ZVO-100	1	$50	$50
Pilot solenoid valve	ZVO-101	1	$50	$50
Pilot solenoid valve	ZVO-400	1	$50	$50
Pilot solenoid valve	ZVO-401	1	$50	$50
Pilot solenoid valve	ZVO-402	1	$50	$50
Pilot solenoid valve	ZVO-403	1	$50	$50
Pilot solenoid valve	ZVO-900	1	$50	$50
Hydrogen compressor	CNH-300	1	$150,000	$150,000
Hydrogen chiller	GN-900	1	$350,000	$350,000
Hydrogen cooling block	GN-901	1	-	$-
Hydrogen dispenser	WUN-900	1	-	$-
IR flame detector	RAH-100	1	$1,500	$1,500
IR flame detector	RAH-900	1	$1,500	$1,500
Hydrogen filter	FF-300	1	$2,500	$2,500
PLC		1	$5,000	$5,000
Tubing		1	$20,000	$20,000

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Fittings		1	$15,000	$15,000
Electrical upgrades		1	$50,000	$50,000
Fencing		1	$5,000	$5,000
Bollards		1	$5,000	$5,000

10.4 Design for the 300 kg/day Near-Term Liquid Station

P&ID

	Measured Variable	Readout of function	Output Function	Modifier
A	Air	Alarm		
B	Burner	Storage	Users Choice	Users Choice
C	Compressor			Closed
D	Dispenser			
E	Electrolyzer	Sensor (primary Element)		
F	Flow	Filter		
G	Chiller	Glass, viewing		
H	Hand			High
I	Current	Indicator		
J	Power			
K	Time		Control Station	
L	Level	Light		Low
M	Conductivity			Middle
N	Users Choice	Users Choice	Hydrogen	Users Choice
O	Water	Orifice, restriction	Air	Open
P	Pressure			
Q	Quantity			
R	Radiation	Record, Reduce		
S	Speed, Frequency		Switch	
T	Temperature		Transmit	
U	Multivariate	Multifunction	Multifunction	Multifunction
V	Vibration		Valve	
W	Weight	Well	Water	
X	Unclassified	Unclassified	Unclassified	Unclassified
Y	State		Relay	
Z	Position		Actuator	



Line Service Identification codes
CCA-CLEAN COMPRESSED AIR
CHW-CHILLED WATER
H-HYDROGEN
N-NITROGEN

Insulation codes
F1- Soda-lime silicate glass (FOAMGLAS) 1" wall thickness
F2- Buna N Foam 3/8" thick

Pipe Specification Details

3000PSI	Min. pressure rating of 3,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
6500PSI	Min. pressure rating of 6,500 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
15000PSI	Min. pressure rating of 15,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
POLY	Polyamide (Nylon) pneumatic tubing, light and heat stabilized.
0.032CU	0.032" wall copper alloy 122 seamless tubing
SCH40	Schedule 40 iron pipe

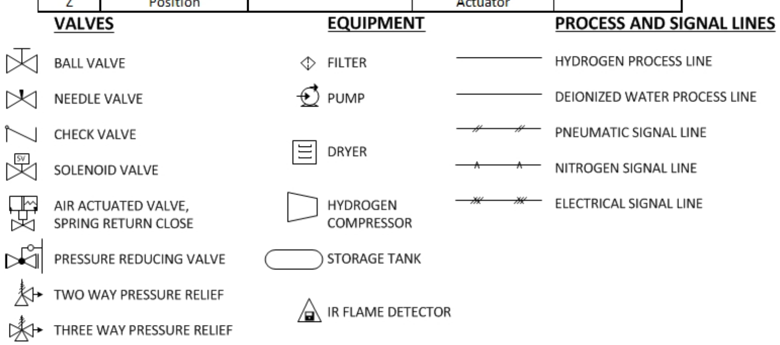


Figure 31. P&ID legend: 300 kg/day near-term liquid station

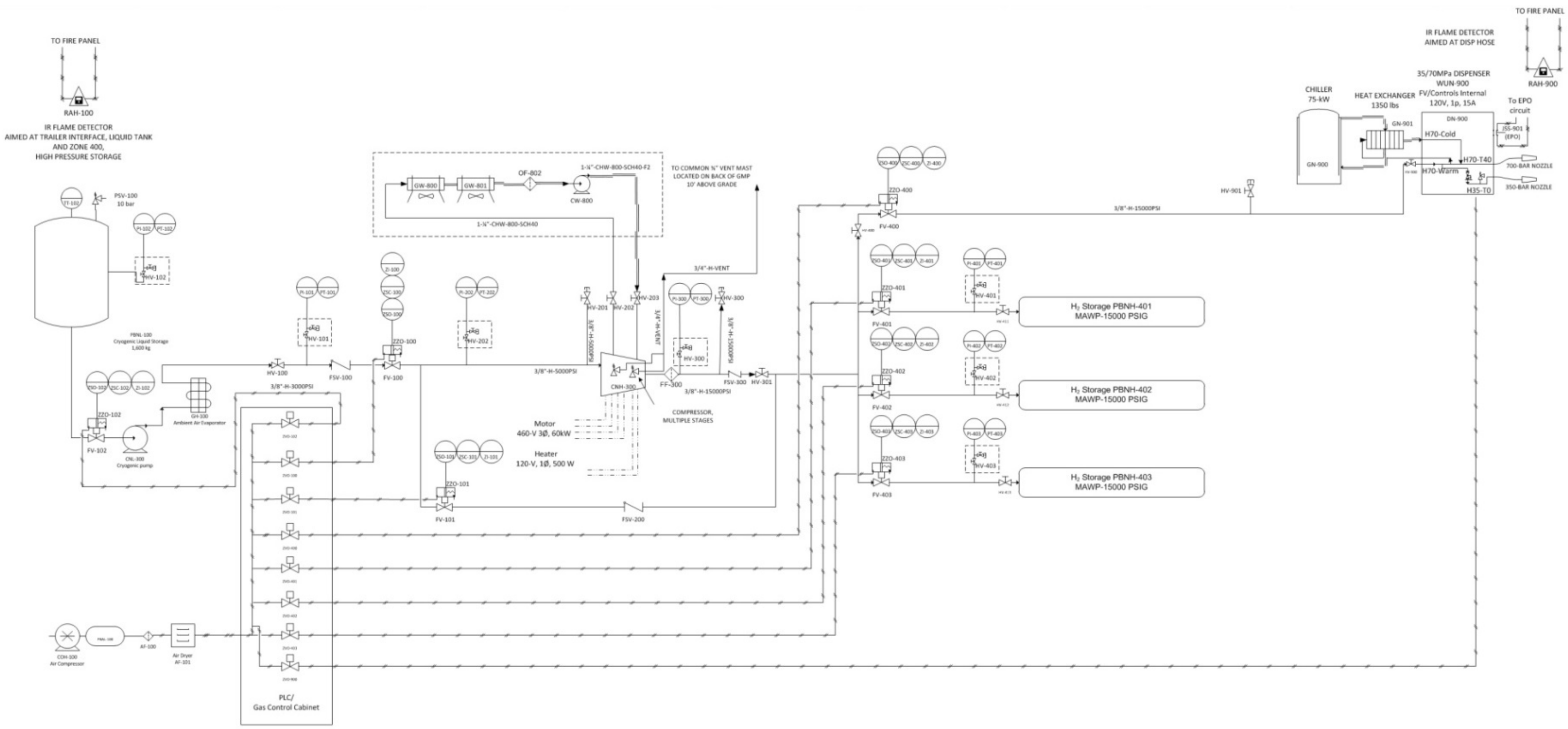


Figure 32. P&ID for the 300 kg/day near-term liquid station

Layout

The separation distances for liquid hydrogen storage tanks and piping are much greater than those for compressed gas. In addition, the use of a wall to reduce separation distances is hindered by two factors: (1) the wall cannot be placed on two adjacent sides surrounding the equipment and (2) the reduction in separation distances achieved with a wall is not as drastic or as broadly applied as it is with gaseous equipment. These factors necessitate larger lots than the gaseous station counterparts. One example layout is shown in Figure 33. Nearly all of the on-site equipment is the same as the gaseous delivery station except the tube trailers are replaced with a 6,000-gallon liquid hydrogen storage tank and an ambient air vaporizer is added. The dispensing equipment and attendant's building are assumed to be the same size and shape. The design accommodates a tractor-trailer delivery for the liquid hydrogen as well as normal vehicle traffic flow. The layout adheres to the same restrictions on placement and width of driveways and structures as in the gaseous delivery station (see Figure 34).

