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A Near-Term Economic Analysis of Hydrogen Fueling Stations

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A Near-term Economic Analysis of Hydrogen Fueling Stations

By

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ABSTRACT

There is growing interest in hydrogen as a transportation fuel in California. Plans are underway to construct a "Hydrogen Highway" network of stations across the state to stimulate fuel cell vehicle deployment. One of the key challenges however in the planning and financing of this network is determining the costs of the stations. The purpose of this thesis is to examine the near-term costs of building stations and answer the fundamental question, 'how much would new hydrogen stations cost now?' The costs for seven different station types are analyzed with respect to size, siting factors, and operating factors. The first chapter of the thesis reviews the existing body of knowledge on hydrogen station costs. In the second chapter, I present hydrogen station cost data in a database, the Compendium of Hydrogen Refueling Equipment Costs (CHREC), created to organize and analyze data collected from equipment suppliers, existing stations and literature. The third chapter of the report presents the Hydrogen Station Cost Model (HSCM), an engineering/economic model also created as part of this thesis, to analyze the cost of stations. In the final chapter of the report, the HSCM model is applied to the case of the proposed California Hydrogen Highway Network to indicate the costs of different hydrogen infrastructure options.

Based on these cost analyses, I conclude the following:

- Existing hydrogen station cost analyses tend to under-estimate true station costs by assuming high production volume levels for equipment, neglecting station installation costs, and omitting important station operating costs.
- Station utilization (i.e. capacity factor) has the most significant impact on hydrogen price.
- Hydrogen fuel costs can be reduced by siting stations at strategic locations such as government-owned fleet yards and facilities that use hydrogen for industrial purposes.
- Hydrogen fuel costs ($/kg) are higher at small stations (10-30 kg/day) that are burdened with high installation costs and low utilization of station infrastructure.
- Energy stations that produce electricity for stationary uses and hydrogen for vehicles have the potential for low-cost hydrogen due to increased equipment utilization. Costs of energy stations are uncertain because few have been built.
- The Hydrogen Station Cost Model is a flexible tool for analyzing hydrogen station costs for a variety of conditions and assumptions.

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EXECUTIVE SUMMARY

The following summary highlights the results of the thesis. It presents costs for seven types of individual hydrogen fueling stations and the total estimated cost of the California Hydrogen Highway fueling station network. These results and more, along with their assumptions, are presented in great detail in Chapter 3 and 4. Several conclusions from the analysis are also presented to highlight important lessons in hydrogen station economics.

Summary of Results

Costs are calculated for seven different station types, listed in Table 0-1. Station costs are presented both individually (by-station) and collectively as a network of stations. They are also presented under different station siting and vehicle demand scenarios to show their sensitivity to different assumptions. The baseline capacity factor used throughout the analysis is 47% unless stated otherwise.

Table 0-1: Station Types and Sizes

Station Type	**Capacity Range (kg/day)**
1. Steam methane reformer	100-1000
2. Electrolyzer, using grid or intermittent electricity	30-100
3. Mobile refueler	10
4. Delivered liquid hydrogen	1000
5. PEM/Reformer energy station	1000
6.. High temp. fuel cell energy station	91[1]
7.. Pipeline delivered hydrogen station	100

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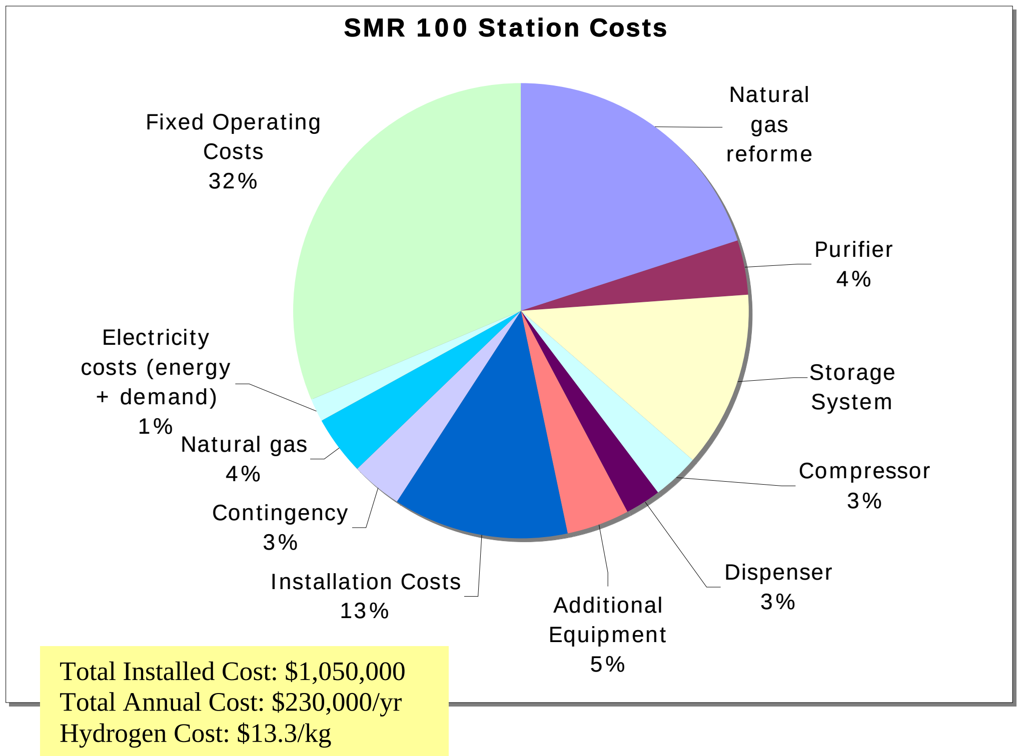
[1] This size was selected because the costs provided by Fuel Cell Energy for this type of station are for a 91 kg/day unit.

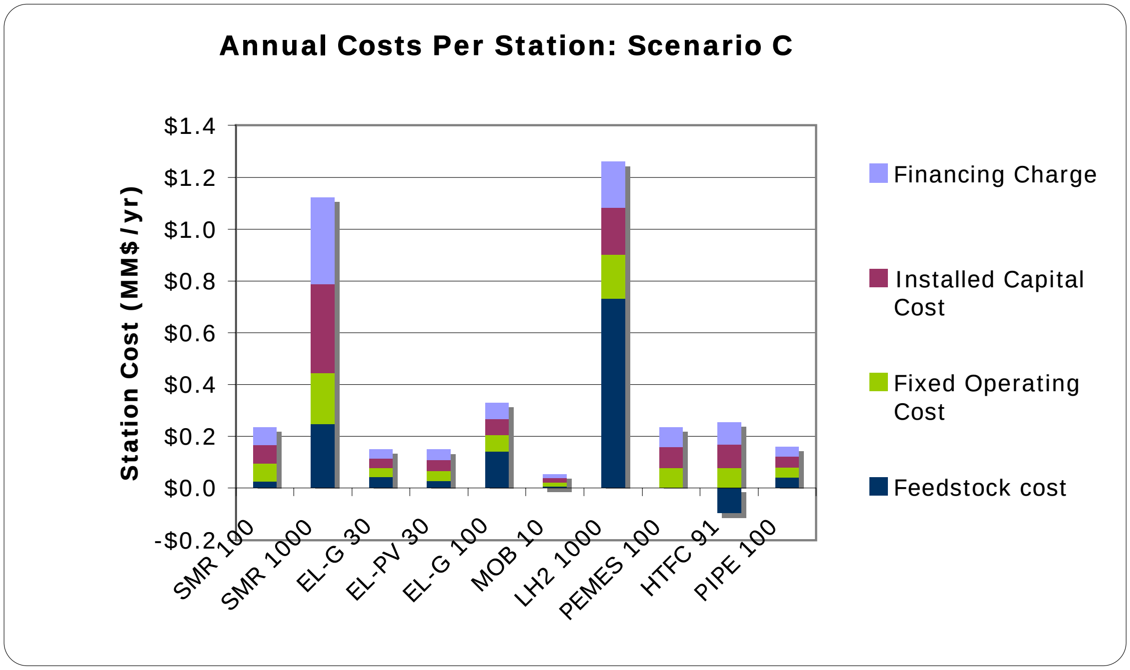
Pie charts have been created for each station type to illustrate what costs are considered for each individual station and the amount each cost item contributes to overall hydrogen price. The figure below presents the pie chart for a reformer-type station.

Figure 0-1: Reformer Station Costs (100kg/day)



The figure below shows annual station costs for the seven different types of stations analyzed in this analysis.

Figure 0-2: Annual Costs per Station[2]



To show how these costs compare to other more well-known studies, Figure 0-2 compares the HSCM model results for reformer-type stations to results from a report by the National Academy of Science. The figure below shows where NAS costs fall between HSCM costs for two production volume scenarios.

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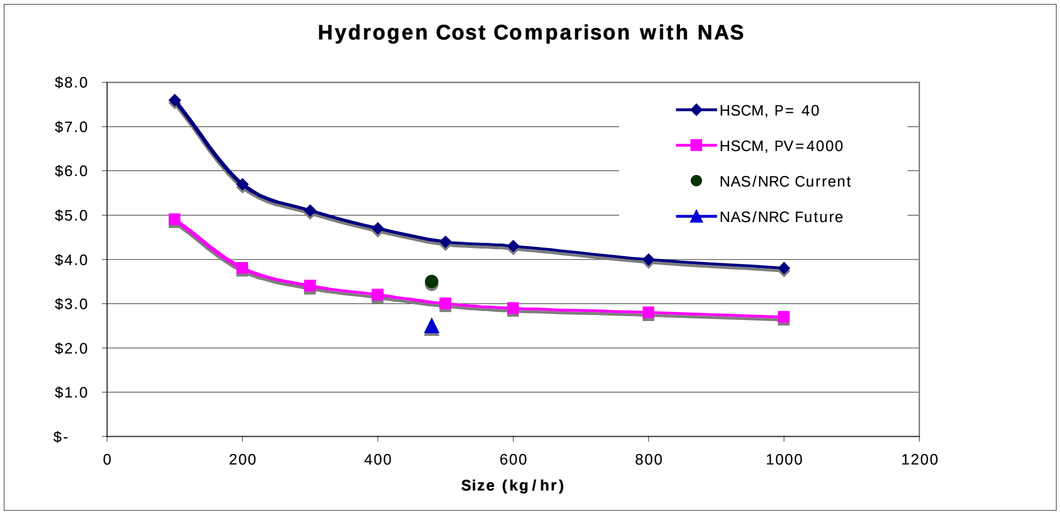
[2] The high-temperature fuel cell (HTFC) energy station shows negative feedstock cost since it actually generates some revenue through electricity sales. The HTFC net station cost is actually ~$160,000/yr. Note that the HTFC costs presented in this report are low due to high capacity factor assumptions.

Figure 0-3: Hydrogen Cost Comparison for Reformer Station, NAS



Costs for a network of stations were evaluated under three demand scenarios. The key assumptions for the demand scenarios are listed in Table 0-1.

Table 0-2: Demand Scenario Assumptions

Scenarios:	A	B	C
Total # of Stations	50	250	250
Hydrogen Price to Customer ($/kg)	$3.0	$3.0	$3.0
LD Vehicles	***2,000***	***10,000***	***20,000***
HD Vehicles	10	100	300
Rated Capacity of Stations (kg/yr)	2,496,509	7,580,685	7,580,685
Total Hydrogen Produced/yr (kg/yr)	459,289	2,027,025	3,755,114
Capacity Factor (%)	16%	24%	47%

The figure below shows how station costs decrease under three siting scenarios: 1) Basecase 2) Public Fleet Location and 3) Champion Applications. Demand scenario B

(250 stations, 10,000 vehicles, 24% capacity factor) is used for this case. The assumptions for each scenario are presented in the table below the figure.

Figure 0-4: Station Cost Under 3 Siting Scenarios, Station Mix B

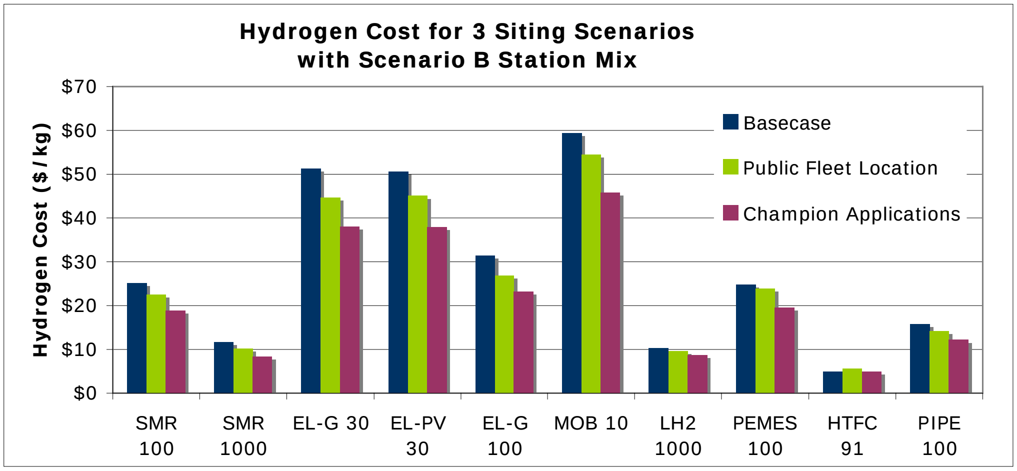
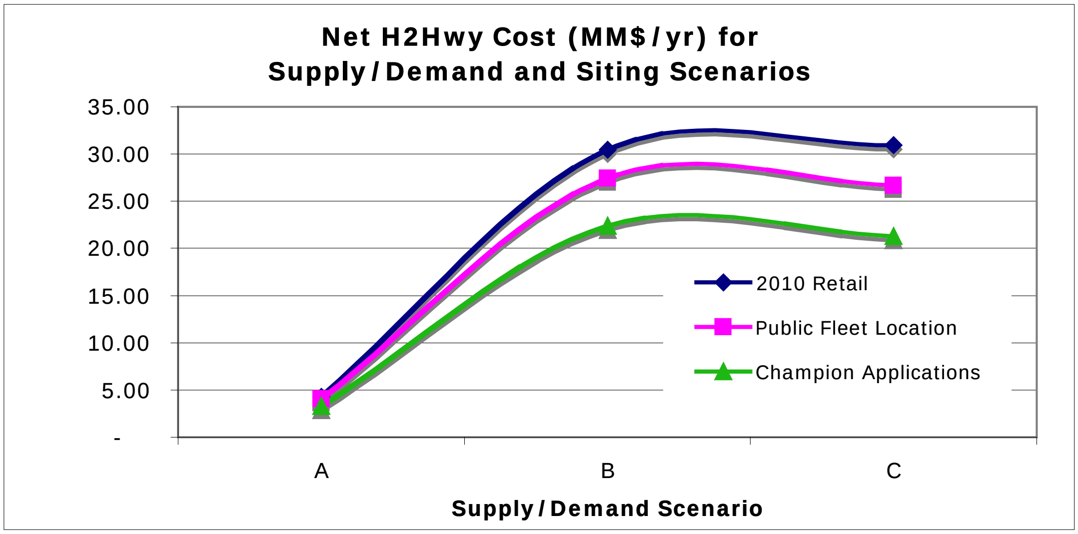