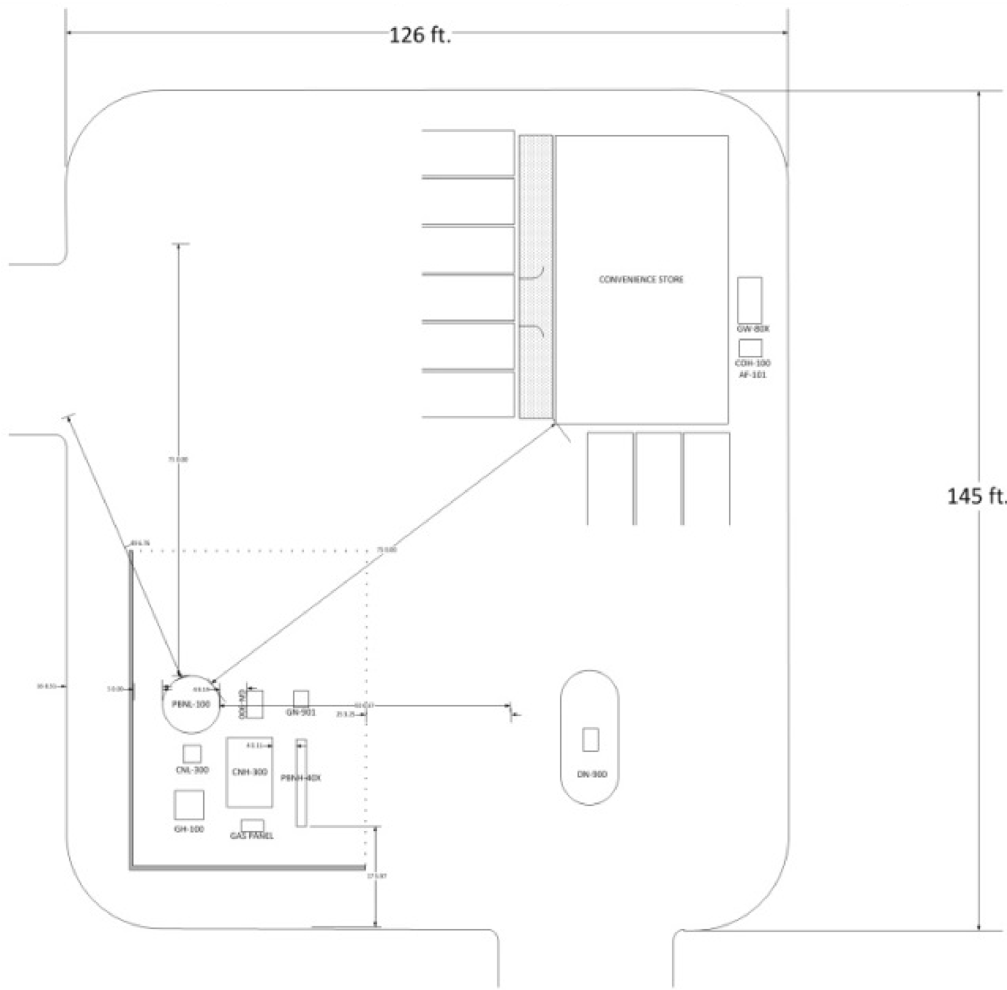


Figure 33. Layout of liquid hydrogen station on greenfield site with dimensions

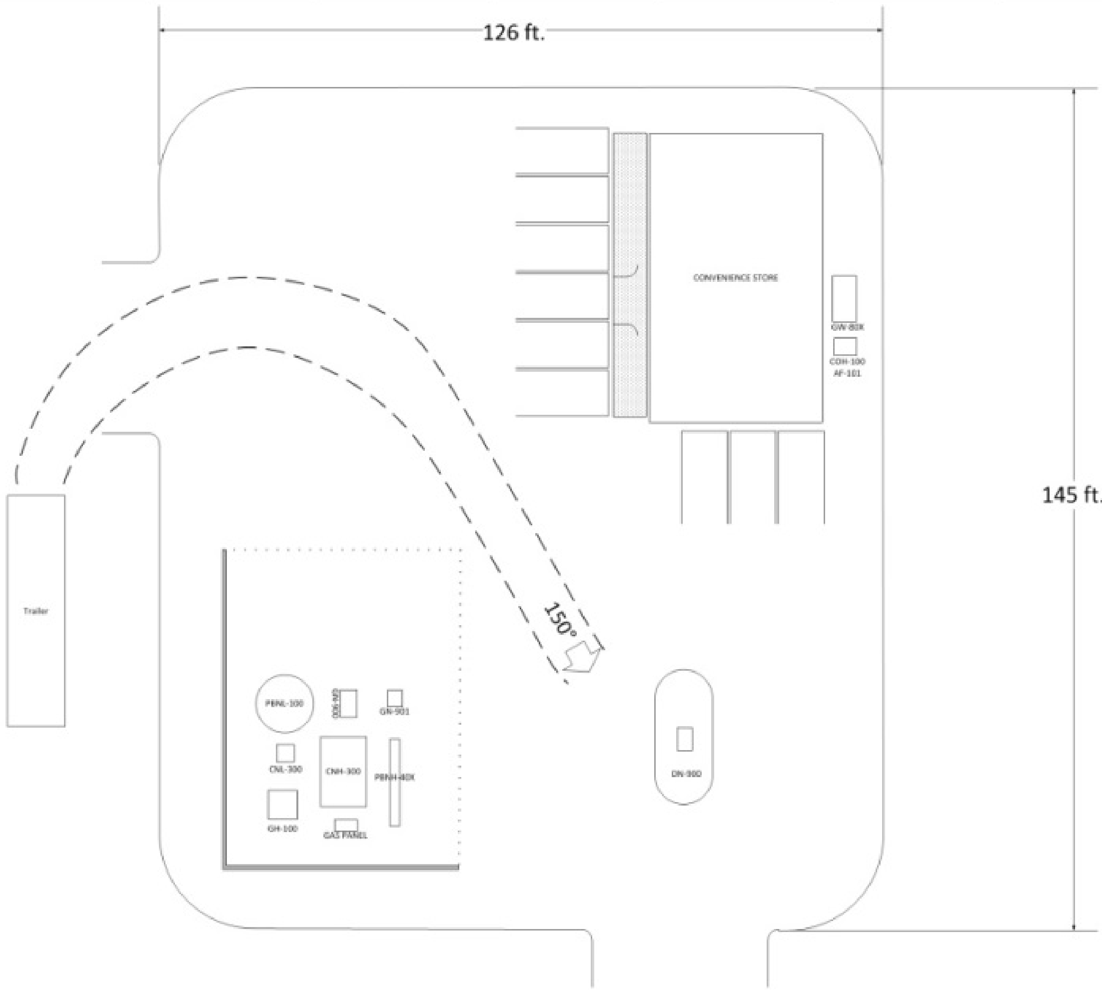


Figure 34. Liquid station layout showing delivery truck path

Bill of Materials

Table 17. Bill of Materials for 300 kg/day Near-Term Liquid Station

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Hydrogen tank 401	PBNH-401	1	$40,000	$40,000
Hydrogen tank 402	PBNH-402	1	$40,000	$40,000
Hydrogen tank 403	PBNH-403	1	$40,000	$40,000
Pressure transmitter w/ indicator	PT-101	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-102	1	$1,000	$1,000
Temperature trans. w/ indicator	TT-102	1	$300	$300
Pressure transmitter w/ indicator	PT-202	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-300	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-401	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-402	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-403	1	$1,000	$1,000
Block and bleed valve	HV-101	1	$500	$500
Block and bleed valve	HV-102	1	$500	$500
Block and bleed valve	HV-202	1	$500	$500
Block and bleed valve	HV-300	1	$500	$500
Block and bleed valve	HV-401	1	$500	$500
Block and bleed valve	HV-402	1	$500	$500
Block and bleed valve	HV-403	1	$500	$500
Position switch open	ZSO-100	1	incl w/ valve	$-
Position switch closed	ZSC-100	1	incl w/ valve	$-
Position indicator	ZI-100	1	incl w/ valve	$-
Air operator	ZZO-100	1	incl w/ valve	$-
Air operated valve	FV-100	1	$2,000	$2,000
Position switch open	ZSO-101	1	incl w/ valve	$-
Position switch closed	ZSC-101	1	incl w/ valve	$-
Position indicator	ZI-101	1	incl w/ valve	$-
Air operator	ZZO-101	1	incl w/ valve	$-
Air operated valve	FV-101	1	$2,000	$2,000
Position switch open	ZSO-400	1	incl w/ valve	$-
Position switch closed	ZSC-400	1	incl w/ valve	$-
Position indicator	ZI-400	1	incl w/ valve	$-
Air operator	ZZO-400	1	incl w/ valve	$-
Air operated valve	FV-400	1	$2,000	$2,000
Position switch open	ZSO-401	1	incl w/ valve	$-
Position switch closed	ZSC-401	1	incl w/ valve	$-
Position indicator	ZI-401	1	incl w/ valve	$-
Air operator	ZZO-401	1	incl w/ valve	$-
Air operated valve	FV-401	1	$2,000	$2,000
Position switch open	ZSO-402	1	incl w/ valve	$-
Position switch closed	ZSC-402	1	incl w/ valve	$-
Position indicator	ZI-402	1	incl w/ valve	$-
Air operator	ZZO-402	1	incl w/ valve	$-

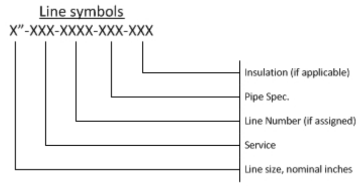
Description	Tag Number	Quantity	Approx Cost	Ext Cost
Air operated valve	FV-402	1	$2,000	$2,000
Position switch open	ZSO-403	1	incl w/ valve	$-
Position switch closed	ZSC-403	1	incl w/ valve	$-
Position indicator	ZI-403	1	incl w/ valve	$-
Air operated valve	FV-403	1	$2,000	$2,000
Air operator	ZZO-403	1	incl w/ valve	$-
Isolation hand valve	HV-100	1	$500	$500
Isolation hand valve	HV-201	1	$500	$500
Isolation hand valve	HV-202	1	$500	$500
Isolation hand valve	HV-203	1	$500	$500
Isolation hand valve	HV-300	1	$500	$500
Isolation hand valve	HV-301	1	$500	$500
Isolation hand valve	HV-411	1	$500	$500
Isolation hand valve	HV-412	1	$500	$500
Isolation hand valve	HV-413	1	$500	$500
Isolation hand valve	HV-400	1	$500	$500
Isolation hand valve	HV-901	1	$500	$500
Isolation hand valve	HV-900	1	$500	$500
Check valve	FSV-100	1	$400	$400
Check valve	FSV-200	1	$400	$400
Check valve	FSV-300	1	$400	$400
Coolant pump	CW-800	1	$1,200	$1,200
Air-cooled water chiller	GW-800	1	$4,000	$4,000
Air-cooled water chiller	GW-801	1	$4,000	$4,000
Coolant filter	OF-802	1	$50	$50
Instrument air compressor	COH-100	1	$1,000	$1,000
Instrument air receiver	PBAL-100	1	-	$-
Instrument air filter	AF-100	1	$50	$50
Instrument air dryer	AF-101	1	$2,500	$2,500
Pilot solenoid valve	ZVO-100	1	$50	$50
Pilot solenoid valve	ZVO-101	1	$50	$50
Pilot solenoid valve	ZVO-400	1	$50	$50
Pilot solenoid valve	ZVO-401	1	$50	$50
Pilot solenoid valve	ZVO-402	1	$50	$50
Pilot solenoid valve	ZVO-403	1	$50	$50
Pilot solenoid valve	ZVO-900	1	$50	$50
Hydrogen compressor	CNH-300	1	$150,000	$150,000
Hydrogen chiller	GN-900	1	$350,000	$350,000
Hydrogen cooling block	GN-901	1	-	$-
Hydrogen dispenser	WUN-900	1	-	$-
IR flame detector	RAH-100	1	$1,500	$1,500
IR flame detector	RAH-900	1	$1,500	$1,500
Hydrogen filter	FF-300	1	$2,500	$2,500
PLC		1	$5,000	$5,000
Tubing		1	$20,000	$20,000

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Fittings		1	$15,000	$15,000
Electrical upgrades		1	$50,000	$50,000
Fencing		1	$5,000	$5,000
Bollards		1	$5,000	$5,000
Cryogenic liquid tank	PBNL-100	1	$317,000	$317,000
Evaporator	GH-100	1	$28,500	$28,500
Cryogenic liquid pump	CNL-300	1	$340,000	$340,000

10.5 Design for the 300 kg/day Future Liquid Station

P&ID

	Measured Variable	Readout of function	Output Function	Modifier
A	Air	Alarm		
B	Burner	Storage	Users Choice	Users Choice
C	Compressor			Closed
D	Dispenser			
E	Electrolyzer	Sensor (primary Element)		
F	Flow	Filter		
G	Chiller	Glass, viewing		
H	Hand			High
I	Current	Indicator		
J	Power			
K	Time		Control Station	
L	Level	Light		Low
M	Conductivity			Middle
N	Users Choice	Users Choice	Hydrogen	Users Choice
O	Water	Orifice, restriction	Air	Open
P	Pressure			
Q	Quantity			
R	Radiation	Record, Reduce		
S	Speed, Frequency		Switch	
T	Temperature		Transmit	
U	Multivariate	Multifunction	Multifunction	Multifunction
V	Vibration		Valve	
W	Weight	Well	Water	
X	Unclassified	Unclassified	Unclassified	Unclassified
Y	State		Relay	
Z	Position		Actuator	



Line Service Identification codes
CCA-CLEAN COMPRESSED AIR
CHW-CHILLED WATER
H-HYDROGEN
N-NITROGEN

Insulation codes
F1- Soda-lime silicate glass (FOAMGLAS) 1" wall thickness
F2- Buna N Foam 3/8" thick

Pipe Specification Details

3000PSI	Min. pressure rating of 3,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
6500PSI	Min. pressure rating of 6,500 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
15000PSI	Min. pressure rating of 15,000 PSI 316/316L austenitic stainless steel tubing UNS S31600 (316), UNS S31603 (316L)
POLY	Polyamide (Nylon) pneumatic tubing, light and heat stabilized.
0.032CU	0.032" wall copper alloy 122 seamless tubing
SCH40	Schedule 40 iron pipe