Table 0-3: Siting Scenario Assumptions

Scenario:	*Basecase*	*Public Fleet Location*	*Champion Applications*
Station Assumptions			
Natural gas ($/MMBtu)	$7.00	$6.00	$5.00
Electricity ($/kWh)	$0.10	$0.06	$0.05
Demand charge ($/kW/mth)	$13	$13	$13
Capacity Factor	24%	34%	44%
After-tax rate of return	10%	8%	6%
recovery period in years	15	15	15
% of labor allocated to fuel sales	50%	30%	20%
Real Estate Cost ($/ft^2/month)	$0.50	$0.50	$-
Contingency	20%	15%	10%
Property Tax	1%	1%	1%

The total cost for a network of stations is presented in Figure 0-5. The three demand scenarios are combined with three siting scenarios (e.g. 2010 Retail, Public Fleet, Champion) for a total of nine data points. This provides an upper and lower bound on the H2Hwy Network cost estimate for scenarios A, B, and C.

Figure 0-5: H2Hwy Net Cost Range for Demand/Supply and Siting Scenarios



The above results demonstrate the flexibility of the HSCM as a tool for calculating station costs under a variety of assumptions and comparing results to other analyses. The HSCM, though applied in this report to California's Hydrogen Highway Network, is flexible enough to model the construction of hydrogen stations in any region.

Conclusions

The following conclusions can be drawn from the report's analysis:

1. Existing analyses on the economics of hydrogen stations under-estimate the costs of building hydrogen stations in the near-term. They often omit important installation costs such as permitting and site development, and overlook operating costs such as liability insurance and maintenance. Many analyses also use equipment costs associated with higher production volumes than what industry is experiencing today.

2. In order to achieve hydrogen costs competitive with current gasoline prices, production volumes for stations will need to reach levels in the 1000's. This is equivalent to about 6% of gasoline stations in California.[3]
3. Capacity factor, or station utilization, has the biggest impact on hydrogen cost. Station operators should try to maintain high station utilization in order to achieve low hydrogen cost.
4. The strategic location of stations and vehicles is critical to station economics. The scenario analysis showed that "Champion Applications" resulted in the lowest cost hydrogen. This involves building stations on state-owned land to reduce real-estate costs and installation costs (easier permitting process), and taking advantage of fleet vehicle clusters to increase capacity factor.
5. Large stations (1000 kg/day) like the reformer station and liquid hydrogen station exhibit the lowest costs since they are able to spread their installation and capital costs over a large volume of hydrogen sales. These large stations also show the result of equipment scale economies on reducing cost.
6. Electrolyzer refueling stations yield high hydrogen costs due to low throughput (30-100 kg/day) and high electrolyzer capital costs at small scale. At low capacity factors (<30%), capital costs dominate and thus electricity price does not substantially affect hydrogen cost.
7. Mobile refuelers yield the most expensive hydrogen due to their small size (10kg/day) and the high cost to refill them.

[3] This assumes units are made from a single manufacturer.

8. Energy stations have the potential for lower cost hydrogen due to increased equipment utilization (hydrogen is produced for cars and stationary power). Costs for these station types are the most uncertain since only a few PEM/Reformer energy station have been built and no HTFC energy stations have yet been built.
9. Station sited near an industrial demand for hydrogen can share the hydrogen use and thus take advantage of scale-economies and high capacity factors.
10. Pipeline stations have potential for low cost at low flow rates when sited near existing pipelines.

INTRODUCTION

Motivation

Industry and government face two key challenges in planning new hydrogen infrastructure: 1) the lack of accurate data on current station costs; 2) the need to find cost-effective infrastructure development strategies. These issues are especially important in California since the state is planning to build a intrastate network of fueling stations (i.e. the Hydrogen Highway Network). The author addresses both of these problems in this thesis.

The first challenge makes it is difficult to accurately estimate the cost of building new stations since station costs are highly variable and unpredictable. Actual station costs often exceed the budgeted amount, sometimes by multiples. While there are many estimates of the anticipated costs of fueling stations, most analyses to date project costs below what station builders are experiencing today. Furthermore, there is no literature reporting the actual costs of station construction.

The second challenge requires a new transparent modeling tool to explore a variety of hydrogen infrastructure deployment scenarios. The tools available today do not provide the ability to explore different station mixes, operating assumptions, and siting conditions.

To address the first challenge, the author has created a database to collect and organize cost information on hydrogen station equipment called CHREC (Compendium of Hydrogen Refueling Equipment Costs). It collects and organizes data from equipment suppliers, existing stations, and literature.

To address the second challenge, the author has created the Hydrogen Station Cost Model (HSCM), an engineering/economic model to determine the costs of several types of hydrogen stations under various conditions and assumptions. Data from CHREC are the key input to the HSCM. Its flexible structure also enables comparison of different infrastructure deployment strategies in a variety of geographical regions. The model can be used by governments that are planning to build networks of hydrogen infrastructure[4].

Background

Hydrogen fueling stations are the building blocks of a hydrogen transportation infrastructure. While their primary function is to provide hydrogen fuel for vehicles, this goal can be achieved in many different ways. For instance, some stations produce hydrogen on-site while others have fuel delivered from centralized production plants in liquid or gaseous form. Hydrogen can also be produced from a variety of feedstocks, such as water and electricity, natural gas, or biomass (e.g. agricultural waste, wood clippings, etc.).

[4] These projects are underway in California, Canada, Iceland, Tasmania, and Norway.

Despite the many variations on station design, most stations contain the following pieces of hardware:

1. Hydrogen production equipment (e.g. electrolyzer, steam reformer) or storage equipment (if delivered)
2. Purifier: purifies gas to acceptable vehicle standard
3. Compressor: compresses gas to achieve high-pressure 5,000 psi fueling and minimize storage volume
4. Storage vessels (liquid or gaseous)
5. Safety equipment (e.g. vent stack, fencing, bollards)
6. Mechanical equipment (e.g. underground piping, valves)
7. Electrical equipment (e.g. control panels, high-voltage connections)

Building stations also require the following installation tasks:

1. Engineering and Design
2. Site preparation
3. Permitting
4. Installation
5. Commissioning (i.e. ensuring the station works properly)

Operating stations typically incur the following recurring expenses:

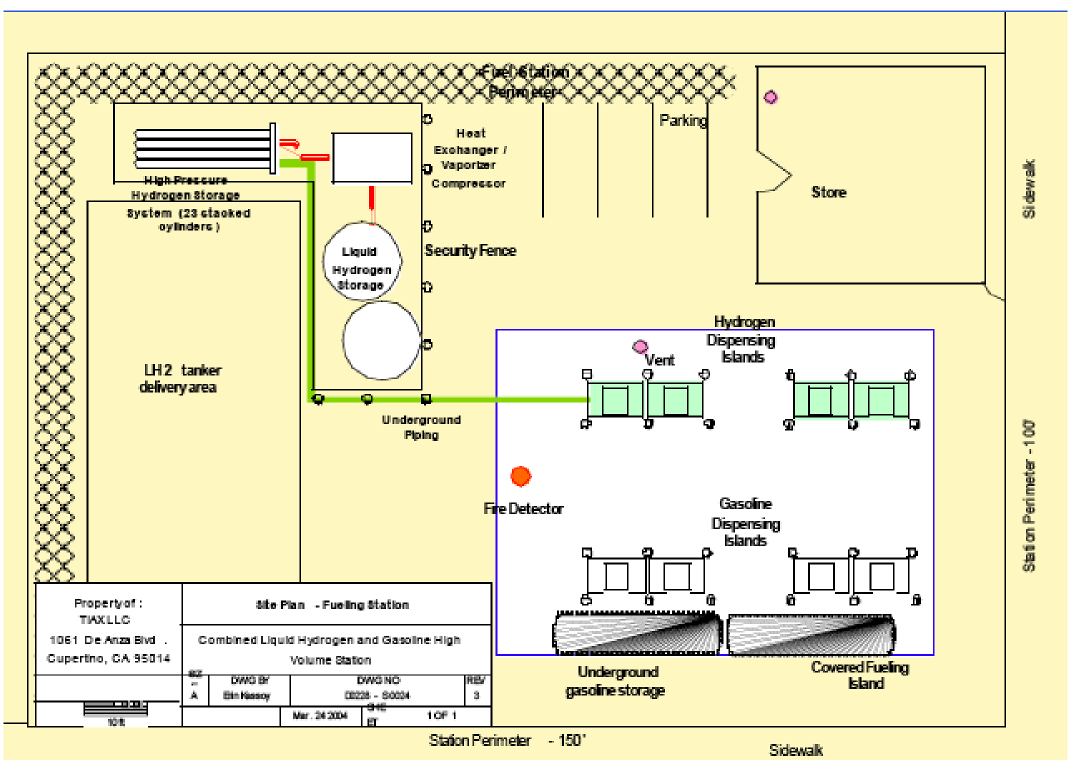
1. Equipment Maintenance
2. Labor (station operator)
3. Feedstock costs (e.g. natural gas, electricity)

4. Insurance

5. Rent

It is important for station economic analyses to include all of these costs when evaluating hydrogen price. Many analyses in the existing body of literature omit some of these, particularly in the areas of permitting and site preparation. The following figure provides an example of a hydrogen fueling station co-located with a conventional retail gasoline station.

Figure 0-1: Site Layout for Combined Gasoline/Liquid Hydrogen Fueling Station[5]



[5] Diagram provided by Erin Kassoy of Tiax, LLC

Scope

The HSCM has been applied to specific task of determining the cost of the California Hydrogen Highway (H2Hwy) Network. As such, the results of the analysis (presented in Chapter 4) use inputs and assumptions generated by the H2Hwy Blueprint Panel. The analysis, while California specific, can be applied to other geographical areas interested in hydrogen infrastructure expansion.

This report answers the following research questions:

1. What are the near term (2005-2010) costs of hydrogen fueling stations?
2. What is at the source of the variability and unpredictability of station costs?
3. What accounts for the differences between the calculated costs of this study and the costs estimated by other reports (NAS, Simbeck, Ogden, etc.)?
4. What strategies are available to lower the cost of hydrogen in the near-term?

Research Tools & Methodology:

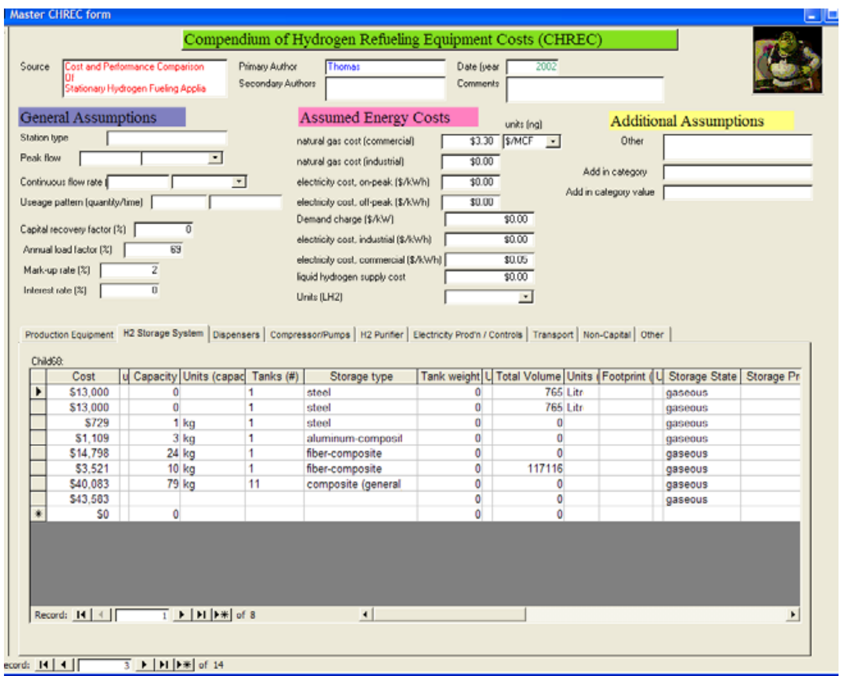
The following research tools are used to answer the aforementioned questions. These tools were created by the author for this analysis.

Compendium of Hydrogen Refueling Equipment Costs (CHREC):

The CHREC database is a virtual "one-stop shop" for information on the costs of hydrogen refueling stations. This includes capital costs for equipment (e.g. compressors, storage tanks), non-capital costs for construction (e.g. design, permitting), and total station costs (e.g. $/station, $/kg).

The CHREC is a tool to compare existing cost estimates, and compare these estimates to real cost data. It compiles and organizes cost estimates obtained from a variety of authors (e.g. Thomas, Ogden, Simbeck) for the major components in a hydrogen refueling station. It also compiles actual historical cost data from existing stations and vendors (e.g. Air Products, Stuart, H2Gen). All cost data are standardized to 2004 dollars. The following figure shows the CHREC user interface:

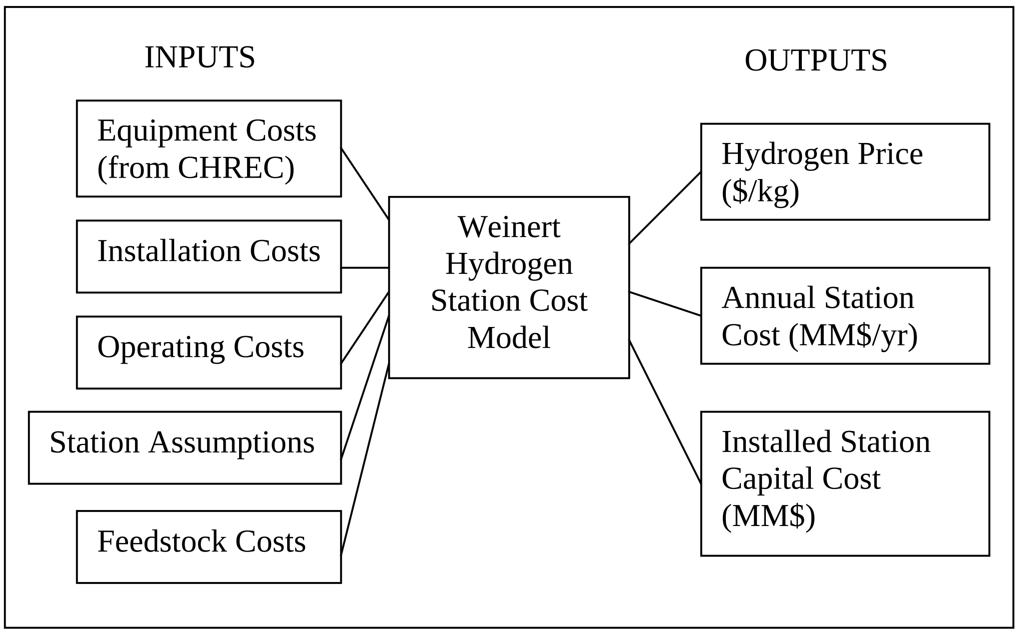
Figure 0-2: CHREC Database Example Form



The Weinert Hydrogen Station Cost Model (HSCM):

The HSCM is a research tool created by the author to analyze the economics of different types and sizes of hydrogen stations. It also calculates the overall cost of developing a hydrogen station network assuming a vehicle demand and station-type mix. Technological learning are modeled through progress ratios assumed for various station components. The following figure shows the key inputs and outputs of this model. The model and the methodology it follows are discussed in detail in Chapter 3 and 4.

Figure 0-3: HSCM Structure



Thesis Outline

The first chapter of the thesis reviews the existing body of knowledge on hydrogen station costs. In the second chapter, I present hydrogen station cost data in a database, the Compendium of Hydrogen Refueling Equipment Costs (CHREC), created to organize and analyze data collected from equipment suppliers, existing stations and literature. The third chapter of the report presents the Hydrogen Station Cost Model (HSCM), an engineering/economic model also created as part of this thesis, to analyze the cost of stations. In the final chapter of the report, the HSCM model is applied to the case of the proposed California Hydrogen Highway Network to indicate the costs of different hydrogen infrastructure options.

1. Literature Review on Hydrogen Fueling Station Costs and Configurations

Summary

This review analyzes and evaluates available literature on hydrogen equipment costs, station costs, and energy station configurations. It presents the results, assumptions, strengths, and the limitations of each relevant source. It is meant to provide a summary on the current state of understanding for hydrogen fueling station costs and the relationship between cost and fueling station configuration.

Previous analyses have addressed some of the problems and research questions posed in this report. The purpose of the following literature review is to determine which results from these reports can be used in this analysis, which results need to be re-analyzed, and which research questions are not addressed at all. The following tables summarize my evaluation of the reviewed reports into three main categories: Hydrogen Station and Equipment Costs Results, Energy Station Model Functions/Capabilities, and Energy Station Results/Misc. The matrix ranks the degree to which they adequately address the given factors. Factors are ranked according to the degree to which it addresses each of these factors.

N =none, the subject is not addressed at all;

I = inadequately, the subject is addressed, but a more thorough analysis needs to be done (possible due to the author's use of simplified assumptions, obsolete data, etc.);

A =adequately, the subject is covered with sufficient breadth and accuracy such that the results are still relevant and a repeat analysis would be redundant.

Table 1-1: Literature Review Summary for Station & Equipment Costs

			Hydrogen Station and Equipment Costs						
year	Source	Primary Author	Capital Equipment Costs	Non-Capital Station Costs	Operating Costs	Includes Cost Equations	Explores Cost vs. Capacity	Explores Cost vs. Production Volume	Validates cost data with Industry
02	Cost and Performance Comparison Of Stationary Hydrogen Fueling Applications	Myers, Duane B.	A	N	I	N	I	A	A
01	Distributed Hydrogen Fueling Systems Analysis	Thomas, C.E. (Sandy)	I	N	I	A	I	A	I
02	Hydrogen Supply: Cost Estimate for Hydrogen Pathways-Scoping Analysis	Simbeck, Dale	A	I	A	I	A?	I	A
99	Survey of the Economics of Hydrogen Technologies	Padro, C.E.G.	I	N	N	N	I	A	A
98	Costs of Storing and Transporting Hydrogen	Amos, Wade	A	N	A	N	I	N	A
03	A Critical Review and Analysis of Publications on the Costs of Hydrogen Infrastructure for Transport	Sepideh	I	N	N	N	N	I	A
04	National Academy of Science Report	NAS	A	I	A		A	N	A
00	Assessment of Hydrogen Fueled Proton Exchange Membrane Fuel Cells for Generation and	Kreutz, Ogden	I	N	A	A	I	I	I

	Cogeneration								
9 9	Analysis of Utility Hydrogen Systems & Hydrogen Airport Ground Support Equipment	Thomas	I	N	I	A	A	A	A
0 2	Economic Analysis of Hydrogen Energy Station Concepts	Lipman	I	I	I	N	A	I	I

Table 1-2: Literature Review Summary for Model Results and Misc.

	Source	Primary Author	Model Results and Miscellaneous Factors			
			Performs sensitivity anayses on key variables	Includes Technical Info on equipment	Includes rational for design choices	Explores regional effects of station siting
2002	Cost and Performance Comparison Of Stationary Hydrogen Fueling Applia	Myers, Duane B.	N	A	A	N
2001	Distributed Hydrogen Fueling Systems Analysis	Thomas, C.E. (Sandy)	A	A	A	I
2002	Hydrogen Supply: Cost Estimate for Hydrogen Pathways-Scoping Analysis	Simbeck, Dale	N	N	A	I
1999	Survey of the Economics of Hydrogen Technologies	Padro, C.E.G.	N	N	N	N
1998	Costs of Storing and Transporting Hydrogen	Amos, Wade	N	A	A	N
2003	A Critical Review and Analysis of Publications on the Costs of Hydrogen Infrastructure for Transport	Sepideh	N	N	N	N

2004	National Academy of Science Report	NAS	A			

Hydrogen Station & Equipment Cost Report Synopsis

The following section provides a synopsis of literature containing information on the costs of hydrogen stations and hydrogen equipment. In this section, the author comments on the different approaches used by each author in determining costs and examine their assumptions. The reviewed reports, listed in order of usefulness to this research, include:

Dale Simbeck and Elaine Chang (Jul-02) "Hydrogen Supply: Cost Estimate for Hydrogen Pathways - Scoping Analysis"

Duane B. Myers et al. (Apr-02) "Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances"

C. E. (Sandy) Thomas et al. (2001) "Distributed Hydrogen Fueling Systems Analysis"

Sepideh, S. "A Critical Review and Analysis of Publications on the Costs of Hydrogen Infrastructure for Transport" (2004)

Amos, W. (Nov-98) "Costs of Storing and Transporting Hydrogen"

C.E.G. Padró and V. Putsche (Sep-99) "Survey of the Economics of Hydrogen Technologies"

Some reports look primarily at the pieces of equipment individually while others examine their costs in the context of a station. Some discuss how equipment costs relate to production volume and capacity. These reports are useful in determining the cost of hydrogen at different types of stations.

Simbeck and Chang (2002) analyzes the total station costs for several different types of stations through the use of a comprehensive spreadsheet model. Sepideh (2004) is useful in evaluating data from several reports on hydrogen equipment costs. Myers (2002) provides an in depth analyses of reformer, compressor, and storage equipment costs. Amos (1998) is most useful in determining storage costs. Padro and Putsche (1999) looks at over 100 publications covers to present hydrogen cost data for production, storage, transport, stationary power, and transportation applications.

The purpose of this section is to determine where there is sufficient knowledge on hydrogen and energy station costs and where this knowledge is limited. Another purpose is to identify particularly useful cost data and cost models to input into CHREC. The questions asked in the review of these reports are:

1. Do the cost models and data accurately reflect today's equipment costs?
2. What aspects of hydrogen stations is there limited amount of information on?
3. Are the assumptions used to determine costs valid appropriate for near-term station designs (e.g. size, capacity factor)?
4. What station costs items (listed in "Background" section) are neglected?

The conclusion after reviewing these papers is that most of the cost models presented in these reports accurately reflect "reality" for large stations (>100 kg/day) at high production volume levels (> 100 units/yr). These reports in general lack information on near-term, actual equipment and station costs. None of the literature provides cost estimates of actual stations. One reason is that some of the older reports were written before any hydrogen stations were actually built. Some of the equipment cost data from older reports under-estimate the true costs experienced in 2004. Very few reports from literature look at non-capital costs of building stations. Also, there is a limited amount of recent data from equipment manufacturers in literature. While some assumptions in these reports are valid, many use production volume and utilization estimates that are unrealistically high for near term scenarios.

Evaluation of Sources

1. Dale Simbeck and Elaine Chang (Jul-02) "Hydrogen Supply: Cost Estimate for Hydrogen Pathways - Scoping Analysis" SFA Pacific, Mountain View, CA

This paper is particularly unique and valuable to understanding hydrogen station economics. It provides results from detailed spreadsheets that calculate hydrogen cost based on several different production technologies, feedstocks, and distribution options. The costs for each option are broken down into capital costs, fixed operating costs, and variable operating costs to determine a unit hydrogen cost ($/kg). The final hydrogen costs are broken-down further into the sub-costs for production, handling, transmission, and storage. The assumptions made in determining these costs are clearly defined in the report. To support their results, the authors validated their calculations by comparing them with cost estimates made by the chemical gas company Air Products. Their findings were in relative agreement.

The model created for this analysis is one of the most transparent analyses on hydrogen station costs to date since it includes their calculation spreadsheets in the appendix. Since the paper covers all the major types of hydrogen production, it allows for more meaningful cost comparisons between production methods since the same assumptions are used for each production technology. This model was also adopted by the National Academy of Sciences as their tool to analyze hydrogen costs (after modifications by Jim Sweeney).

Non-Capital Costs:

The report makes general assumptions about the costs for General Facilities, Engineering Permitting & Startup, Contingencies, Working Capital, Land & Misc. It assumes each of these categories cost a certain percentage of the total capital equipment cost (20%, 10%, 10%, and 5%, respectively). While this may be correct for more established fueling station types, it can be misleading for near-term hydrogen stations. For example, it has been found that for recently built stations, these costs can exceed the total capital cost of equipment[6]. To address differences in costs at different geographical locations, a “site specific” factor is used to increase or decrease the final capital costs of the station.

While it is a relatively recent source of cost information, several of the cost figures have been obtained directly from older sources (e.g. Amos 1998).

The report does not address a relationship between cost and equipment production volume. It also does not provide costs for the low production volume scenario.

Its lowest capacity assumption is 480 kg/day max production, or 723 vehicles (103 fill-ups/day). The sizing scale factor used in this study is valid over a range 100-10,000 kg/day[7]. It would be useful to examine the cost of smaller scale hydrogen stations since, in the near-term, smaller hydrogen generation devices will be implemented.

The report does not show how costs change as key variables change. It would be useful to use this model to perform a sensitivity analyses on important variables to see how they

[6] Weinert, J. (2004) “The LAX Hydrogen Fueling Station Development: A Historical, Technical, and Economic Overview with a Discussion of the Obstacles Encountered and Lessons Learned”, National Hydrogen Association Annual Conference Proceedings, Los Angeles, CA.

affect the overall cost of hydrogen. The National Academy of Science Report (which uses a modified version of this model) does this analysis however.

Besides presenting detailed cost information, the paper also describes the theory, advantages, and disadvantages of different station configurations. Throughout the paper, the author makes conclusions about the value of different station configuration options. For example, "From Table 15, it shows that the lower infrastructure requirements of forecourt production do not compensate for the higher operating costs." (p.24) It also states that "until composite materials become more economical, it may be better to stick to 5000 psi than 10,000 psi."

Storage Sizing

The report addresses the relationship between storage volume and production rate and its effect on hydrogen costs. The amount of storage required given a hydrogen demand (FCV/day) or production volume (kg/day) is calculated using three key assumptions: load factor, hours at peak surge, and maximum surge fill-up rate. Simbeck assumes a load factor of 90% (amount of time the hydrogen equipment is actually used), the storage system will need to store enough to handle 3 hours of fueling at peak surge (maximum hydrogen flow rate at a station), and that the peak surge rate is 2 times the average production rate. These three assumptions, along with the assumption that the compressor output and the production rate output are identical, yield an estimated station storage capacity of 108 kg. (90% load factor x 3 hr peak surge x 2 peak surge:avg production ratio x 20 kg/hr = 108 kg of storage). Though this method simplifies the relationship between storage, hydrogen demand, and hydrogen production rate, it is sufficient for the purpose of Simbeck and Chang's analysis. The HSCM does not adopt this assumption. It uses a method developed by Tiax to calculate storage and compressor requirement.

Compressor Sizing:

The author assumes the compressor output and the hydrogen production rate output are identical. This is a reasonable assumption for most stations unless there is a buffer storage tank between the reformer and compressor. The compressor and production need to operate in synch to prevent low compressor inlet pressure.