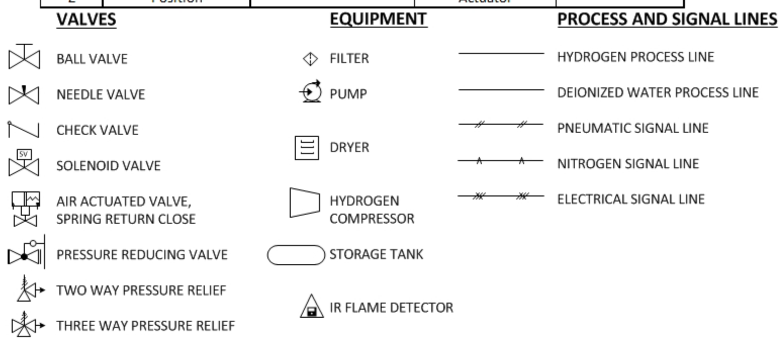


Figure 35. P&ID legend: 300 kg/day future liquid station

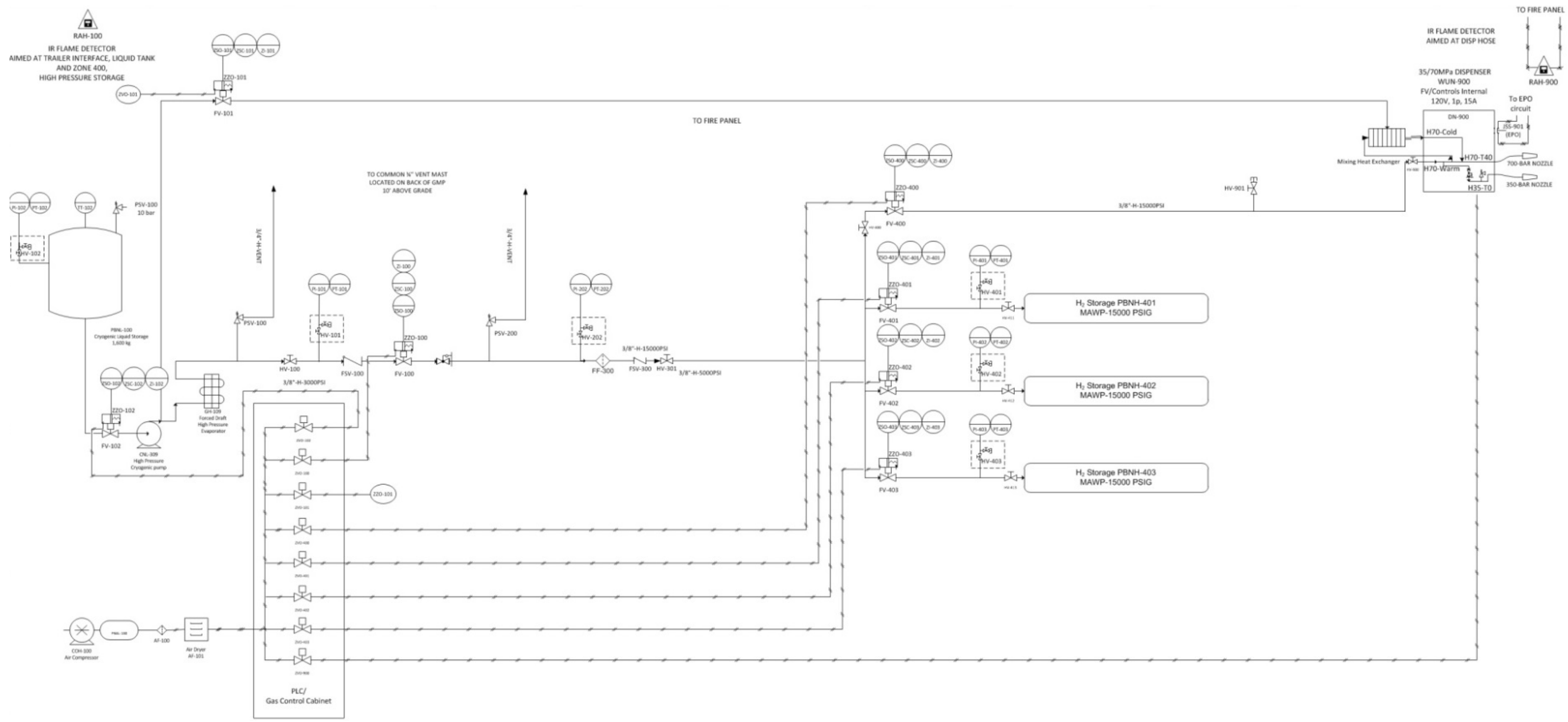


Figure 36. P&ID for the 300 kg/day future liquid station

Bill of Materials

Table 18. Bill of Materials for 300 kg/day Future Liquid Station

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Hydrogen tank 401	PBNH-401	1	$40,000	$40,000
Hydrogen tank 402	PBNH-402	1	$40,000	$40,000
Hydrogen tank 403	PBNH-403	1	$40,000	$40,000
Pressure transmitter w/ indicator	PT-101	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-102	1	$1,000	$1,000
Temperature trans. w/ indicator	TT-102	1	$300	$300
Pressure transmitter w/ indicator	PT-202	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-401	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-402	1	$1,000	$1,000
Pressure transmitter w/ indicator	PT-403	1	$1,000	$1,000
Block and bleed valve	HV-101	1	$500	$500
Block and bleed valve	HV-102	1	$500	$500
Block and bleed valve	HV-202	1	$500	$500
Block and bleed valve	HV-301	1	$500	$500
Block and bleed valve	HV-401	1	$500	$500
Block and bleed valve	HV-402	1	$500	$500
Block and bleed valve	HV-403	1	$500	$500
Position switch open	ZSO-100	1	incl w/ valve	$-
Position switch closed	ZSC-100	1	incl w/ valve	$-
Position indicator	ZI-100	1	incl w/ valve	$-
Air operator	ZZO-100	1	incl w/ valve	$-
Air operated valve	FV-100	1	$2,000	$2,000
Position switch open	ZSO-101	1	incl w/ valve	$-
Position switch closed	ZSC-101	1	incl w/ valve	$-
Position indicator	ZI-101	1	incl w/ valve	$-
Air operator	ZZO-101	1	incl w/ valve	$-
Air operated valve	FV-101	1	$2,000	$2,000
Position switch open	ZSO-400	1	incl w/ valve	$-
Position switch closed	ZSC-400	1	incl w/ valve	$-
Position indicator	ZI-400	1	incl w/ valve	$-
Air operator	ZZO-400	1	incl w/ valve	$-
Air operated valve	FV-400	1	$2,000	$2,000
Position switch open	ZSO-401	1	incl w/ valve	$-
Position switch closed	ZSC-401	1	incl w/ valve	$-
Position indicator	ZI-401	1	incl w/ valve	$-
Air operator	ZZO-401	1	incl w/ valve	$-
Air operated valve	FV-401	1	$2,000	$2,000
Position switch open	ZSO-402	1	incl w/ valve	$-
Position switch closed	ZSC-402	1	incl w/ valve	$-
Position indicator	ZI-402	1	incl w/ valve	$-
Air operator	ZZO-402	1	incl w/ valve	$-

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Air operated valve	FV-402	1	$2,000	$2,000
Position switch open	ZSO-403	1	incl w/ valve	$-
Position switch closed	ZSC-403	1	incl w/ valve	$-
Position indicator	ZI-403	1	incl w/ valve	$-
Air operated valve	FV-403	1	$2,000	$2,000
Air operator	ZZO-403	1	incl w/ valve	$-
Isolation hand valve	HV-100	1	$500	$500
Isolation hand valve	HV-301	1	$500	$500
Isolation hand valve	HV-411	1	$500	$500
Isolation hand valve	HV-412	1	$500	$500
Isolation hand valve	HV-413	1	$500	$500
Isolation hand valve	HV-400	1	$500	$500
Isolation hand valve	HV-901	1	$500	$500
Isolation hand valve	HV-900	1	$500	$500
Check valve	FSV-100	1	$400	$400
Check valve	FSV-300	1	$400	$400
Instrument air compressor	COH-100	1	$1,000	$1,000
Instrument air receiver	PBAL-100	1	-	$-
Instrument air filter	AF-100	1	$50	$50
Instrument air dryer	AF-101	1	$2,500	$2,500
Pilot solenoid valve	ZVO-100	1	$50	$50
Pilot solenoid valve	ZVO-101	1	$50	$50
Pilot solenoid valve	ZVO-400	1	$50	$50
Pilot solenoid valve	ZVO-401	1	$50	$50
Pilot solenoid valve	ZVO-402	1	$50	$50
Pilot solenoid valve	ZVO-403	1	$50	$50
Pilot solenoid valve	ZVO-900	1	$50	$50
Hydrogen cooling block	GN-901	1	$50,000	$50,000
Hydrogen dispenser	WUN-900	1	-	$-
IR flame detector	RAH-100	1	$1,500	$1,500
IR flame detector	RAH-900	1	$1,500	$1,500
Hydrogen filter	FF-300	1	$2,500	$2,500
PLC		1	$5,000	$5,000
Tubing		1	$20,000	$20,000
Fittings		1	$15,000	$15,000
Electrical upgrades		1	$50,000	$50,000
Fencing		1	$5,000	$5,000
Bollards		1	$5,000	$5,000
Cryogenic liquid tank	PBNL-100	1	$317,000	$317,000

Description	Tag Number	Quantity	Approx Cost	Ext Cost
Evaporator	GH-109	1	$28,500	$28,500
Cryogenic liquid pump	CNL-309	1	$340,000	$340,000[21]
Pressure safety valve	PSV-100	1	$3,000	$3,000
Pressure safety valve	PSV-200	1	$3,000	$3,000

[21] This cost uses HRSAM defaults. A high pressure, low volume cryogenic hydrogen pump does not exist on the market. If developed, it is expected to be more expensive in the near-term but there is not enough information to estimate such a cost at this time (see Section 6.1 for impact of this assumption on results).

11 Recommendations

11.1 Technology and Commercialization Gaps

The team identified four primary areas for potential station improvement through the course of this task: component technology, station systems, codes and standards, and business practices. Each is described in the following sections.

11.1.1 Component Technology

Costs of individual components have a large impact on the station cost. Many components for hydrogen stations are completely or partially custom and made in small quantities. In order for component costs to fall, the industry must pursue standardization to eliminate non-recurring engineering costs, drive manufacturing volume, and allow interchangeability of parts. This task has identified component-level research and development opportunities that exist in the following areas:

1. Develop standard, off-the-shelf innovative chillers for the high-pressure, high-flowrate environment with reduced cost. For instance, there has been no work in the public domain to cost-optimize the chiller/cold block for high-volume production.
2. Develop standard, off-the-shelf cryogenic hydrogen pumps and evaporators in the flow ranges required for early-market stations. Cryopumps available today typically are much larger than needed. This results in increased station capital and operating costs.
3. Develop high-pressure, high-capacity, and/or compact gaseous hydrogen delivery trailers. Such trailers could enable the delivery of more hydrogen in fewer trips and in a smaller footprint. This would impact both hydrogen cost ($/kg) and the capital cost of the station.
4. Develop safe and acceptable underground hydrogen storage tanks for both liquid and gaseous hydrogen. Underground hydrogen tanks can both reduce station footprint and allow for greater compatibility of hydrogen with existing gasoline station retrofits.