Relationship between Cost and Size:

To appropriately model the effect of size on the cost of the different components, it assumes a cost/unit and cost/size factor for each component. The capital cost (in $/kg/day) for these components are calculated using these assumptions and the following formula.

$$CU_{act} = CU_o * (Size_o / Size_{act})^{(1-CSF)}$$

For example, reformers are assumed to cost $2.00/scf/day based on a 1000 kg/day reformer. Since this equipment exhibits a 75% cost/size factor, reducing the size of the unit to 480 kg/day will increase its unit cost by a factor of $(1000/480)^{(1-0.75)}$ ~ 1.2 to $2.40/scf/day

This approach is useful because it allows one to calculate unit cost for equipment over a range of sizes if the unit costs at a given size and its cost/size factor are known. This approach may be misleading however in predicting the cost of equipment for near term stations when the $Size_o$ (1000 kg/day) deviates significantly from $Size_{act}$ (50-150 kg/day for near term stations).

2. Duane B. Myers et al. (Apr-02) "Cost and Performance Comparison Of Stationary Hydrogen Fueling Appliances" DTI, Arlington, VA

This report analyzes the cost of small-scale stationary reformers and evaluates different purification, compression, storage, and dispenser technologies. The purpose of this 129-page document is to provide "a detailed analysis of the cost of providing small-scale stationary hydrogen fueling appliances (HFA's) for the on-site production and storage of hydrogen from natural gas to fuel hydrogen FCV's."

Four potential reforming systems were studied: 10-atmosphere steam methane reforming (SMR) with pressure-swing adsorption (PSA) as gas cleanup, 20-atm SMR with metal membrane gas cleanup, 10-atm autothermal reforming (ATR) with PSA gas cleanup, and 20-atm ATR with metal membrane gas cleanup."

The sections of interest in this report are: Refueling applicant hydrogen production rate and manufacturing quantity, gas cleanup technologies, hydrogen compressors, stationary storage of compressed hydrogen, dispensers, and total cost of SMR based stationary fueling appliances. The author refers to these appliances as the Hydrogen Fueling Appliance (HFA)

The report concludes that small scale steam reformation units producing pure hydrogen gas stored at 5,000 psi is the most promising hydrogen supply pathway compared to electrolysis and delivered hydrogen and that SMR is the cheapest method for producing hydrogen from natural gas at small scale.

This report provides a very comprehensive analysis of the costs of hydrogen refueling equipment. It is also an excellent source for technical information about steam methane reformer design and operation. It includes technical drawings and explanations of each system involved in the reformation process, including reformate cleanup technologies. One of its most useful features is the bill of materials provided for the reformer system. The report includes a few estimates of the effect of production volume on cost for compressors and storage, but only for a few different production volume levels.

The report uses a robust cost estimation methodology based on the Design for Manufacture and Assembly (DFMA) techniques developed by Boothroyd and Dewhurst, described in *Product Design for Manufacture and Assembly, 2nd edition*. These cost estimates have been entered into CHREC. The costs estimated in this report are lower than the costs calculated from the author’s model (described later in the report).

3. C. E. (Sandy) Thomas et al. (2001) "Distributed Hydrogen Fueling Systems Analysis"

The report examines reformer, storage and compressor costs for several different types of equipment. In particular, the authors developed cost correlations for storage tanks and reformers. These cost estimates are derived from actual vendor manufacturers. The operating costs for compressors can be calculated from the equation compression energy over a given time interval.

This report is one of the few that examines the relationship between equipment costs and production volume. It provides cost estimates for the SMR unit at production volumes of 1, 100 and 10,000. This is useful in conducting future scenario analysis by calculating how costs may come down as production volumes increase. The author's multi-level production volume analysis also allows comparison of his estimates with estimates from other sources since other analyses use a variety of different production volume assumptions.

The report provides some great technical descriptions about cascade storage, booster storage, and hydrogen tank overfilling. It also concludes there is no significant cost advantage in using booster over cascade storage. It looks at the operation scenario of load-following the reformer to reduce storage system cost but concludes there is no significant cost reduction.

The authors analyze the station costs for different regions, including California and Alaska, and show how different energy prices affect the system economics. "In California, a 500-FCV station with a 200-kWe fuel cell generator could sell electricity during six peak hours for 6¢/kWh and hydrogen at $1/gallon gasoline-equivalent. In Alaska, with lower natural gas prices, on-peak electricity could be sold at 6¢/kWh and hydrogen at 60¢/gallon of gasoline-equivalent and still make 10% real, after-tax return on investment." It calculates the price of both hydrogen and electricity prices given various FCV demands. This calculation is useful in locating suitable regions for initial ES deployment

The report looks at only one fuel cell size (200kW) and four different vehicle demand scenarios. It analyzes the price of electricity vs. the amount of time the fuel cell operates per day. It assumes one simplified building electricity demand profile (6hrs per day during peak daytime period). The estimated costs of hydrogen presented in this report are not realistic for today's near-term costs of hydrogen for the following reasons:

- Natural gas prices are based off 1998 data and therefore are low.
- It includes a production progress ratio for compressors.
- Several of the station installation costs are neglected.

The report includes cost equations for storage tanks and reciprocating compressors. It also looks at the trade-off between storage costs vs. reformer, compressor costs, and operating costs in using a cascade system vs. a booster system. It calculates the energy costs of the reformer and compressor for a 50kg/day station, however, it does analyze how operating costs change with reformer and fuel cell size.

The costs presented in this report for storage and compression appear to have been validated with industry (Air Products, BOC, Ford), but not with any of the smaller companies producing equipment for fueling stations today.

The report presents several graphs showing the relationship between a customers' cost of electricity and the selling price of hydrogen for a customer that owns an energy station. Again, the costs presented in this report are lower than those calculated from the author's model.

4. Sepideh (2003) "The Costs of Hydrogen Technologies" (*final draft of PhD dissertation*)

This report summarizes and analyzes cost data from the most relevant reports on hydrogen cost between 1985 and 2000. The main categories of analysis include**:**

a) analysis and comparison of generic costs: hydrogen production equipment, hydrogen storage equipment, transportation equipment etc.

b) analysis and comparison of different hydrogen supply scenarios/pathways and their costs in a particular location

c) analysis and comparison of different types of transport fuels for hydrogen vehicles (hydrogen, methanol, gasoline) and their costs.

d) Conclusions reached regarding generic hydrogen infrastructure costs

This report evaluates a large number of sources on costs and determines which ones are the most valid and useful. It examines the assumptions used for each report's cost figures to understand the differences in results. Specifically, it provides detailed coverage of costs comparisons of compression and dispenser costs, transport costs for both pipeline and truck (pp. 50s) and storage costs from different reports (p.64) The majority of these data are from three reports: Thomas 1997, Amos 1998, and Berry 1996). The summary includes cost information on metal hydride, underground, and liquefied storage.

Sepideh uses a special normalized "Total Cost" factor based on ($million/ton/day) to compare the results of each report. This normalized factor is a useful way of comparing cost data from a variety of reports that use different assumptions. She identifies trends in the cost data based on these normalized numbers and briefly looks at data associated with different production volume assumptions (p.26).

The report presents some of the key assumptions for each total costs (for on-site natural gas reformation) in her cost tables (p.28). It also presents bar graphs showing the relationship between cost and plant size for all the different estimates. It normalizes the data based on the most common assumptions to present a meaningful comparison between data.

The report evaluates the analyzed reports and their data based on "the clarity and transparency with which the methods and equations used have been described, and whether all assumptions made have been clearly stated." This is a useful metric for evaluating the literature.

While this paper provides a thorough analysis of cost data taken from literature from the 90's on the costs of hydrogen infrastructure, it does not consider cost data from the past four years or progress by the most relevant hydrogen equipment companies today (e.g. Quantum, FTI, PPI, PDC machines, Dynetek, Hydrogenics, H2Gen, Harvest).

The data on compressor costs are limited. These data are taken from some older reports (Amos, Thomas, and Ogden), and only from a few different companies (RIX, APCI). The data presented on storage costs (both liquid and gas) are fairly outdated, i.e. 1994-1996. (p.74). The way these data are presented doesn't give information on the pressure of the storage.

5. Amos, W. (Nov-98) "Costs of Storing and Transporting Hydrogen"

The purpose of this report is to analyze the capital and operating costs associated with storing and transporting hydrogen. The report mentions some future trends in hydrogen storage and transportation, but concentrates mostly on current commercial processes. The storage techniques considered are liquid hydrogen, compressed gas, metal hydride, and underground storage. The modes of transportation examined are liquid hydrogen delivery by truck, rail, and barge; gaseous hydrogen delivery by truck, rail, and pipeline; and metal hydride delivery by truck and rail. Amos' key results are presented in a table summarizing the price of hydrogen from a variety of sources.

This report contains many useful tables that summarize the author's findings on costs. It is thorough in describing the technology, how it works, the concerns and benefits of different storage methods, and the size ranges of different components.

This report is unique in that it pulls together cost information from a variety of papers from as far back as 1986 on hydrogen technologies and lists the source of each cost figure. Because he drew from several sources, he is able to present a range of costs for each item, and costs for equipment of varying size. The paper is also unique in that is contains a large amount of operating cost data and information about the efficiencies of various compressors.

Data on merchant hydrogen demand are presented towards the end of the document. This is helpful in determining markets for energy stations since industries that consume hydrogen may be prime candidates for on-site hydrogen production.

This paper is helpful in considering the storage system design of an energy station. For example, it provides a list of items to consider before choosing a storage option and covers the safety, maintenance and reliability of each option.

This paper does not consider how different sub-systems of a fueling station are related (e.g. how the reformer and storage system will be configured).

Amos gives an extensive description of transport costs, however, this is not as important in the economic considerations of energy station design since the hydrogen is usually produced on-site.

6. C.E.G. Padró and V. Putsche (Sep-99) "Survey of the Economics of Hydrogen Technologies"

Since this paper surveys more than 100 publications on the cost of hydrogen technologies, it has many references and sources of their cost estimates. It covers production, storage, transport, stationary power, and transportation applications.

It is helpful because for many of the hydrogen production estimates, the authors give costs for several different production volumes. It also provides the highs and lows of different cost estimates. The paper usually cites where the cost number came from, and comments on the uncertainty of the data.

This paper contains useful charts showing how different factors influence cost. One shows how the price of H2 drops with the # of vehicles served, which is helpful in drawing conclusions about station sizing. For instance, the curve hits its elbow point at 50 vehicles, indicating a “minimum demand” for making hydrogen stations economical.

The authors standardize all the cost estimates to equivalent units and to 1998 dollars, which allows for more meaningful comparison between estimates. Some of the data in this report are a bit outdated since most estimates are from before 1998.

There are not many data points for small-scale reformer-based hydrogen production. There is limited data on composite storage tank costs. Cost projections for stationary fuel cell power are overly optimistic.

Conclusion

There are several studies that evaluate the cost of both hydrogen stations and equipment. An important item missing from these cost studies is an evaluation of total installed station costs, operating costs, and capital costs that consider near-term production volume levels. While the reports cover equipment costs at different sizes and production volumes, most overlook non-capital costs such as installation, permitting, siting, etc. Simbeck’s spreadsheets make rough estimates of these costs based on estimates from other industries.

The next chapter (Chapter 2) compares the cost data obtained from the above literature to data gathered from industry. These data are organized and analyzed using the CHREC, which will be described in detail in the next chapter. Chapter 3 features the Hydrogen

Station Cost Model (HSCM) which uses CHREC data to determine the cost of seven types of hydrogen stations. The final chapter (Chapter 4) applies the model to analyze the costs of California's proposed Hydrogen Highway Network.

2. Survey of Hydrogen Equipment Costs from Literature and Industry

Introduction

The following section presents data from the Compendium of Hydrogen Refueling Equipment Costs (CHREC), an Access database created by the author to collect and organize station equipment cost information from both literature and industry. Each section is devoted to a different equipment category of the database. The final section will attempt to draw conclusions from the cost data. The data are divided into nine categories, based on the main equipment typically included in a station. The data are also broken down into three source categories based on the source of the cost information: literature, industry, or station. Literature data were gathered from reports (see literature survey in Chapter 1). Industry data were gathered by the author from equipment makers/vendors. The author also gathered station data for particular parts of the station from the station's lead contractor (both existing stations and proposed stations). The following tables present these subcategories.

Table 2-1: Equipment Categories

Production Equipment
Storage Equipment
Compressors

Dispensers
Purifiers
Electricity Production/Controls Equipment
Transport (equipment and service)
Hydrogen Costs
Non-Capital Station Costs
Total Station Costs

Table 2-2: Source Categories

Literature
Equipment Supplier (estimate)
Equipment Supplier (actual)
Station builder (estimate)
Station builder (actual)

For each cost quote in the above equipment categories, CHREC provides the following additional information (where available):

Table 2-3: Supplementary Cost Data

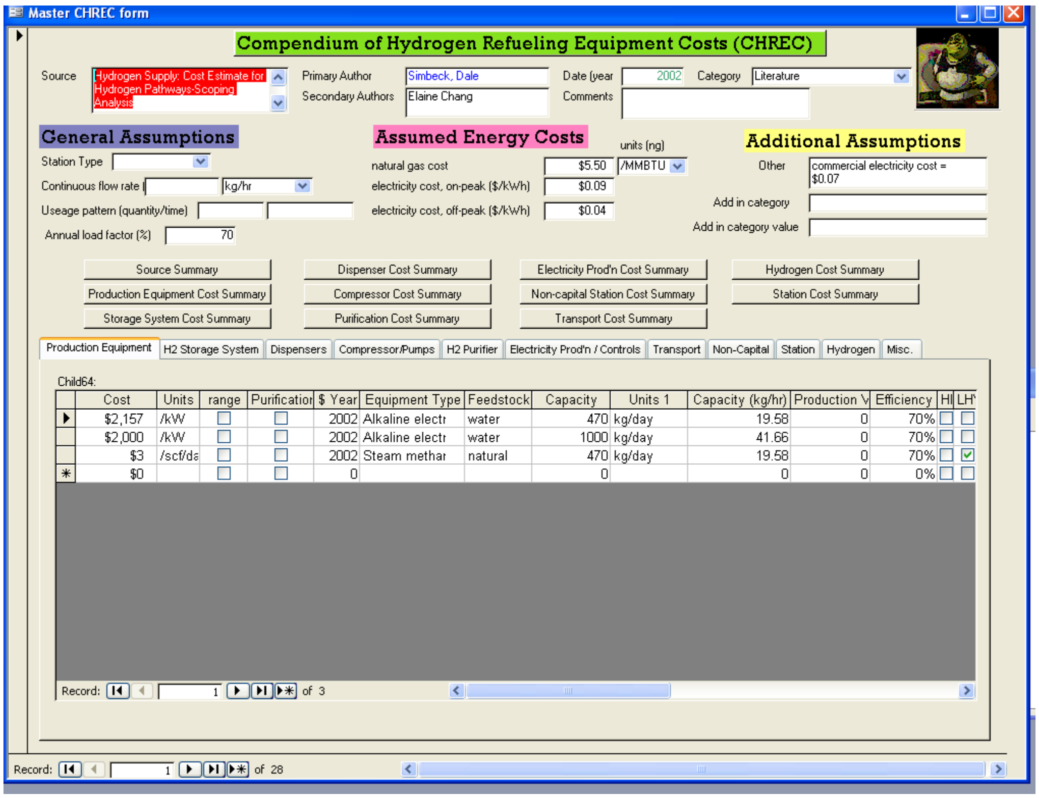
Category	**Description**
Cost	The cost as presented in the source
Total Cost ($2004)	Cost converted to 04 dollars using a deflator index

Normalized Cost (e.g. $2004/kg/hr)	Cost normalized to equipment capacity
Range	(yes/no) indicates if the data are from a range of values (if so, I use the range midpoint)
$ Year	The year the cost was determined (used to convert to 2004 dollars)
SourceID	The source from which the data were obtained
Page/fig/table	The page/figure/table in the source from which the data was directly taken
Equipment Type	The equipment technology (e.g. electrolysis, SMR, etc.)
Capacity	The size/flow rate of the unit (usually in kg or kg/hr)
Production Volume (units/yr)	The number of manufactured units/yr this cost is based on
General equipment characteristics (e.g. pressure, weight, volume, temperature, footprint)	Gives information on the key physical characteristics of the unit. CHREC usually standardizes these to metric units.
Equipment-specific characteristics	Gives information unique to the equipment type (e.g. hydrogen purity, # of compression stages, tank material)
Other equipment included in cost	Other equipment included in the cost estimate besides the main piece of equipment (e.g. valves, piping, controls, etc.)
comments	Any additional comments regarding the quote or the source

In this chapter's summary of cost information, only the most relevant information for each cost in the tables are included (due to space constraints). This usually includes capacity, production volume, 2004 cost, normalized cost, source and year. The tables of cost data for each equipment type can be found in Appendix F.

The graphical user interface of the CHREC database is shown below.

Figure 2-1: CHREC Interface



Sources

Data in CHREC are drawn from the following sources of literature:

Table 2-4: Literature Source Summary

Primary Author	Source	Year
Amos, Wade	Costs of Storing and Transporting	1998

	Hydrogen	
Myers, Duane B.	Cost and Performance Comparison Of Stationary Hydrogen Fueling Appliances	2002
Ogden, Joan	Review of Small Stationary Reformers for Hydrogen Production	2002
Padro, C.E.G.	Survey of the Economics of Hydrogen Technologies	1999
Simbeck, Dale	Hydrogen Supply: Cost Estimate for Hydrogen Pathways-Scoping Analysis	2002
Tax Policy Services Group of Ernst & Young	An Economic Analysis of Various Hydrogen Fuelling Pathways from CAN	2003
Thomas, C.E. (Sandy)	Distributed Hydrogen Fueling Systems Analysis	2001

A list of the companies that provided data in CHREC is presented in Appendix G. To protect the confidentiality of the company supplying cost data, equipment costs do not have a “source” associated with them.

The following table shows the additional information collected (where available) for each source.

Table 2-5: Associated Source Information/Assumptions

Category	**Description**
Source	Report name
Primary Author	Report author

Secondary Authors	Additional authors
Date (year xxxx)	Year the report was published or the cost info was obtained
Comments	Any additional information about the report's origin
Source Category	Classifies the source as either literature, an industry quote, or part of a station quote
Station type	If the cost info pertains to a specific station, this classifies the station according to how it makes/gets its hydrogen.
Continuous flow rate (design)	Station's hydrogen production/usage rate (kg/day)
Usage pattern (hrs/day, days/wk)	Predicted load profile for the station
Annual load factor (%)	Predicted load factor of the station
natural gas cost (commercial)	Assumed natural gas price used by the author/supplier
electricity cost, on-peak ($/kWh)	Assumed electricity price used by the author/supplier
electricity cost, off-peak ($/kWh)	Assumed electricity price used by the author/supplier
Other	Any additional info that would help the CHREC user
Add in category	If there should be another category of info, this allows the user to create one
Add in category value	Holds the data for the add-in category

1. Hydrogen Production

The tables below compare cost data from a variety of sources for electrolysis and natural gas reformation technologies. Capacity and production volume assumptions for the data are included since these are the most important factors that influence cost. The following table shows the additional information collected (where available) for each hydrogen production cost quote.

Table 2-6: Hydrogen Production Equipment Associated Cost Information

Category	**Description**
Cost	The cost as presented in the source
Total Cost ($2004)	Cost converted to 04 dollars using a deflator index
Cost ($2004/kg/hr)	Cost normalized to production capacity
range	(yes/no) indicates if the data are from a range of values (if so, I use the range midpoint)
Purification Included	(yes/no) indicates whether the cost of the purifier is included in the production equipment cost.
$ Year	The year the cost was determined (used to convert to 2004 dollars)
SourceID	The source from which the data was obtained
Page/fig/table	The page/figure/table in the source from which the data were directly taken
Equipment Type	The production technology (e.g. electrolysis, SMR, etc.)
Feedstock	The main feedstock of the unit (e.g. water, n.g.)
Capacity	The average hydrogen flow rate of the unit
Capacity (kg/hr)	Capacity standardized to kilograms per hour
Production Volume (units/yr)	The number of manufactured units/yr this cost is based on
Efficiency	Efficiency of the unit
HHV/LHV	Indicates whether efficiency is based on LHV or HHV
Operating Pressure	Operating pressure of the unit
Footprint (L x W x H)	Footprint of the unit
Other equipment included in	Other equipment included in the cost estimate besides storage

cost	tanks,
comments	Any additional comments regarding the quote or the source

Electrolysis

The following tables summarize electrolyzer cost data from literature and industry. Electrolyzers convert water and electricity into hydrogen and oxygen (vented) and are typically used for small stations that desire on-site hydrogen production capability. Note these electrolyzer costs include purification.

Table 2-7: Electrolyzer Costs - Literature

Capacity (kg/hr)	Prod'n Vol (units/yr)	Year	Total Cost ($2004)	Cost ($/kg/hr)	Cost ($/kW)	Primary Author
20	Not available (n/a/)	2002	$1,461,892	$74,663	$2,241	Simbeck, Dale
42	n/a	2002	$2,884,043	$69,228	$2,078	Simbeck, Dale
4.2	n/a	2004	$196,000	$47,252	$1,419	Tiax/DTI
4.2	n/a	2004	$222,000	$53,280	$1,600[8]	Tiax/DTI
0.11	100	1997	$8,186	$72,229	$2,169	DTI
0.226	100	1997	$11,919	$52,583	$1,579	DTI

[8] $1419/kWin for current technology (64% efficient electrolyzer LHV) about $1600/kW H2 out HHV

Table 2-8: Alkaline Electrolyzers (includes Purification) - Industry

Capacity (kg/hr)[9]	Production Volume (units/yr)	Year	Total Cost ($2004)	Cost ($/kg/hr)	$/kW
1.3	1	2004	$370,000	$274,379	$8,240
2.7	1	2004	$450,000	$166,852	$5,011
5.4	1	2004	$670,000	$124,212	$3,730
3.43	2	2002	$686,044	$200,013	$6,006
1	2	2002	$161,116	$161,116	$4,838
1.3	10	2004	$250,000	$185,391	$5,567
2.7	10	2004	$310,000	$114,943	$3,452
5.4	10	2004	$450,000	$83,426	$2,505
8.33	n/a	2004	$600,000	72,028	$2,163

The tables above show that the electrolyzers reported in the literature are much larger than the electrolyzers quoted by industry. The economies of scale associated with building larger units partially accounts for the large difference between the literature and station costs ($/kg/hr).

The following figure plots electrolyzer costs from both literature and industry.

[9] 1 kg H2/h = 142 MJ/3600 sec ~ 40 kW H2

Figure 2-2: Summary of Alkaline Electrolyzer Costs from Literature and Industry

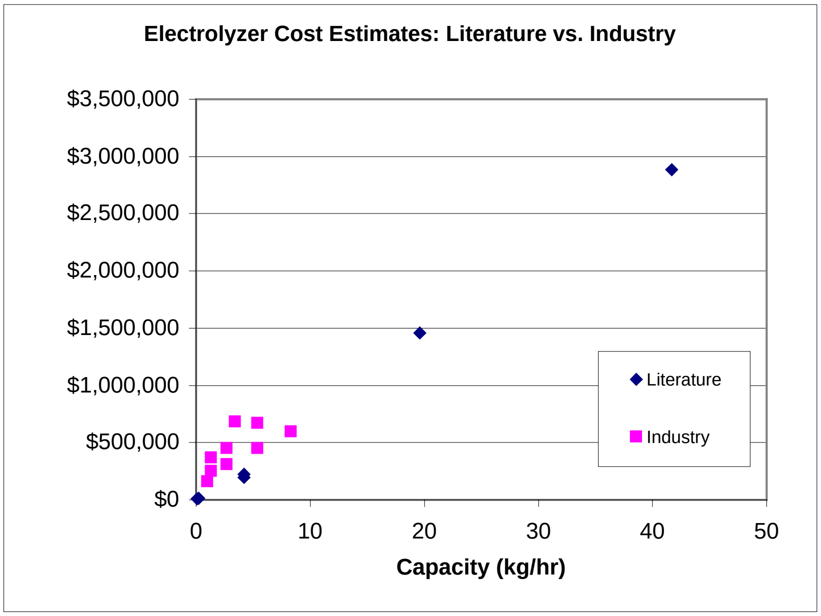
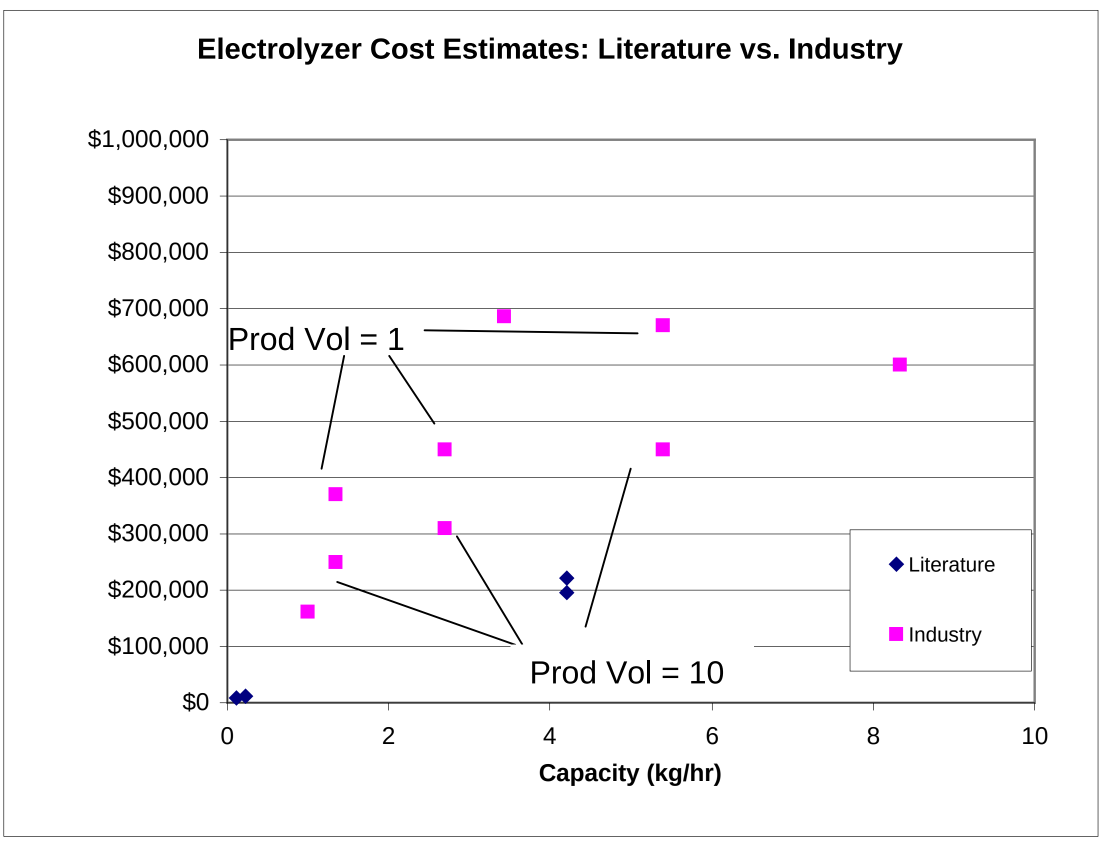


Figure 2-3: Electrolyzer Costs from Industry



Reformation

The following tables summarize steam methane reformer (SMR) cost data from both literature and industry. Reformers convert natural gas and water into hydrogen and carbon dioxide. This equipment is typically used for stations that have a large demand for hydrogen (>150 kg/day) and that desire on-site production capability.