Chillers

Hydrogen chillers are necessary to achieve fill rates fast enough to make the FCEV fill rate competitive with that of gasoline vehicles. Chillers must cool the hydrogen as low as −40°C just prior to dispensing it to the vehicle. Currently, chillers represent a significant amount of the cost of a hydrogen station (see the bill of materials tables in Section 10). Directed research and development should be undertaken to optimize the cost and energy consumption and to standardize chillers for the early market.

Cryogenic Pumps and Evaporators

Liquid hydrogen stations require a cryogenic liquid hydrogen pump and evaporator in order to provide gaseous hydrogen to a compressor/cascade system similar to that used by the gaseous stations. Developing standard, off-the-shelf components of these types will help reduce the cost of liquid stations, which are particularly suited for high throughput stations. Additionally, high-pressure pumps and evaporators, as represented in the future liquid station, could eliminate the compressor and chiller by evaporating liquid right up to the required dispensing pressure. Developing a mixing heat exchanger that would combine liquid and gaseous hydrogen to achieve the −40°C requirement could eliminate the chiller. These two development efforts could result in significant cost savings. While such devices exist, they are experimental and non-standard.

High-Capacity Trailers

High-capacity tube trailers could reduce station footprint and possibly reduce station capital cost. They could also help close the gap between the practical capacity of liquid stations and that of gaseous stations. High-capacity trailers could also help reduce the cost of hydrogen by minimizing the number of deliveries for a given capacity.

Underground Storage

Underground storage, while not likely to be a significant cost savings, could enable the siting of hydrogen in more locations. The required setback distances from both gaseous and liquid storage often limit the ability to place hydrogen infrastructure at existing gasoline stations. Specifically, liquid hydrogen storage greatly increases station size because of the required setback distances. One potential solution to this is locating storage tanks underground, though this has not been done in the context of hydrogen vehicle refueling stations before. Doing so could make liquid stations more compact and potentially amenable to the urban CARB High Use Commuter profile, reducing overall hydrogen station footprint and capital cost.

11.1.2 Station Systems

Besides through improvements at the component level, cost reduction also may be achieved through system innovation. Three areas for system improvement are apparent:

1. Reduce or eliminate the need for hydrogen chillers to achieve −40°C before discharging from the dispenser hose. The chiller is an expensive piece of equipment that contributes significantly to the cost of the station. The dispenser and chiller alone contribute approximately $350,000 to the station capital cost.

2. Reduce the boil-off of liquid hydrogen when being introduced into piping and equipment that has not been used due to low utilization. This effect will only exacerbate the lost revenue due to low utilization, which the analysis shows is one of the largest factors determining the viability of a station.

3. Design novel compression and storage operations to utilize more hydrogen in the tube trailers. Within the context of the station, all of these areas may be addressed through innovative station design concepts rather than focusing on individual components. Again, an improvement in this area will help mitigate the impact of low utilization.

As a small example, during optimization the team analyzed the economic trade-offs of compressor and storage sizing and found that for the selected stations, modifying the storage size had little effect on the overall storage and compression cost contribution (see Figure 37); thus the default HRSAM value was used. For other stations, storage and compression costs could be significantly reduced by using different size storage tanks. Figure 38 shows the trade-offs when storage tank size is modified for a 50 kg/day liquid station using cascade fills and capable of three consecutive fills with one hose. The team did not pursue further research at this time because the savings did not apply to the down selected stations.

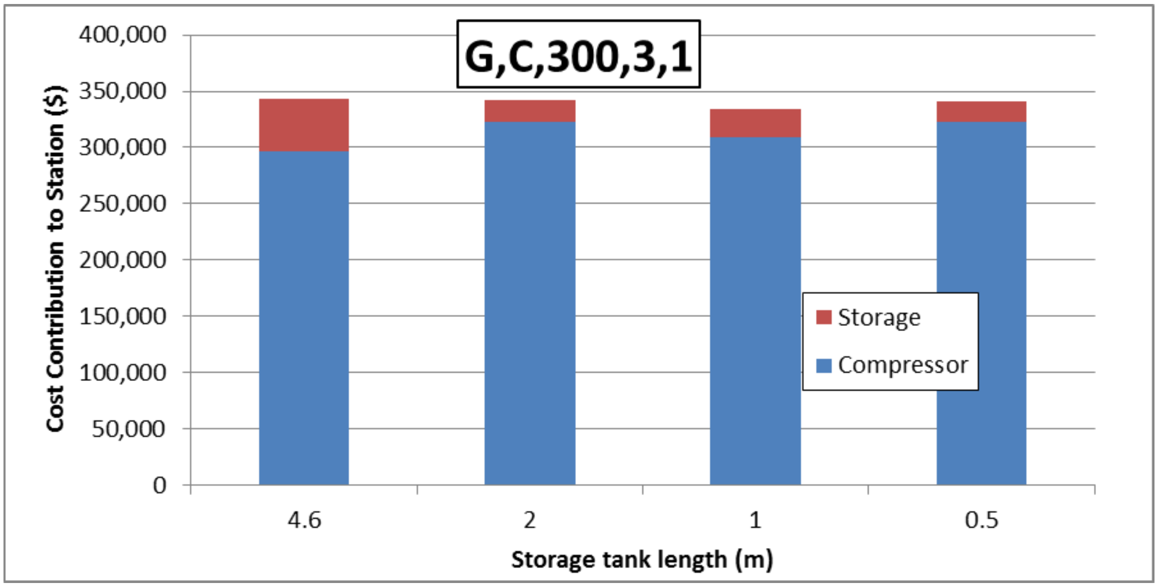


Figure 37. Compressor and storage tank costs for varying storage tank lengths for a gaseous, cascade fill, 300 kg/day station capable of three back-to-back fills with one hose

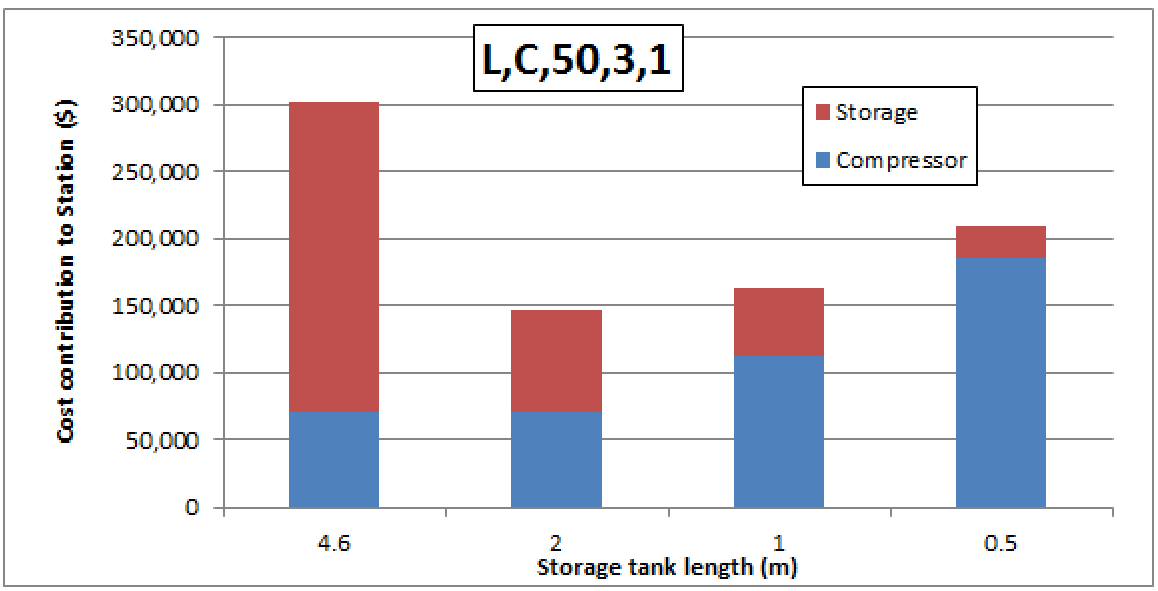


Figure 38. Storage and compressor optimization

11.1.3 Codes and Standards

The station layouts show the additional area needed for stations that have liquid delivery systems, while the economic comparison shows the promise that liquid stations hold for low-cost hydrogen, especially as the station capacity increases. One roadblock to accomplishing this is the required setback distances for liquid storage systems. For instance, the required distance from a building constructed of non-combustible materials (e.g., a station's convenience store) is 20 feet for gaseous storage versus 50 feet for liquid storage. These differences have a significant effect on the ability to place liquid hydrogen in existing gasoline stations and other densely settled urban settings.

This can be addressed through a concentrated effort to find the technical basis behind liquid system releases and hazards and translate those to more technically-robust setback distances. One group working on this is the quantitative risk assessment team at Sandia National Laboratories. This team develops models and tools to help inform codes and standards efforts in hydrogen. In addition, the Performance-Based Option of NFPA 2 may potentially be used to reduce the setbacks, but widespread use of this option requires the comfort of and acceptance by local AHJs, which may only come through clear and demonstrated examples elsewhere.

11.1.4 Business Practices

Utilization can have a significant effect on the cost of hydrogen. Decreasing the utilization from the ramp profile (described in Section 2.2—a starting value of 5% and a final value of 80% over ten years with a ten-year average of 48.5%) to a constant 20% will increase hydrogen cost by more than 35%. If utilization can be managed more effectively, assuring high, constant utilization throughout the station lifetime, the hydrogen cost can be greatly reduced. Some business practices that should be explored through modeling and commercial demonstration are:

- Fleet incorporation— a hydrogen station developer can contract with a local fleet for a specified amount of hydrogen. This will provide firm utilization of hydrogen and go a long way toward reducing the under-utilization risk identified in the analysis.
- Consumer-driven economics— with minimal investment, a station could provide an additional hose without a chiller to provide lower-priced hydrogen for consumers who are comfortable with longer fill times.
- Detailed examination of the trade-off between economies of scale versus economies of mass manufacturing—developers can investigate whether it would be more cost effective to produce many small, modular stations (economies of mass manufacturing) or few, large stations (economies of scale). This is a question raised by the work but outside its scope to address at this time.
- More integration of mobile refuelers into the infrastructure to maximize investment—mobile refuelers can be shuttled between stations depending on usage habits (e.g., located at a High Use Commuter station during the weekdays and moved to an Intermittent connector station location on weekends). This could provide an elastic supply to match changing demand and further maximize utilization.

11.2 Future Reference Station Work

Future work on the H2FIRST Reference Station Design Task will likely be an iterative process. Dialog with stakeholders will continue as the project moves forward. Internal (DOE) and external (H2USA HFSWG and U.S. DRIVE Technology Teams) stakeholders will vet the station designs presented in this report and will provide feedback to the H2FIRST team to indicate necessary modifications. After this takes place, the team will hold a webinar to present the findings from the report to the larger hydrogen community.

Organizations that work with AHJs to build stations could use the findings of this report to improve and speed up acceptance of station development.

These designs consider current technology. The team sees value in performing sensitivity and further optimization studies. As innovation results in new technology and as economies of scale become more impactful, these station designs should be revisited. The work conducted under this task offers a robust starting point for evaluating the recommendations presented in this section. Future work may focus on individual component development or large system changes. Either way, station designs will need to be updated to reflect the evolving hydrogen station.

Appendix A: Detailed Model Assumptions and Parameters

Table A-1. List of Stations Simulated

Concept No.	Design Capacity (kg/day)	Consecutive Fills	Hoses	Fill Configuration	Hydrogen Delivery Method
1	50	2	1	Cascade	Gas (tube trailer)
2	50	2	2	Cascade	Gas (tube trailer)
3	50	3	1	Cascade	Gas (tube trailer)
4	50	3	2	Cascade	Gas (tube trailer)
5	50	4	1	Cascade	Gas (tube trailer)
6	50	4	2	Cascade	Gas (tube trailer)
7	50	5	1	Cascade	Gas (tube trailer)
8	50	5	2	Cascade	Gas (tube trailer)
9	50	6	1	Cascade	Gas (tube trailer)
10	50	6	2	Cascade	Gas (tube trailer)
11	100	2	1	Cascade	Gas (tube trailer)
12	100	2	2	Cascade	Gas (tube trailer)
13	100	3	1	Cascade	Gas (tube trailer)
14	100	3	2	Cascade	Gas (tube trailer)
15	100	4	1	Cascade	Gas (tube trailer)
16	100	4	2	Cascade	Gas (tube trailer)
17	100	5	1	Cascade	Gas (tube trailer)
18	100	5	2	Cascade	Gas (tube trailer)
19	100	6	1	Cascade	Gas (tube trailer)
20	100	6	2	Cascade	Gas (tube trailer)
21	200	2	1	Cascade	Gas (tube trailer)
22	200	2	2	Cascade	Gas (tube trailer)
23	200	3	1	Cascade	Gas (tube trailer)
24	200	3	2	Cascade	Gas (tube trailer)
25	200	4	1	Cascade	Gas (tube trailer)
26	200	4	2	Cascade	Gas (tube trailer)
27	200	5	1	Cascade	Gas (tube trailer)
28	200	5	2	Cascade	Gas (tube trailer)
29	200	6	1	Cascade	Gas (tube trailer)
30	200	6	2	Cascade	Gas (tube trailer)
31	300	2	1	Cascade	Gas (tube trailer)
32	300	2	2	Cascade	Gas (tube trailer)
33	300	3	1	Cascade	Gas (tube trailer)
34	300	3	2	Cascade	Gas (tube trailer)
35	300	4	1	Cascade	Gas (tube trailer)
36	300	4	2	Cascade	Gas (tube trailer)
37	300	5	1	Cascade	Gas (tube trailer)

Concept No.	Design Capacity (kg/day)	Consecutive Fills	Hoses	Fill Configuration	Hydrogen Delivery Method
38	300	5	2	Cascade	Gas (tube trailer)
39	300	6	1	Cascade	Gas (tube trailer)
40	300	6	2	Cascade	Gas (tube trailer)
41	50	2	1	Compressor	Gas (tube trailer)
42	50	2	2	Compressor	Gas (tube trailer)
43	50	3	1	Compressor	Gas (tube trailer)
44	50	3	2	Compressor	Gas (tube trailer)
45	50	4	1	Compressor	Gas (tube trailer)
46	50	4	2	Compressor	Gas (tube trailer)
47	50	5	1	Compressor	Gas (tube trailer)
48	50	5	2	Compressor	Gas (tube trailer)
49	50	6	1	Compressor	Gas (tube trailer)
50	50	6	2	Compressor	Gas (tube trailer)
51	100	2	1	Compressor	Gas (tube trailer)
52	100	2	2	Compressor	Gas (tube trailer)
53	100	3	1	Compressor	Gas (tube trailer)
54	100	3	2	Compressor	Gas (tube trailer)
55	100	4	1	Compressor	Gas (tube trailer)
56	100	4	2	Compressor	Gas (tube trailer)
57	100	5	1	Compressor	Gas (tube trailer)
58	100	5	2	Compressor	Gas (tube trailer)
59	100	6	1	Compressor	Gas (tube trailer)
60	100	6	2	Compressor	Gas (tube trailer)
61	200	2	1	Compressor	Gas (tube trailer)
62	200	2	2	Compressor	Gas (tube trailer)
63	200	3	1	Compressor	Gas (tube trailer)
64	200	3	2	Compressor	Gas (tube trailer)
65	200	4	1	Compressor	Gas (tube trailer)
66	200	4	2	Compressor	Gas (tube trailer)
67	200	5	1	Compressor	Gas (tube trailer)
68	200	5	2	Compressor	Gas (tube trailer)
69	200	6	1	Compressor	Gas (tube trailer)
70	200	6	2	Compressor	Gas (tube trailer)
71	300	2	1	Compressor	Gas (tube trailer)
72	300	2	2	Compressor	Gas (tube trailer)
73	300	3	1	Compressor	Gas (tube trailer)
74	300	3	2	Compressor	Gas (tube trailer)
75	300	4	1	Compressor	Gas (tube trailer)
76	300	4	2	Compressor	Gas (tube trailer)
77	300	5	1	Compressor	Gas (tube trailer)
78	300	5	2	Compressor	Gas (tube trailer)

Concept No.	Design Capacity (kg/day)	Consecutive Fills	Hoses	Fill Configuration	Hydrogen Delivery Method
79	300	6	1	Compressor	Gas (tube trailer)
80	300	6	2	Compressor	Gas (tube trailer)
81	50	2	1	Cascade	Liquid trailer
82	50	2	2	Cascade	Liquid trailer
83	50	3	1	Cascade	Liquid trailer
84	50	3	2	Cascade	Liquid trailer
85	50	4	1	Cascade	Liquid trailer
86	50	4	2	Cascade	Liquid trailer
87	50	5	1	Cascade	Liquid trailer
88	50	5	2	Cascade	Liquid trailer
89	50	6	1	Cascade	Liquid trailer
90	50	6	2	Cascade	Liquid trailer
91	100	2	1	Cascade	Liquid trailer
92	100	2	2	Cascade	Liquid trailer
93	100	3	1	Cascade	Liquid trailer
94	100	3	2	Cascade	Liquid trailer
95	100	4	1	Cascade	Liquid trailer
96	100	4	2	Cascade	Liquid trailer
97	100	5	1	Cascade	Liquid trailer
98	100	5	2	Cascade	Liquid trailer
99	100	6	1	Cascade	Liquid trailer
100	100	6	2	Cascade	Liquid trailer
101	200	2	1	Cascade	Liquid trailer
102	200	2	2	Cascade	Liquid trailer
103	200	3	1	Cascade	Liquid trailer
104	200	3	2	Cascade	Liquid trailer
105	200	4	1	Cascade	Liquid trailer
106	200	4	2	Cascade	Liquid trailer
107	200	5	1	Cascade	Liquid trailer
108	200	5	2	Cascade	Liquid trailer
109	200	6	1	Cascade	Liquid trailer
110	200	6	2	Cascade	Liquid trailer
111	300	2	1	Cascade	Liquid trailer
112	300	2	2	Cascade	Liquid trailer
113	300	3	1	Cascade	Liquid trailer
114	300	3	2	Cascade	Liquid trailer
115	300	4	1	Cascade	Liquid trailer
116	300	4	2	Cascade	Liquid trailer
117	300	5	1	Cascade	Liquid trailer
118	300	5	2	Cascade	Liquid trailer
119	300	6	1	Cascade	Liquid trailer

Concept No.	Design Capacity (kg/day)	Consecutive Fills	Hoses	Fill Configuration	Hydrogen Delivery Method
120	300	6	2	Cascade	Liquid trailer
121	50	2	1	Compressor	Liquid trailer
122	50	2	2	Compressor	Liquid trailer
123	50	3	1	Compressor	Liquid trailer
124	50	3	2	Compressor	Liquid trailer
125	50	4	1	Compressor	Liquid trailer
126	50	4	2	Compressor	Liquid trailer
127	50	5	1	Compressor	Liquid trailer
128	50	5	2	Compressor	Liquid trailer
129	50	6	1	Compressor	Liquid trailer
130	50	6	2	Compressor	Liquid trailer
131	100	2	1	Compressor	Liquid trailer
132	100	2	2	Compressor	Liquid trailer
133	100	3	1	Compressor	Liquid trailer
134	100	3	2	Compressor	Liquid trailer
135	100	4	1	Compressor	Liquid trailer
136	100	4	2	Compressor	Liquid trailer
137	100	5	1	Compressor	Liquid trailer
138	100	5	2	Compressor	Liquid trailer
139	100	6	1	Compressor	Liquid trailer
140	100	6	2	Compressor	Liquid trailer
141	200	2	1	Compressor	Liquid trailer
142	200	2	2	Compressor	Liquid trailer
143	200	3	1	Compressor	Liquid trailer
144	200	3	2	Compressor	Liquid trailer
145	200	4	1	Compressor	Liquid trailer
146	200	4	2	Compressor	Liquid trailer
147	200	5	1	Compressor	Liquid trailer
148	200	5	2	Compressor	Liquid trailer
149	200	6	1	Compressor	Liquid trailer
150	200	6	2	Compressor	Liquid trailer
151	300	2	1	Compressor	Liquid trailer
152	300	2	2	Compressor	Liquid trailer
153	300	3	1	Compressor	Liquid trailer
154	300	3	2	Compressor	Liquid trailer
155	300	4	1	Compressor	Liquid trailer
156	300	4	2	Compressor	Liquid trailer
157	300	5	1	Compressor	Liquid trailer
158	300	5	2	Compressor	Liquid trailer
159	300	6	1	Compressor	Liquid trailer
160	300	6	2	Compressor	Liquid trailer