Table 2-9: Summary of SMR Costs from Literature

Capacity (kg/hr)	Prod'n Vol (units/yr)	Purification Included	Total Cost ($2004)	Cost ($/kg/hr)	Cost ($/kW)	Primary Author	Year
4.8	250	No	$109,632	$22,888	$687	Myers, Duane B.	2002
4.8	250	No	$116,893	$24,403	$733	Myers, Duane B.	2002
19.6	n/a	No	$575,659	$29,400	$883	Simbeck, Dale	2002
20.8	1	No	$642,621	$30,851	$926	Thomas, Sandy	2001
20.8	100	No	$218,320	$10,481	$315	Thomas, Sandy	2001

20.8	10000	No	$74,092	$3,557	$107	Thomas, Sandy	2001
2	10000	Yes	$9,342	$4,671	$140	Thomas, Sandy	2001
8.3	10000	Yes	$12,025	$1,444	$43	Padro, C.E.G.	1999
16.7	10000	Yes	$16,754	$1,006	$30	Padro, C.E.G.	1999

The efficiency of these units varies from 70% to 75%, for some no efficiency was reported.

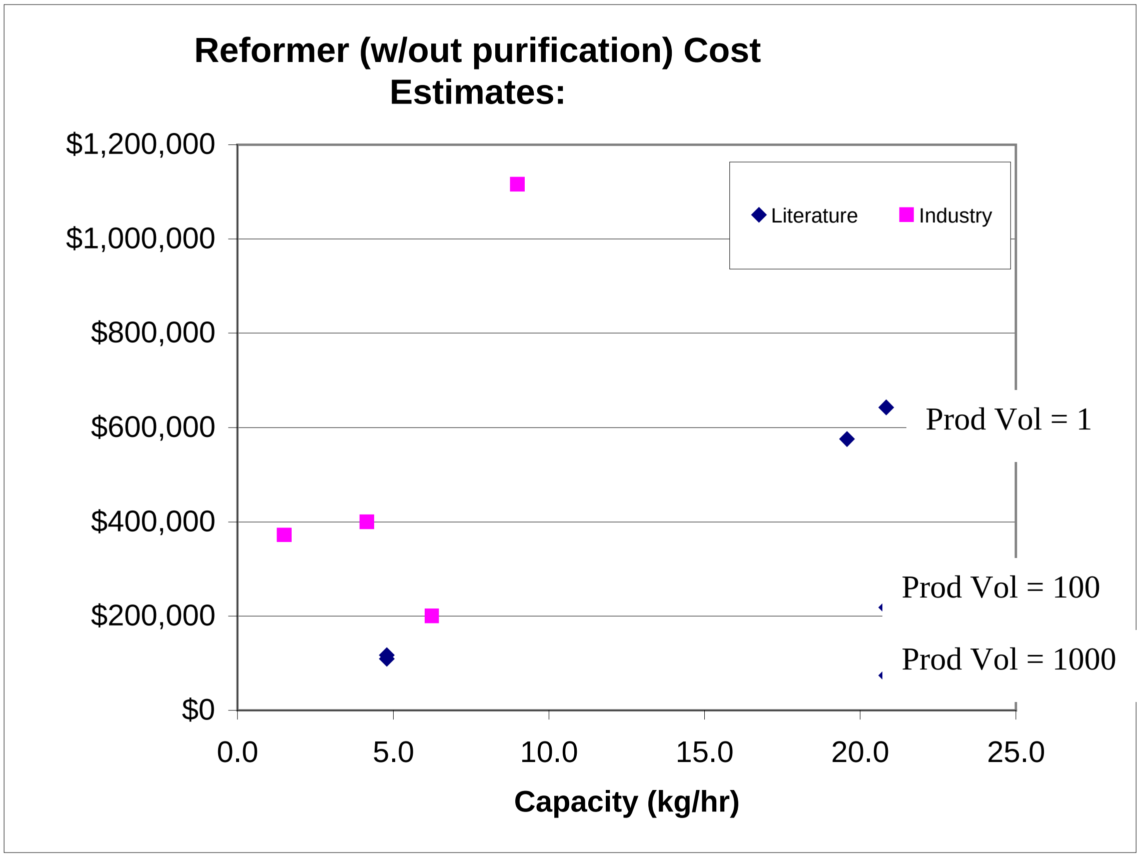
Table 2-10: Summary of SMR Costs from Industry

Capacity (kg/hr)	**Prod'n Vol (units/yr)**	**Purification Included**	**Total Cost ($2004)**	**Cost ($/kg/hr)**	**Cost ($/kW)**	**Year**
1.5	Low	No	$372,000	$248,000	$7,447	2004
4.16	Low	No?	$400,000	$96,154	$2,888	2004
6.25	Low	No	$200,000	$32,000	$961	2004
9	Low	No	$1,116,000	$124,000	$3,724	2004
1.32	4	Yes	$295,000	$223,485	$6,711	2004
5.08	Low	Yes	$286,093	$56,317	$1,691	2003

20.35	Low	Yes	$840,000	$41,278	$1,240	2004
33.07	Low	Yes	$900,000	$27,215	$817	2004

The following figure plots reformer cost against capacity for both industry and literature:

Figure 2-4: Steam Methane Reformer Costs[10]



[10] Large reformer costs estimates have been excluded from the curve since they distort the scale

2. Hydrogen Storage

Hydrogen Storage data collected in CHREC are presented in the following figures and tables. Table 2-11 shows the additional information collected (where available) for each hydrogen storage cost quote. Hydrogen for stations is typically stored either in high-pressure gas cylinders made of steel of composites, or as a liquid in special cryogenic tanks.

Table 2-11: Storage System Associated Cost Information

Category	**Description**
Cost	The cost as presented in the source
Total Cost ($2004)	Cost converted to 04 dollars using a deflator index
Cost ($/kg)	Cost normalized to storage capacity
Range	(yes/no) indicates if the data are from a range of values (if so, I use the range midpoint)
$ Year	The year the cost was determined (used to convert to 2004 dollars)
Source ID	The source from which the data were obtained
Page/fig/table	The page/figure/table in the source from which the data were directly taken
Capacity	The capacity of the storage system (SS) (how much hydrogen it can store)
Capacity (kg)	Capacity standardized to kilograms
Tanks (#)	The number of tanks in the SS

Tank Material	The material used for the storage tanks
Tank weight	The weight of the SS (without hydrogen)
Total Volume (L)	Volume of the SS in litres (by water)
Footprint (L x W x H)	Footprint of the SS
State	The physical state the hydrogen is stored (gas, liquid, solid)
Pressure	Storage pressure
Pressure (atm)	Storage pressure converted to atm units
Pressure (psi)	Storage pressure converted to psi units
Location/configuration	The location of the storage system (above/below ground, rooftop, etc.)
Operation type (casc/boost)	Indicates whether the system is cascade or booster type design
Cascades	Number of cascade banks in the storage system
Production Volume (units/yr)	The number of manufactured units/yr this cost is based on
Equipment included in cost	Other equipment included in the cost estimate besides storage tanks,
Comments	Any additional comments regarding the quote or the source

The following table shows the cost data collected from literature on gaseous storage systems:

Table 2-12: Gaseous Hydrogen Storage System Costs from Literature

Tank Material	Pressure (psi)	Capacity (kg)	Prod'n Vol (units/yr)	Total Cost ($2004)	Cost ($/kg)	Primary Author	Year
	2057	50	n/a	$20,789	$415	Simbeck, Dale	2002
	2900	227	n/a	$352,168	$1,551	Amos, Wade	1995

	5000		250	$45,303		Myers, Duane B.	2002
	5878	188	n/a	$126,848	$674	Simbeck, Dale	2002
	5878	400	n/a	$109,351	$273	Simbeck, Dale	2002
	7936	50	n/a	$109,143	$2,182	Simbeck, Dale	2002
		4.5	n/a	$4,105	$912	Amos, Wade	1995
		19.2	10000	$9,841	$512	Thomas, C.E.	2001
		200	1	$369,879	$1,849	Thomas, C.E.	2001
		200	100	$232,875	$1,164	Thomas, C.E.	2001
		200	10000	$165,586	$827	Thomas, C.E.	2001
		250	n/a	$211,075	$844	Amos, Wade	1995
		450	n/a	$620,033	$1,377	Amos, Wade	1995
		1240	n/a	$988,769	$797	Amos, Wade	1995
aluminum-composite	3600	3	10	$1,153	$384	Myers, Duane B.	2002
composite	6000	20	100	$13,559	$677	Thomas,	2001

(general)						C.E.	
composite (general)	6000	20	100	$12,833	$641	Thomas, C.E.	2001
composite (general)	7000	79	n/a	$41,665	$527	Myers, Duane B.	2002
composite (general)	8000	20	100	$11,915	$595	Thomas, C.E.	2001
composite (general)	8000	180	100	$208,243	$1,156	Thomas, C.E.	2001
fiber-composite	3500	24	1800	$15,382	$640	Myers, Duane B.	2002
fiber-composite	7000	10	250	$3,660	$365	Myers, Duane B.	2002
steel	6000		10	$13,513		Myers, Duane B.	2002
steel	7000	1	100	$758	$757	Myers, Duane B.	2002
steel	7000		1500	$13,513		Myers, Duane B.	2002

The following table shows the cost data collected from literature on liquid storage systems:

Table 2-13: Liquid Hydrogen Storage System Costs from Literature

State	Capacity (kg)	Total Cost ($2004)	Cost ($/kg)	Primary Author	$ Year
Liquid	270	$142,476	$527	Amos,	1995

				Wade	
Liquid	3,288	$155,000	$47	Simbeck, Dale	2002

Note the steep scale economies with liquid storage systems. The small system has a cost roughly the same as the large system though it is an order of magnitude smaller. The next table shows the cost data collected from industry on gaseous storage systems.

Table 2-14: Gaseous Hydrogen Storage System Costs from Industry

Capacity (kg)	Pressure (psi)	Tank Material	Equipment included in cost	Total Cost ($2004)	Cost ($/kg)	Year
5	5076	composite (general)		$6,016	$1,222[11]	2003
9	6526	composite (general)		$12,439	$1,397	2003
50	5000	steel		$55,000	$1,100	2003
50	5000	composite (general)		$55,000	$1,100	2003
60	6344	aluminum-composite		$102,176	$1,702	2003
60	6600	steel	Mounting	$72,762	$1,212	2003

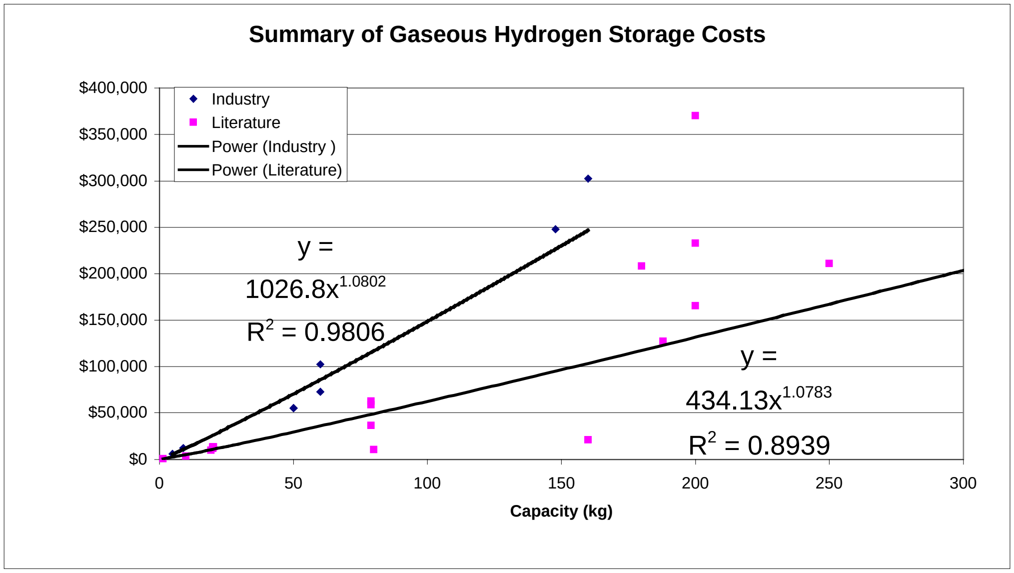
[11] This quote is for tanks only.

			equipment, valves, and piping			
148	6526	composite (general)	Cylinders, Cyl. Manifold, Priority Filling Panel	$247,964	$1,677	2003
160	6526	composite (general)	Cylinders, Cyl. Manifold, Priority Filling Panel	$302,740	$1,892	2003

Note: production volume assumptions are not available for this data

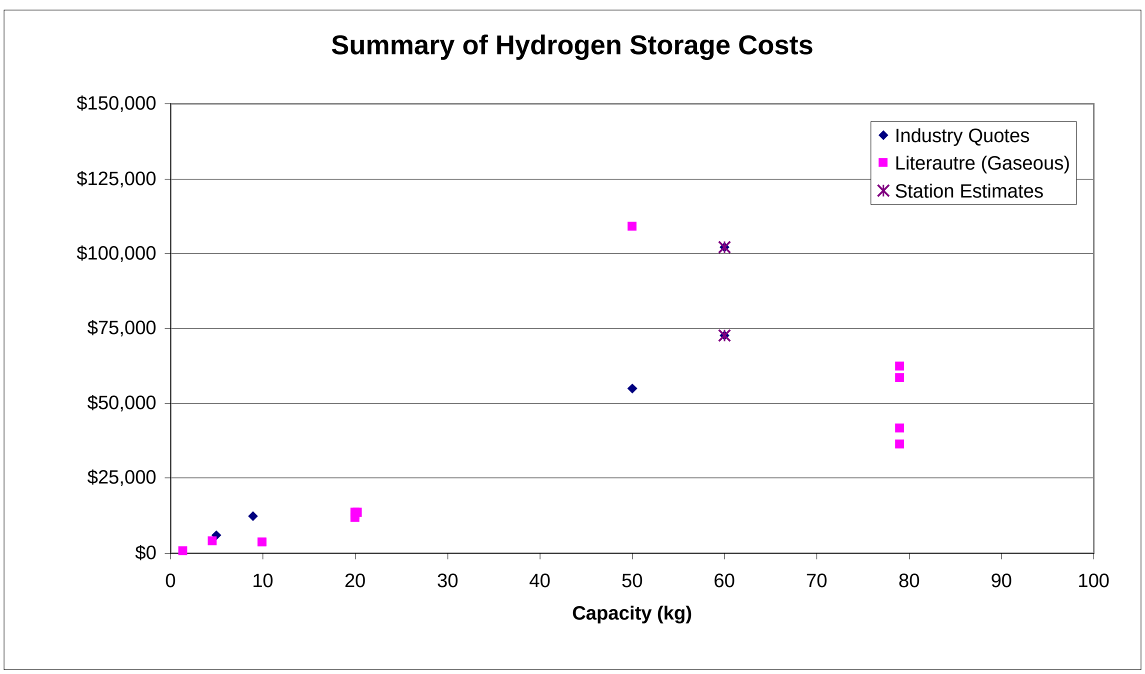
The following figure shows the difference in storage cost estimates between industry and literature for gaseous storage systems. The line fit to industry data estimates the relationship between cost and size

Figure 2-5: Gaseous Hydrogen Storage System Costs



The figure below shows just the cost of only the small-scale systems.