Table A-2. Economic Ranking Data for Top 50 Stations

	Capital Cost Ranking				Fuel Cost Ranking				Combined Cost Ranking			
Rank	Station ID	M_{cap}	M_{fuel}	ROI	Station ID	M_{cap}	M_{fuel}	ROI	Station ID	M_{cap}	M_{fuel}	ROI
1	G, C, 50, 2, 1	0%	316%	7.52	G, C, 300, 2, 1	33%	0%	7.42	G, C, 300, 2, 1	33%	0%	7.42
2	G, C, 50, 3, 1	0%	316%	7.52	G, C, 300, 3, 1	33%	0%	7.42	G, C, 300, 3, 1	33%	0%	7.42
3	G, C, 50, 4, 1	0%	316%	7.52	G, C, 300, 4, 1	35%	2%	7.41	L, C, 300, 2, 1	30%	7%	7.59
4	G, C, 50, 5, 1	0%	316%	7.52	G, C, 300, 5, 1	35%	2%	7.41	L, C, 300, 3, 1	30%	7%	7.59
5	G, C, 100, 2, 1	5%	128%	7.47	G, C, 300, 6, 1	37%	3%	7.40	L, C, 300, 4, 1	30%	7%	7.59
6	L, C, 50, 2, 1	7%	424%	7.65	L, C, 300, 2, 1	30%	7%	7.59	G, C, 300, 4, 1	35%	2%	7.41
7	L, C, 50, 3, 1	7%	424%	7.65	L, C, 300, 3, 1	30%	7%	7.59	G, C, 300, 5, 1	35%	2%	7.41
8	G, C, 50, 6, 1	8%	343%	7.53	L, C, 300, 4, 1	30%	7%	7.59	L, C, 300, 5, 1	31%	8%	7.58
9	G, C, 100, 3, 1	9%	136%	7.45	L, C, 300, 5, 1	31%	8%	7.58	G, C, 300, 6, 1	37%	3%	7.40
10	L, C, 100, 2, 1	10%	172%	7.65	L, C, 300, 6, 1	33%	9%	7.58	L, C, 300, 6, 1	33%	9%	7.58
11	L, C, 50, 4, 1	10%	430%	7.68	L, C, 300, 2, 2	46%	19%	7.58	G, C, 200, 2, 1	21%	34%	7.43
12	L, C, 50, 5, 1	10%	430%	7.68	L, C, 300, 3, 2	50%	22%	7.56	G, C, 200, 3, 1	21%	34%	7.43
13	L, C, 100, 3, 1	13%	177%	7.63	G, B ,300, 2, 1	66%	24%	7.33	G, C, 200, 4, 1	24%	37%	7.42
14	G, C, 100, 4, 1	13%	141%	7.48	G, B ,300, 3, 1	66%	24%	7.33	L, C, 300, 2, 2	46%	19%	7.58
15	G, C, 100, 5, 1	13%	141%	7.48	G, B ,300, 4, 1	66%	24%	7.33	L, C, 200, 2, 1	20%	48%	7.62
16	G, C, 100, 6, 1	15%	141%	7.52	L, C, 300, 4, 2	59%	26%	7.57	G, C, 200, 5, 1	29%	41%	7.45
17	L, C, 100, 4, 1	18%	185%	7.65	G, B ,300, 5, 1	70%	26%	7.33	G, C, 200, 6, 1	29%	41%	7.45
18	L, C, 100, 5, 1	18%	185%	7.65	G, B ,300, 6, 1	70%	26%	7.33	L, C, 300, 3, 2	50%	22%	7.56
19	L, C, 50, 6, 1	19%	456%	7.68	L, C, 300, 5, 2	63%	28%	7.58	L, C, 200, 3, 1	22%	51%	7.61
20	L, C, 200, 2, 1	20%	48%	7.62	G, C, 200, 2, 1	21%	34%	7.43	L, C, 200, 4, 1	24%	53%	7.60
21	L, C, 50, 2, 2	20%	484%	7.64	G, C, 200, 3, 1	21%	34%	7.43	L, C, 200, 5, 1	28%	55%	7.62
22	G, C, 200, 2, 1	21%	34%	7.43	G, C, 300, 2, 2	88%	37%	7.38	L, C, 300, 4, 2	59%	26%	7.57
23	G, C, 200, 3, 1	21%	34%	7.43	G, C, 200, 4, 1	24%	37%	7.42	L, C, 200, 6, 1	30%	57%	7.61
24	L, C, 200, 3, 1	22%	51%	7.61	G, C, 200, 5, 1	29%	41%	7.45	G, B ,300, 2, 1	66%	24%	7.33
25	L, C, 100, 6, 1	23%	190%	7.67	G, C, 200, 6, 1	29%	41%	7.45	G, B ,300, 3, 1	66%	24%	7.33
26	G, C, 200, 4, 1	24%	37%	7.42	G, C, 300, 3, 2	96%	41%	7.39	G, B ,300, 4, 1	66%	24%	7.33

	Capital Cost Ranking				Fuel Cost Ranking				Combined Cost Ranking			
Rank	Station ID	M_{cap}	M_{fuel}	ROI	Station ID	M_{cap}	M_{fuel}	ROI	Station ID	M_{cap}	M_{fuel}	ROI
27	L, C, 200, 4, 1	24%	53%	7.60	G, C, 300, 4, 2	99%	42%	7.41	L, C, 300, 5, 2	63%	28%	7.58
28	L, C, 200, 5, 1	28%	55%	7.62	G, C, 300, 5, 2	107%	46%	7.42	G, B ,300, 5, 1	70%	26%	7.33
29	G, C, 200, 5, 1	29%	41%	7.45	L, C, 200, 2, 1	20%	48%	7.62	G, B ,300, 6, 1	70%	26%	7.33
30	G, C, 200, 6, 1	29%	41%	7.45	G, C, 300, 6, 2	112%	50%	7.41	L, C, 200, 2, 2	37%	68%	7.60
31	L, C, 50, 3, 2	29%	510%	7.64	L, C, 200, 3, 1	22%	51%	7.61	L, C, 200, 3, 2	42%	72%	7.58
32	L, C, 300, 2, 1	30%	7%	7.59	L, C, 200, 4, 1	24%	53%	7.60	G, C, 300, 2, 2	88%	37%	7.38
33	L, C, 300, 3, 1	30%	7%	7.59	L, C, 200, 5, 1	28%	55%	7.62	G, B ,200, 2, 1	56%	73%	7.32
34	L, C, 300, 4, 1	30%	7%	7.59	L, C, 200, 6, 1	30%	57%	7.61	G, B ,200, 3, 1	56%	73%	7.32
35	L, C, 200, 6, 1	30%	57%	7.61	L, C, 200, 2, 2	37%	68%	7.60	L, C, 200, 4, 2	50%	79%	7.58
36	L, C, 300, 5, 1	31%	8%	7.58	L, C, 200, 3, 2	42%	72%	7.58	G, C, 100, 2, 1	5%	128%	7.47
37	G, C, 300, 2, 1	33%	0%	7.42	G, B ,200, 2, 1	56%	73%	7.32	G, B ,200, 4, 1	59%	75%	7.34
38	G, C, 300, 3, 1	33%	0%	7.42	G, B ,200, 3, 1	56%	73%	7.32	L, C, 200, 5, 2	54%	81%	7.60
39	L, C, 100, 2, 2	33%	217%	7.64	G, B ,200, 4, 1	59%	75%	7.34	G, B ,200, 5, 1	60%	76%	7.33
40	L, C, 100, 3, 2	33%	217%	7.64	G, B ,200, 5, 1	60%	76%	7.33	G, C, 300, 3, 2	96%	41%	7.39
41	L, C, 300, 6, 1	33%	9%	7.58	G, B ,200, 6, 1	63%	78%	7.35	G, C, 300, 4, 2	99%	42%	7.41
42	G, B ,50, 2, 1	34%	471%	7.33	L, C, 200, 4, 2	50%	79%	7.58	G, B ,200, 6, 1	63%	78%	7.35
43	G, C, 300, 4, 1	35%	2%	7.41	L, C, 200, 5, 2	54%	81%	7.60	G, C, 100, 3, 1	9%	136%	7.45
44	G, C, 300, 5, 1	35%	2%	7.41	G, C, 200, 2, 2	77%	88%	7.42	G, C, 300, 5, 2	107%	46%	7.42
45	L, C, 50, 4, 2	37%	537%	7.64	G, C, 200, 3, 2	84%	95%	7.40	G, C, 100, 4, 1	13%	141%	7.48
46	G, C, 300, 6, 1	37%	3%	7.40	G, C, 200, 4, 2	85%	95%	7.43	G, C, 100, 5, 1	13%	141%	7.48
47	L, C, 200, 2, 2	37%	68%	7.60	G, C, 200, 5, 2	94%	101%	7.43	G, C, 100, 6, 1	15%	141%	7.52
48	G, B ,50, 3, 1	38%	484%	7.34	G, C, 200, 6, 2	100%	105%	7.47	G, C, 300, 6, 2	112%	50%	7.41
49	G, B ,50, 4, 1	38%	484%	7.34	G, C, 100, 2, 1	5%	128%	7.47	G, C, 200, 2, 2	77%	88%	7.42
50	G, B ,50, 5, 1	38%	484%	7.34	G, C, 100, 3, 1	9%	136%	7.45	G, C, 200, 3, 2	84%	95%	7.40
STD DEV		**12%**	**180%**	**0.11**		**27%**	**34%**	**0.10**		**26%**	**39%**	**0.10**
Avg		**22%**	**196%**	**7.54**		**51%**	**47%**	**7.47**		**47%**	**49%**	**7.47**

Table A-3. Summary of HRSAM Changes for the Economic Screening Analysis

<table>
<tr><th rowspan="2">Parameter</th><th rowspan="2">Old (Default) Value</th><th rowspan="2">New Value</th><th colspan="3">HRSAM – 09082014 Changes</th></tr>
<tr><th>Sheet</th><th>Cell</th><th>New Value</th></tr>
<tr><td>Real after-tax discount rate</td><td>10.0%</td><td>15.0%</td><td>Scenario</td><td>C17</td><td>15.0%</td></tr>
<tr><td>Cascade storage size</td><td>9.91 ft^3 (0.4 m OD x 4.572 m Long with 0.06 m wall thickness)</td><td>In addition to default, 1.98 ft^3 and 49.6 ft^3 (1/5x and 5x)</td><td>Refueling Station – Gaseous H2</td><td>B101</td><td>[no change unless doing sensitivity analysis]
=(1/5)*4.572 [for small volume case]
=5*4.572 [for large volume case]</td></tr>
<tr><td rowspan="2">Chiller cost</td><td rowspan="2">Function of refrigeration capacity (reference: 2 kg/min at -40 C from 40 C ambient = $72,107)</td><td rowspan="2">$113,500 per kg/min of capacity</td><td>Refueling Station – Gaseous H2</td><td>B227</td><td>no</td></tr>
<tr><td>Refueling Station – Gaseous H2</td><td>E236</td><td>=B71*113500
[B71 is chiller capacity in kg/min]</td></tr>
<tr><td rowspan="2">Low-to-high pressure compressor cost (for cascade fill systems</td><td rowspan="2">See Figure 2, “HRSAM, Cascade” data series</td><td rowspan="2">2.0-times the default</td><td>Refueling Station – Gaseous H2</td><td>B227</td><td>no</td></tr>
<tr><td>Refueling Station – Gaseous H2</td><td>E242</td><td>=B241*IF(B26="Cascade Dispensing",2.0,1.9)*(IF(B242<=300,(9896.3*B242^0.6641),(6893.2*B242^0.7464)))*Cost_Indexes!M8/Cost_Indexes!M26
[same as original equation but with the *2 factor at the front if it’s cascade (low-to-high) compressor]</td></tr>
<tr><td rowspan="2">Low-to-medium pressure compressor cost (for booster fill systems)</td><td rowspan="2">See Figure 2, “HRSAM, Booster” data series</td><td rowspan="2">1.9-times the default</td><td>Refueling Station – Gaseous H2</td><td>B227</td><td>no</td></tr>
<tr><td>Refueling Station – Gaseous H2</td><td>E242</td><td>=B241*IF(B26="Cascade Dispensing",2.0,1.9)*(IF(B242<=300,(9896.3*B242^0.6641),(6893.2*B242^0.7464)))*Cost_Indexes!M8/Cost_Indexes!M26
[same as original equation but with the *1.9 factor at the front if it’s booster (low-to-medium) compressor]</td></tr>
</table>

Parameter	Old (Default) Value	New Value	HRSAM – 09082014 Changes		
			Sheet	Cell	New Value
Medium-to-high pressure compressor (for booster fill systems)	$150,000 for 1 kg/min capacity	$260,000 for 1 kg/min capacity	Refueling Station – Gaseous H2	B227	no
			Refueling Station – Gaseous H2	E239	=B238*260000 [B238 is the number of 1 kg/min booster compressors, which is set to one per hose]
Dispenser	$46,378 single hose	$57,500 per hose	Refueling Station – Gaseous H2	B228	no
			Refueling Station – Gaseous H2	E244	=B244*57500 [B244 is number of dispensers, one hose per dispenser as specified in B57]
			Refueling Station – Liquid H2	B192	no
			Refueling Station – Liquid H2		=B202*57500 [B202 is number of dispensers, one hose per dispenser as specified in B55]
High-pressure storage (for cascade fill systems)	$2,500/kg	$1,190/kg	Refueling Station – Gaseous H2	B230	no
			Refueling Station – Gaseous H2	E252	IF(OR(B26="Booster Compressor Dispensing",B25=350),B252*822,B252*1190) [B252 is the capacity of the storage tank] [The "822" number is also needed to take care of the medium pressure storage case (see below)]
			Refueling Station – Liquid H2	B194	no
			Refueling Station – Liquid H2	E208	=IF(B25=350,B208*822,B208*1190) [B208 is the capacity of the storage tank] [The "822" number is also needed to take care of the medium pressure storage case (see below)]

Parameter	Old (Default) Value	New Value	HRSAM – 09082014 Changes		
			Sheet	Cell	New Value
Medium-pressure storage (for booster fill or 350-bar dispensing systems)	$1,500/kg	$822/kg	Refueling Station – Gaseous H2	B230	no
			Refueling Station – Gaseous H2	E252	=IF(OR(B26="Booster Compressor Dispensing",B25=350),B252*822,B252*1190) [B252 is the capacity of the storage tank] [The "1190" number is also needed to take care of the high pressure storage case (see above)]
			Refueling Station – Liquid H2	B194	no
			Refueling Station – Liquid H2	E208	=IF(B25=350,B208*822,B208*1190) [B208 is the capacity of the storage tank] [The "1190" number is also needed to take care of the high pressure storage case (see above)]
Accumulator (small high pressure storage for booster fill systems)	$2,500/kg	$985/kg	Refueling Station – Gaseous H2	B230	no
			Refueling Station – Gaseous H2	E250	=B250*985 [B250 is the capacity of the accumulator]
Low pressure storage (for 20-bar supply systems)	$1,200/kg	$645/kg	Refueling Station – Gaseous H2	B231	no
			Refueling Station – Gaseous H2	E255	=IF(B24="20 bar supply",B254*B255*645,0) [B254 is number of low pressure storage tanks, B255 is capacity of each tank]
Installation factor – equipment	1.2 for Compressor, Dispenser, Cryo storage, Evaporator, and Cryo pump; 1.3 for Refrigeration, and Gas Storage systems	1.3 for all	Refueling Station – Gaseous H2	F239, F242, F244	1.3
			Refueling Station – Liquid H2	F200, F202, F210, F212	

Parameter	Old (Default) Value	New Value	HRSAM – 09082014 Changes		
			Sheet	Cell	New Value
Utilization	80%	Case 1: Ramp Case 2: 20%	Scenario	H16- H45	Case 1: 16% 27% 38% 49% 60% 65% 70% 75% 80% 80% … 80% Case 2: 20% … 20%

Parameter	Old (Default) Value	New Value	HRSAM – 09082014 Changes		
			Sheet	Cell	New Value
Hourly use profile	Chevron profile	Chevron profile with one hour of specified number of consecutive fills	Refueling Station – Gaseous H2	D795-D818	Chevron profile: 1.1% 0.7% 0.6% 0.5% 0.7% 1.2% 2.1% 3.1% 4.2% 5.5% 6.1% 6.2% 6.5% 7.0% 7.3% 7.7% 7.8% 7.4% 6.7% 5.6% 4.3% 3.3% 2.6% 1.8%
			Refueling Station – Gaseous H2	E795-E810, E812-E818	=D795*(1-E811)/(1-D811) [D795 is the Chevron profile value for the same hour (the cell directly to the left of the formula). E811 is the specified capacity at the peak hour (see formula below). D811 is the Chevron profile capacity at the peak hour.]

Parameter	Old (Default) Value	New Value	HRSAM – 09082014 Changes		
			Sheet	**Cell**	**New Value**
			Refueling Station – Gaseous H2	E811	=MIN(B59*B58*B142/B32,100%) [B59 is # of consecutive fills, B58 is kg/fill, B32 is station design capacity, B142 is # of hoses]
			Refueling Station – Liquid H2	E679-E694, E696-E702	=D679*(1-E695)/(1-D695) [D679 is the Chevron profile value for the same hour (the cell directly to the left of the formula). E695 is the specified capacity at the peak hour (see formula below). D695 is the Chevron profile capacity at the peak hour.]
			Refueling Station – Liquid H2	E695	=MIN(B57*B56*B110/B30,100%) [B57 is # of consecutive fills, B56 is kg/fill, B30 is station design capacity, B110 is # of hoses]

Other changes:
Refueling Station – Gaseous H2, C248:
=IF(**B229**="yes",(IF(B153="","",IF(B248=480, (-0.004318*(B153*B64/0.7456999)^2 + 46.179999*(B153*B64/0.7456999) + 20724)*Cost_Indexes!N8,(1.0658*(B153*B64/0.7456999) + 54393)*Cost_Indexes!N8))),"N/A")

Refueling Station – Gaseous H2, B59:
=IF(Scenario!C20*(B53+B56)<=60,Scenario!C20,ROUNDDOWN(60/(B53+B56),**0**))

Refueling Station – Gaseous H2, B80:
=(B53+B56)***E811***B32/B58/B142/60

Refueling Station – Liquid H2, B64:
=(B53+B54)***E695***B30/B56/B110/6

Appendix B: Station Separation Distances

Table B-1. Separation Distances for Liquid Storage Systems (in feet)
From NFPA 2 (2011), Table 8.3.2.4.5.1 except as noted

	Exposure	Insulation or barrier wall effect	3,500 gal to 15,000 gal: No insulation or wall	3,500 gal to 15,000 gal: With insulation or wall
1	Building or structure	Reduce to 1/3 but not less than 5 ft.		
	Sprinklered building constructed of non-combustible materials	Reduce to 1/3 but not less than 5 ft.	5	5
	Unsprinklered 3+ hour fire wall	Reduce to 1/3 but not less than 5 ft.	5	5
	Unsprinklered building constructed of non-combustible materials without 3 hour fire wall	Reduce to 1/3 but not less than 5 ft.	50	16.7
	Sprinklered building of combustible material	Reduce to 1/3 but not less than 5 ft.	50	16.7
	Unsprinklered building of combustible material	Reduce to 1/3 but not less than 5 ft.	75	25
2	Wall openings			
	Operable		75	75
	Inoperable		50	50
3	Air compressor intakes, HVAC inlets		75	75
4	Combustible liquids and fill openings if below ground	Reduce to 1/3 but not less than 5 ft.	75	25.0
5	Between LH2 containers		5	5
6	Non-H2 flammable gas	Reduce to 1/3 but not less than 5 ft.	75	25.0
7	Liquid Oxygen	Reduce to 1/3 but not less than 5 ft.	75	25.0
8	Combustible solids	Reduce to 1/3 but not less than 5 ft.	75	25.0
9	Open flames and welding		50	50
10	Places of public assembly		75	75
11	Public ways, railroads, property lines	Reduce to 1/3 but not less than 5 ft.	50	16.7
12	Inlet to underground sewer		5	5
13	Overhead power lines			
	Wires for electric trolley, train, or bus (horizontal distance)		50	50
	Other electric wires (horizontal distance)		25	25
	Overhead piping of other hazardous materials		15	15
x	Distance from parked cars to fill connection [Table 8.3.2.4.5.3]		25	25
x	Unclassified electrical equipment [Table 8.3.1.2.6]		25	25

Table B-2. Separation Distances for Low-Pressure Storage Systems (up to 3,000 psi) such as the Anticipated Bulk Hydrogen Delivery Trailer

From NFPA 2 (2011), Table 7.3.2.3.1.2(a) with barrier wall reductions from Section 7.3.2.3.1.1(B) and (C)

	Exposure	Barrier wall effect	250 psi < P <3,000 psi, 0.747 in. inner diameter	
			No barrier wall	With barrier wall
1	Lot lines	Reduce by half	45	22.5
2	Exposed persons other than those involved in servicing of the system	Reduce by half	25	12.5
3	Buildings and structures, combustible construction, noncombustible non-fire-rated construction	No additional setback beyond wall		
	Combustible construction	No additional setback beyond wall	20	Stops at wall
	Noncombustible non-fire-rated construction	No additional setback beyond wall	20	Stops at wall
	Fire-rated construction with a fire resistance rating of not less than 2 hours	Space required for maintenance	5	Stops at wall
4	Openings in buildings of fire-rated or non-fire-rated construction (doors, windows, and penetrations)	Reduce by half		
	Openable, fire-rated or non-fire-rated	Reduce by half	45	22.5
	Unopenable, fire-rated or non-fire-rated	Reduce by half	20	10
5	Air intakes (HVAC, compressors, other)	No effect	15	15
6	Fire barrier walls or structures used to shield the bulk system from exposures	Space required for maintenance	5	Stops at wall
7	Unclassified electrical equipment	No additional setback beyond wall	15	Stops at wall
8	Utilities (overhead) including electric power, building services, or hazardous materials piping	No effect	20	20
9	Ignition sources such as open flames and welding	No additional setback beyond wall	45	Stops at wall
10	Parked cars	Reduce by half	25	12.5
11	Flammable gas storage systems including other hydrogen systems above ground	No additional setback beyond wall		Stops at wall
	Nonbulk	No additional setback beyond wall	20	Stops at wall
	Bulk	No additional setback beyond wall	15	Stops at wall
12	Aboveground vents or exposed piping and components of flammable gas storage systems including other hydrogen systems below ground, gaseous or cryogenic	No additional setback beyond wall	20	Stops at wall
13	Hazardous materials (other than flammable gases) storage below ground, physical hazard materials or health hazard materials	No additional setback beyond wall	20	Stops at wall
14	Hazardous materials storage (other than flammable gases) above ground, physical hazard materials or health hazard materials	No additional setback beyond wall	20	Stops at wall

15	Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper and combustible waste and vegetation other than that found in maintained landscaped	No additional setback beyond wall	20	Stops at wall
16	Heavy timber, coal, or other slow-burning combustible solids	No additional setback beyond wall	20	Stops at wall

Table B-3. Separation Distances for High-Pressure Storage Systems (7,500 to 15,000 psi) such as the Cascade Hydrogen Storage System

From NFPA 2 (2011), Table 7.3.2.3.1.2(a) with barrier wall reductions from Section 7.3.2.3.1.1(B) and (C)

	Exposure	Barrier wall effect	7,500 psi < P <15,000 psi, 0.282 in. inner diameter	
			No barrier wall	With barrier wall
1	Lot lines	Reduce by half	35	17.5
2	Exposed persons other than those involved in servicing of the system	Reduce by half	15	7.5
3	Buildings and structures, combustible construction, noncombustible non-fire-rated construction	No additional setback beyond wall		
	Combustible construction	No additional setback beyond wall	15	Stops at wall
	Noncombustible non-fire-rated construction	No additional setback beyond wall	15	Stops at wall
	Fire-rated construction with a fire resistance rating of not less than 2 hours	Space required for maintenance	5	Stops at wall
4	Openings in buildings of fire-rated or non-fire-rated construction (doors, windows, and penetrations)	Reduce by half		
	Openable, fire-rated or non-fire-rated	Reduce by half	35	17.5
	Unopenable, fire-rated or non-fire-rated	Reduce by half	15	7.5
5	Air intakes (HVAC, compressors, other)	No effect	35	35
6	Fire barrier walls or structures used to shield the bulk system from exposures	Space required for maintenance	5	Stops at wall
7	Unclassified electrical equipment	No additional setback beyond wall	15	Stops at wall
8	Utilities (overhead) including electric power, building services, or hazardous materials piping	No effect	15	15
9	Ignition sources such as open flames and welding	No additional setback beyond wall	35	Stops at wall
10	Parked cars	Reduce by half	15	7.5
11	Flammable gas storage systems including other hydrogen systems above ground	No additional setback beyond wall		Stops at wall
	Nonbulk	No additional setback beyond wall	15	Stops at wall
	Bulk	No additional setback beyond wall	15	Stops at wall
12	Aboveground vents or exposed piping and components of flammable gas storage systems including other hydrogen systems below ground, gaseous or cryogenic	No additional setback beyond wall	15	Stops at wall
13	Hazardous materials (other than flammable gases) storage below ground, physical hazard materials or health hazard materials	No additional setback beyond wall	15	Stops at wall

14	Hazardous materials storage (other than flammable gases) above ground, physical hazard materials or health hazard materials	No additional setback beyond wall	15	Stops at wall
15	Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper and combustible waste and vegetation other than that found in maintained landscaped	No additional setback beyond wall	15	Stops at wall
16	Heavy timber, coal, or other slow-burning combustible solids	No additional setback beyond wall	15	Stops at wall

Table B-4. Separation Distances for High-Pressure Tubing, Piping, and Equipment Based on High Pressure (7,500 to 15,000 psi) and 0.203 in. Tubing Inner Diameter

(Based on the 3/8-inch line size and 0.086-in. wall given in the P&IDs.) This is used for the compressor, chiller, and heat exchanger/cooling block as well as connecting tubing. From NFPA 2 (2011), Table 7.3.2.3.1.2(a), with distances calculated from Table 7.3.2.3.1.2(c) and barrier wall reductions from Section 7.3.2.3.1.1(B) and (C).