Figure 2-6: Small Scale Gaseous Hydrogen Storage System Costs (0-100kg)



3. Hydrogen Compression

This section summarizes the cost data of hydrogen compression technologies from a variety of sources. Compressors turn the low-pressure hydrogen emitted from electrolyzers and reformers into high-pressure hydrogen to enable high-pressure vehicle fill-ups. The following table shows the additional information collected (where available) for each hydrogen compressor cost quote.

Table 2-15: Compressor Associated Cost Information

Category	**Description**
Cost	The cost as presented in the source
Total Cost ($2004)	Cost converted to 04 dollars using a deflator index
Cost ($/kg/hr)	Cost normalized to compressor capacity
range	(yes/no) indicates if the data are from a range of values (if so, I use the range midpoint)
Dollar Year	The year the cost was determined (used to convert to 2004 dollars)
SourceiD	The source from which the data were obtained
Page/fig number(s)	The page/figure/table in the source from which the data were directly taken
Capacity	The normal flow rate of the compressor
Capacity (kg/hr)	Capacity standardized to kilograms per hour
Type	The compressor technology (reciprocating, diaphragm, etc.)
stages (#) of boost time (min)	The number of stages (or boost time) for the compressor
Power (kW)	Compressor power
Speed (rpm)	Average compressor motor operating speed
State	Gaseous or liquid

Inlet Pressure	Pressure at the compressor inlet
Outlet Pressure	Pressure at the compressor outlet
Outlet Pressure (psi)	Pressure converted to psi
compression ratio	Ratio of outlet pressure to inlet pressure
Footprint (L x W x H)	Footprint of the compressor unit
Weight	Weight of the unit
Prod'n Volume (units/yr)	The number of manufactured units/yr this cost is based on
Equipment included in cost	Other equipment included in the cost estimate besides storage tanks,
Other comments	Any additional comments regarding the quote or the source

The tables below summarize compressor cost estimates from various reports and industry. Note that most of the quotes contain limited information on compressor power, pressure ratio, number of stages, and efficiency, all of which impact cost. Typically, compressor electrical power is roughly 5-8% of the energy in the compressed hydrogen.[12]

Table 2-16: Compressor Costs from Literature

Type	Capacity (kg/hr)	Power (kW)	Outlet Pressure (psi)	Prod'n Volume (units/yr)	Total Cost ($2004)	Cost ($/kg/hr)	Primary Author	Year
reciprocating	5		7000	10	$62,368	$12,474	Myers, Duane B.	2002
reciprocating	5		7000	n/a	$26,427	$5,285	Myers, Duane B.	2002
reciprocating	5		7000	n/a	$22,860	$4,572	Myers, Duane B.	2002

[12] Ogden, J. (2004), Personal communication.

reciprocating	5		7000	n/a	$21,600	$4,320	Myers, Duane B.	2002
reciprocating	5		7000	n/a	$19,938	$3,988	Myers, Duane B.	2002
reciprocating	29.31	113	6000	75	$124,735	$4,256	Myers, Duane B.	2002
Unidentified	2			n/a	$4,940	$2,470	Thomas, C.E.	2001
Unidentified	2.08			n/a	$12,930	$6,216	Myers, Duane B.	2002
Unidentified	9		6000	n/a	$79,102	$8,789	Thomas, C.E.	2001
Unidentified	20.65	38	5882	n/a	$118,499	$5,738	Simbeck, Dale	2002
Unidentified	20.83			1	$99,984	$4,800	Thomas, C.E.	2001
Unidentified	20.83			100	$33,961	$1,630	Thomas, C.E.	2001
Unidentified	20.83			10000	$11,496	$552	Thomas, C.E.	2001
Unidentified	49		6000	n/a	$154,670	$3,157	Thomas, C.E.	2001
Unidentified	58		6000	n/a	$193,862	$3,342	Thomas, C.E.	2001
Unidentified		250		n/a	$241,857		Amos, Wade	1995
Unidentified				10000	$7,214		Padro, C.E.G.	1998
Unidentified				10000	$6,486		Padro, C.E.G.	1998

Table 2-17: Reciprocating Compressor Costs from Industry

Capacity (kg/hr)	Total Cost ($2004)	Cost ($/kg/hr)	Dollar Year
2.59	$43,936	$16,964	2003
2.59	$40,870	$15,780	2003
6.5	$119,000	$18,308	2004
7.63	$81,741	$10,713	2003
15.26	$122,611	$8,035	2003
30.53	$173,699	$5,689	2003
45.8	$209,461	$4,573	2003
45.8	$148,155	$3,235	2003
49.61	$214,570	$4,325	2003
61.06	$280,984	$4,602	2003
61.06	$235,005	$3,849	2003
61.06	$199,243	$3,263	2003
83.96	$214,570	$2,556	2003
122.13	$357,616	$2,928	2003
129.77	$408,704	$3,149	2003
183.2	$357,616	$1,952	2003

Table 2-18: Diaphragm Compressor Costs from Industry

Capacity (kg/hr)	Total Cost ($2004)	Cost ($/kg/hr)	Year

3.05	$62,327	$20,435	2003
6.87	$64,371	$9,370	2003
6.87	$62,327	$9,072	2003
7.6	$195,000	$25,658	2004
7.6	$125,000	$16,447	2004
13.74	$64,371	$4,685	2003
33.58	$91,958	$2,738	2003
61.06	$245,222	$4,016	2003

Note that there are large discrepancies in costs from one quote to another since they come from different manufacturers (price for 3.05 kg/hr vs. the 6.87 kg/hr compressor).

Table 2-19: Booster Compressor Costs from Industry

Capacity (kg/hr)	**Total Cost ($2004)**	**Cost ($/kg/hr)**	**Year**
0.38	$23,500	$61,843	2003
0.45	$10,218	$22,706	2003
1.06	$33,718	$31,810	2003
1.06	$25,544	$24,098	2003
4.58	$43,936	$9,593	2003
4.58	$10,218	$2,231	2003
10.68	$40,870	$3,827	2003
21.37	$56,197	$2,630	2003
22.9	$71,523	$3,123	2003
30.53	$86,850	$2,845	2003

Table 2-21 presents cost data on liquid hydrogen pumps.

Table 2-20: Liquid Pumps

Source Category	Capacity (kg/hr)	Power (kW)	Total Cost ($2004)	Cost ($/kg/hr)	Source	Dollar Year
Industry (actual)	61	n/a	$102,176	$1,673		2003
Industry (actual)	305	n/a	$60,284	$197		2003
Industry (actual)	61	n/a	$45,979	$753		2003
Literature	42	33.3	$259,865	$6,238	Simbeck, Dale	2002
Literature	20	15.7	$153,404	$7,835	Simbeck, Dale	2002

The following figures show the relationship between compressor cost and size for different compressor types from a variety of sources. The second figure uses a smaller capacity scale to more clearly depict the relationship for smaller compressors.

Figure 2-7: Reciprocating Compressor Costs

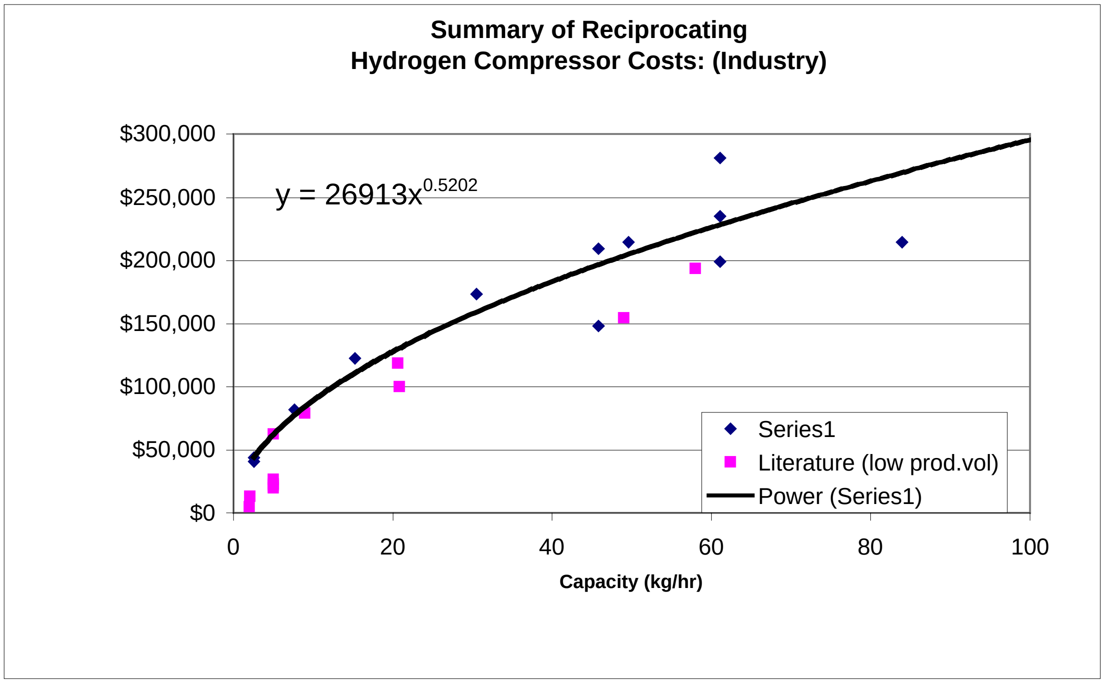


Figure 2-8: Diaphragm Compressor Costs

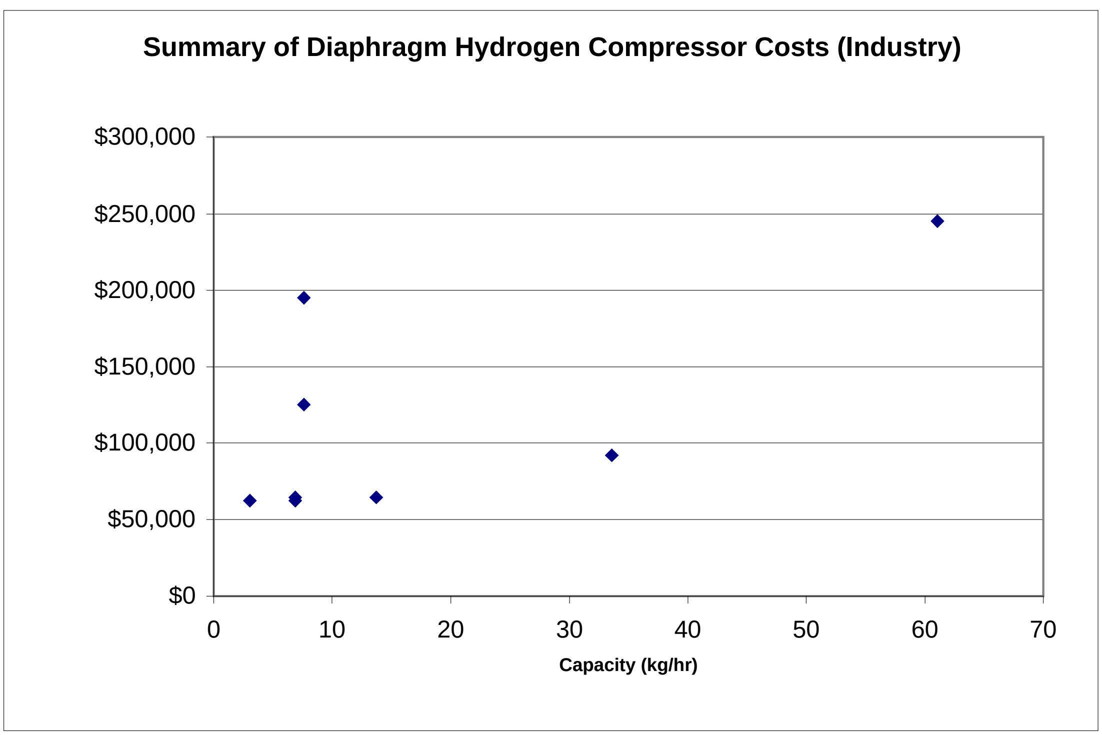
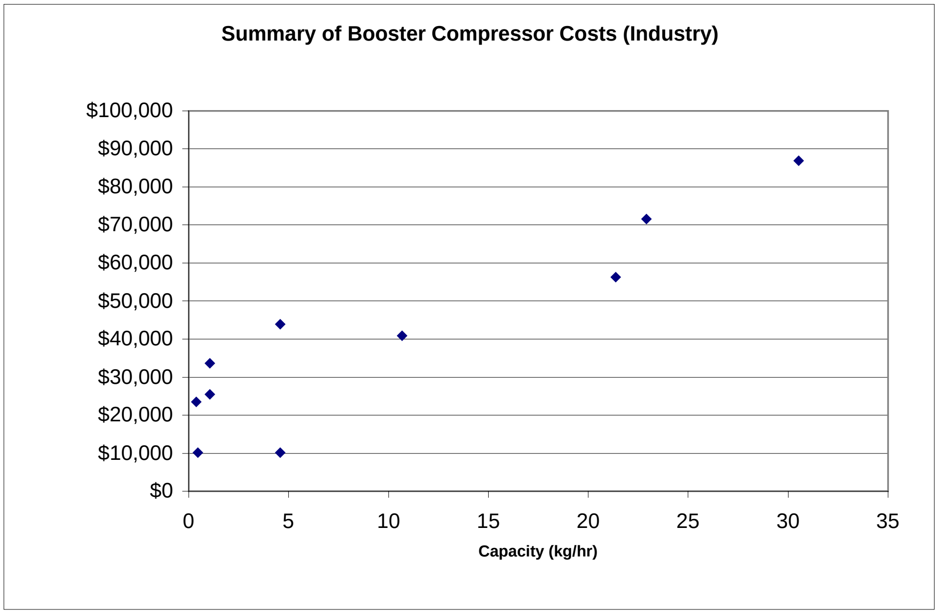


Figure 2-9: Booster Compressor Costs



4. Hydrogen Purification

Table 2-22 summarizes cost data from literature on different hydrogen purification technologies. Since there are so few data points, the information is not put into a figure. Table 2-23 show data collected from industry.