			7,500 psi < P <15,000 psi, 0.203 in. inner diameter (formula)	
	Exposure	Barrier wall effect	No barrier wall	With barrier wall
1	Lot lines	Reduce by half	24.5	12.3
2	Exposed persons other than those involved in servicing of the system	Reduce by half	11.2	5.6
3	Buildings and structures, combustible construction, noncombustible non-fire-rated construction	No additional setback beyond wall		
	Combustible construction	No additional setback beyond wall	10.2	Stops at wall
	Noncombustible non-fire-rated construction	No additional setback beyond wall	10.2	Stops at wall
	Fire-rated construction with a fire resistance rating of not less than 2 hours	Space required for maintenance	5	Stops at wall
4	Openings in buildings of fire-rated or non-fire-rated construction (doors, windows, and penetrations)	Reduce by half		
	Openable, fire-rated or non-fire-rated	Reduce by half	24.5	12.3
	Unopenable, fire-rated or non-fire-rated	Reduce by half	11.2	5.6
5	Air intakes (HVAC, compressors, other)	No effect	24.5	24.5
6	Fire barrier walls or structures used to shield the bulk system from exposures	Space required for maintenance	Unspecified	Stops at wall
7	Unclassified electrical equipment	No additional setback beyond wall	15	Stops at wall
8	Utilities (overhead) including electric power, building services, or hazardous materials piping	No effect	10.2	10.2
9	Ignition sources such as open flames and welding	No additional setback beyond wall	24.5	Stops at wall
10	Parked cars	Reduce by half	11.2	5.6
11	Flammable gas storage systems including other hydrogen systems above ground	No additional setback beyond wall		Stops at wall
	Nonbulk	No additional setback beyond wall	Unspecified	Stops at wall
	Bulk	No additional setback beyond wall	Unspecified	Stops at wall
12	Aboveground vents or exposed piping and components of flammable gas storage systems including other hydrogen systems below ground, gaseous or cryogenic	No additional setback beyond wall	11.2	Stops at wall
13	Hazardous materials (other than flammable gases) storage below ground, physical	No additional setback beyond wall	11.2	Stops at wall

	hazard materials or health hazard materials			
14	Hazardous materials storage (other than flammable gases) above ground, physical hazard materials or health hazard materials	No additional setback beyond wall	10.2	Stops at wall
15	Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper and combustible waste and vegetation other than that found in maintained landscaped	No additional setback beyond wall	10.2	Stops at wall
16	Heavy timber, coal, or other slow-burning combustible solids	No additional setback beyond wall	11.2	Stops at wall

Appendix C: 3D Station Model

As a follow-up to the work presented by Sandia National Laboratories in 2014 in the report *Safety, Codes and Standards for Hydrogen Installations: Hydrogen Fueling System Footprint Metric Development* by Harris et. al., the team laid out the components of the 100 kg/day gaseous station on the Pasadena #1 station (Figure C-1).

This was done to elucidate some of the challenges that remain with each specific site selection and layout, even with a standard set of components and reference design. Some of the issues encountered included tube trailer ingress/egress, maintenance access, and the minimum distance to exposures (setbacks) from NFPA 2 (see Table 7.3.2.3.1.2(a) in NFPA 2). In short, while it is possible to fit a station at certain brownfield sites, it will always entail a host of site-specific challenges, a non-optimized layout, and the sacrifice of some features of the site.

The minimum distance to exposures for the bulk storage remains the single greatest challenge to siting a station in a brownfield. With tube trailer delivery of ~3,600 psi (250 bar), the lot line setback is 45 feet. On a typical gas station lot that is only 200 feet long on a side, this can present a significant challenge. Even when employing the mitigation of a 2-hour rated firewall (see NFPA 2 [2011] § 7.3.2.3.1.1), which allows distances to be halved for certain exposures (such as lot lines), placement of hydrogen equipment in the Pasadena #1 site (Figure C-2) results in the consumption of 8–10 parking spaces and a layout that may be less than ideal for maintaining the compressor (the most maintenance-intensive component in a hydrogen station).

The team included space for two 40-foot trailers, as a 20-foot trailer will likely provide insufficient on-site storage for a 100 kg/day station. The space for the second trailer is necessary to allow for easy drop-and-swap capability for the tractor driver.

The team now has the components and solid models available to further explore site-specific issues with brownfield sites.

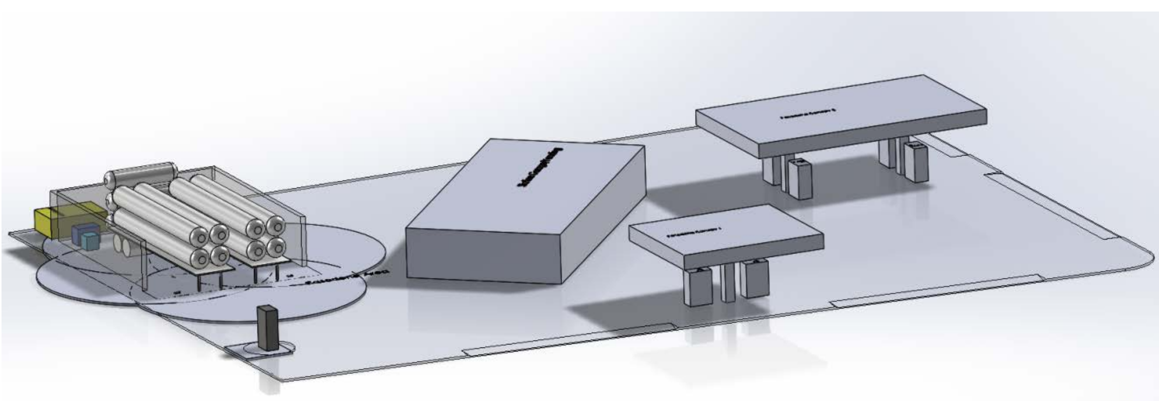


Figure C-1. Pasadena #1 with a 100 kg/day gaseous hydrogen station

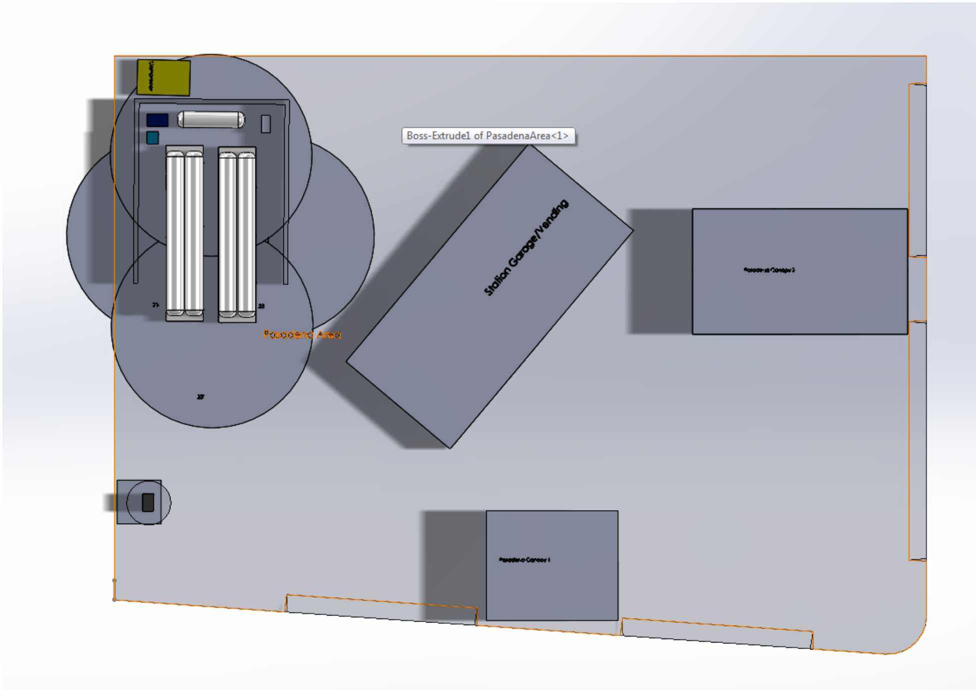


Figure C-2. Pasadena #1 plan view showing major components and offsets reduced by the 2-hour rated firewall

Appendix D: “Global Production” Fuel Cell Vehicle Rollout Model

FCEV rollout estimates based on manufacturer's public statements and estimates for global production volumes as of Q1CY2014

Year	OEM Global Production (no growth)						Annual Global Production	Cumulative Global Production	CA Production if 30% of Global
	Hyundai	Toyota	Honda	BMW	Daimler	GM			
2014	1,500						1,500	1,500	**450**
2015	2,000	4,000	2,000				8,000	9,500	**2,850**
2016	2,000	4,000	2,000				8,000	17,500	**5,250**
2017	2,000	4,000	2,000	2,000	2,000	2,000	14,000	31,500	**9,450**
2018	2,000	4,000	2,000	2,000	2,000	2,000	14,000	45,500	**13,650**
2019	2,000	4,000	2,000	2,000	2,000	2,000	14,000	59,500	**17,850**
2020	2,000	4,000	2,000	2,000	2,000	2,000	14,000	73,500	**22,050**
2021	2,000	4,000	2,000	2,000	2,000	2,000	14,000	87,500	**26,250**
2022	2,000	4,000	2,000	2,000	2,000	2,000	14,000	101,500	**30,450**
2023	2,000	4,000	2,000	2,000	2,000	2,000	14,000	115,500	**34,650**
2024	2,000	4,000	2,000	2,000	2,000	2,000	14,000	129,500	**38,850**
2025	2,000	4,000	2,000	2,000	2,000	2,000	14,000	143,500	**43,050**
2026	2,000	4,000	2,000	2,000	2,000	2,000	14,000	157,500	**47,250**
2027	2,000	4,000	2,000	2,000	2,000	2,000	14,000	171,500	**51,450**
2028	2,000	4,000	2,000	2,000	2,000	2,000	14,000	185,500	**55,650**