Table 2-21: Purification Equipment Cost from Literature

Source Category	Technology	Capacity (kg/hr)	Cost (2004$)	Cost ($/kg/hr)	Primary Author	Year
Literature		2	$2,816	$1,335	Thomas, Sandy	2001
Literature	PSA	4.79	$18,788	$3,773	Myers, Duane B.	2002
Literature	membrane	4.79	$25,551	$5,132	Myers, Duane B.	2002
Literature	PSA	4.79	$27,793	$5,582	Myers, Duane B.	2002

Table 2-22: Purification Equipment Cost from Industry

Technology	Capacity (kg/hr)	Production Volume (units/yr)	Purity requirement (%)	Cost (2004$)	Cost ($/kg/hr)	Year
PSA	3		99.999	100000	$33,333	2004
PSA	9		99.999	200000	$22,222	2004

Note the large difference between literature and industry costs for purifiers, nearly an order of magnitude different. One possible reason for this is technological immaturity and hence lack of industry data on PSA purification technology. The model uses the industry estimates in its calculations of purifier cost.

5. Dispensers

The following table summarizes the cost data on different hydrogen dispensers. Dispensers are used to deliver high-pressure hydrogen to the vehicles storage tank. This equipment is relatively immature technology, as evidenced by the low number of industry quotes.

Table 2-23: Hydrogen Dispenser Cost Summary from Literature

Pressure (psi)	Capacity (kg/hr)	Production Volume (units/yr)	Dispensers (#)	Total Cost ($2004)	Cost ($/disp)	Primary Author
	2	10000	1	$5,111	$5,111	Thomas, Sandy
		10000	1	$5,424	$5,424	Padro, C.E.G.
	20.83	10000	1	$9,281	$9,281	Thomas, Sandy
	20.83	100	1	$27,105	$27,105	Thomas, Sandy
	20.83	1	1	$79,945	$79,945	Thomas, Sandy

4997	48	0	2	$15,592	$7,796	Simbeck, Dale
	76.33	250	1	$21,517	$21,517	Myers, Duane B.
	300	0	1	$31,184	$31,184	Simbeck, Dale
Liquid	5000	0	2	$103,946	$51,973	Simbeck, Dale
Liquid	4000	0	2	$155,919	$77,960	Simbeck, Dale

Table 2-24: Hydrogen Dispenser Cost Summary from Industry

Pressure (psi)	Capacity (kg/hr)	Production Volume (units/yr)	Dispensers (#)	Total Cost ($2004)	Cost ($/disp)
5000	1197.6	0	1	$45,000	$45,000
5000	0.16	0	1	$20,789	$20,789
5000	0.16	0	1	$72,762	$72,762
5076		0	1	$81,741	$81,741

6. Electricity Production/Controls Equipment

The following tables summarize the cost data on different electricity production/controls equipment. Electricity production equipment is used to generate electricity on-sire. Control equipment is used to turn equipment on and off, control valves in the storage system lines, and ensure the entire system operates safely.

Table 2-25: Electricity Production/Control Cost Summary from Literature

Equipment Type	Power	Prod'n Vol (units/yr)	Total Cost ($2004)	Cost ($/kW)	Primary Author	Year
Combined Cycle Gas Turbine	0	0			Padro, C.E.G.	1999
Fuel Cell_MCFC	25	10000	$37,912	$1,516	Padro, C.E.G.	1999
Fuel Cell_MCFC	250	10000	$486,839	$1,947	Padro, C.E.G.	1999
Fuel Cell_MCFC	3250	10000	$4,837,617	$1,488	Padro, C.E.G.	1999
Fuel Cell_MCFC	100000	10000	$67,150,259	$672	Padro, C.E.G.	1999
Fuel Cell_PAFC	200	100	$671,503	$3,358	Padro, C.E.G.	1999
Fuel Cell_PEM	7	0	$62,754	$8,965	Padro, C.E.G.	1999
Fuel Cell_PEM	7	0	$28,609	$4,087	Padro, C.E.G.	1999
Fuel Cell_PEM	10	1	$33,962	$3,396	Padro, C.E.G.	1999
Fuel Cell_PEM	10	10000	$13,019	$1,302	Padro, C.E.G.	1999
Fuel Cell_PEM	100	1	$79,945	$799	Thomas, Sandy	2001
Fuel Cell_PEM	100	100	$48,727	$487	Thomas, Sandy	2001
Fuel Cell_PEM	100	10000	$29,742	$297	Thomas, Sandy	2001
Power electronics	0	1	$74,566		Thomas, Sandy	2001
Power electronics	0	100	$37,020		Thomas, Sandy	2001
Power electronics	0	10000	$18,352		Thomas, Sandy	2001
Power electronics	0	0			Padro, C.E.G.	1999

Table 2-26: Electricity Production/Control Cost Summary from Stations & Industry

Equipment Type	Power	Prod'n Vol (units/yr)	Total Cost ($2004)	Cost ($/kW)	Primary Author	Year
Control Panel	0	0	$30,653			2003
Control Panel	0	0	$54,664		Confidential	2003
Fuel Cell_PAFC	120	0	$107,285	$894	Confidential	2003
Fuel Cell_PEM	10	0	$25,000	$2,500	Nippon Oil	2004

7. Station Installation Costs

The following table summarizes data on the non-capital installation costs of various stations. These data were collected by reviewing reports and records from several station construction projects funded by the South Coast Air Quality Management District (SCAQMD). Each station funded by the SCAQMD was required to report the non-capital costs listed below. The LAX airport hydrogen station by Praxair and BP was one project in particular which provided a large amount of detailed data on station installation costs.[13] When one cost estimate included two expense categories, the information is put in two expense categories columns. The first table below organizes the data by station to show the various installation expenses for various types of stations. The second shows the data organized by expense to show how the expenses varied from station to station.

[13] Weinert, J. (2004)

Table 2-27: Installation Costs (by Station)

Station	Station type	Station Size (kg/hr)	Expense 1	Expense 2	Cost ($2004)	% of cap. Cost	Year
1	On Site Electrolysis	1.3	Training		$5,109		2003
1	On Site Electrolysis	1.3	Permitting		$15,326		2003
1	On Site Electrolysis	1.3	Engineering/Design		$17,370		2003
1	On Site Electrolysis	1.3	Site Preparation		$34,740		2003
1	On Site Electrolysis	1.3	Comissioning		$36,272		2003
2	On Site Electrolysis		Site Preparation		$117,502		2003
3	On Site Electrolysis	1	Permitting		$10,395	2%	2002
3	On Site Electrolysis	1	Delivery		$12,474	3%	2002
3	On Site Electrolysis	1	O&M (non-fuel)		$13,513	3%	2002
3	On Site Electrolysis	1	Safety/HazOps		$31,184	7%	2002
3	On Site Electrolysis	1	Comissioning		$49,478	12%	2002
3	On Site Electrolysis	1	Labor		$51,973	12%	2002
3	On Site Electrolysis	1	Engineering/Design	Permitting	$69,644	16%	2002
3	On Site Electrolysis	1	Site Preparation		$72,243	17%	2002
3	On Site Electrolysis	1	Installation		$111,430	26%	2002
			Station Capital Cost		**$428,500**	**98%**	
4	On Site Electrolysis	3	Labor		$11,674	1%	2003
4	On Site Electrolysis	3	Comissioning		$17,868	2%	2003
4	On Site Electrolysis	3	Permitting		$45,979	4%	2003
4	On Site Electrolysis	3	O&M (non-fuel)		$64,371	6%	2003
4	On Site Electrolysis	3	Site Preparation		$73,185	7%	2003
4	On Site Electrolysis	3	Installation		$88,745	9%	2003
			Station Capital Cost		**$1,026,000**	**29%**	
5	Delivered LH2		Engineering/Design	Installation	$82,354	**26%**	2003

			Station Capital Cost		**$312,760**		
6	Renewable Electrolysis		Site Preperation	Permitting	$200,000		

Table 2-28: Installation Costs (by Expense)

Station size (kg/hr)	Station type	Expense 1	Expense 2	Cost ($2004)	Cost ($/kg/day)	Year
3	On Site Electrolysis	Commissioning		$17,868	$248	2003
1.3	On Site Electrolysis	Commissioning		$36,272	$1,163	2003
1	On Site Electrolysis	Commissioning		$49,478	$2,062	2002
				Average	**$1,157**	
1.3	On Site Electrolysis	Delivery		$12,474	$400	2002
1.3	On Site Electrolysis	Engineering/Design		$17,370	$557	2003
3	On Site Electrolysis	Engineering/Design	Permitting	$69,644	$967	2002
n/a	Delivered LH2	Engineering/Design	Installation	$82,354		2003
3	On Site Electrolysis	Installation		$88,745	$1,233	2003
1.3	On Site Electrolysis	Installation		$111,430	$3,571	2002
				Average	**$2,402**	
3	On Site Electrolysis	Labor		$11,674	$162	2003
1.3	On Site Electrolysis	Labor		$51,973	$1,666	2002
				Average	**$914**	
1.3	On Site Electrolysis	O&M (non-fuel)		$13,513	$433	2002
3	On Site Electrolysis	O&M (non-fuel)		$64,371	$894	2003
				Average	**$664**	
1.3	On Site Electrolysis	Permitting		$10,395	$333	2002
1.3	On Site Electrolysis	Permitting		$15,326	$491	2003
3	On Site Electrolysis	Permitting		$45,979	$639	2003
				Average	**$488**	
1.3	On Site Electrolysis	Safety/HazOps		$31,184	$999	2002
1.3	On Site Electrolysis	Site Preparation		$34,740	$1,113	2003
1.3	On Site Electrolysis	Site Preparation		$72,243	$2,315	2002
3	On Site Electrolysis	Site Preparation		$73,185	$1,016	2003
n/a	On Site Electrolysis	Site Preparation		$117,502		2003
n/a	Renewable Electrolyzer	Site Preparation	Permitting	$200,000		2004
				Average	**$1,482**	
1.3	On Site Electrolysis	Training		$5,109		2003

Installation costs are typically calculated as a certain percentage of the capital equipment. In fact, one industry representative estimates that station installation costs represent ~118% of the station capital cost (54% of total station cost).[14] The report by NAS/NRC uses the following percentages based on what is typically experienced in the fuels industry and comments on how these values may differ for hydrogen stations:

Table 2-29: Simbeck Estimates for Installation Costs of Hydrogen Stations

Installation Cost Categories	**% of capital cost**	**$ (for on-site 480 kg/day NG station)**	**Typical %**
General Facilities	20%	$230,000	20-40% typical, should be low for this
Engineering Permitting & Startup	10%	$120,000	10-20% typical, low eng after first few
Contingencies	10%	$120,000	10-20% typical, low after the first few
Working Capital, Land & Misc.	5%	$60,000	5-10% typical, high land costs for this
Total	**45%**		

The non-capital installation costs presented in the rows above are for an on-site 480 kg/day natural gas reformation station. The table below shows how these numbers compare to industrial data,

Table 30: Station Installation Cost Comparison

Station Source	Installation Cost as percentage of Station Capital Cost	Station Type
Simbeck and Chang	45%	Reformer
Chevron Texaco	117%	Reformer
Station 3	98%	Electrolyzer

[14] Chevron-Texaco, "Hydrogen Infrastructure and Generation", Information submission for California Hydrogen Highway working group, July 2004

Station 4	29%	Electrolyzer
Station 5	26%	Liquid Hydrogen

As shown in the table, installation costs for stations appear to be highly variable. The variability is most likely due to site specific factors, although stations 4 and 5 are most likely artificially low since the data on installation costs for these stations is incomplete.

Conclusions

Data have been collected from a variety of literature and industry sources. This information has been organized into the CHREC database for means of comparison. In general, literature data are more optimistic in their cost estimates of hydrogen equipment. There is a limited amount of data on the non-capital costs of hydrogen station installation. Only Simbeck and Chang (2002) quantify the non-capital installation costs which are given as a certain percentage of equipment capital cost. In general, the installation costs for the stations reported in this chapter bracket Simbeck and Chang estimates and show high variability (26%-117% of capital costs).

In the next chapter, the industry data are normalized and scaled for size and production volume for use in the Weinert Hydrogen Station Cost Model.

3. The Hydrogen Station Cost Model (HSCM)

Introduction

This chapter introduces and describes the Hydrogen Station Cost Model (HSCM). The HSCM is intended to be a general tool for analyzing hydrogen refueling station economics. In Chapter 4, the model is applied to analyze costs for the California Hydrogen Highway Network.

The HSCM was created to achieve the following two goals:

1. Obtain realistic near term hydrogen station costs
2. Identify important factors that affect station cost and quantify their effect.

This provides insight into the difficult questions surrounding the hydrogen infrastructure expansion, such as, how many stations, how big, what kind of stations should they be (e.g. electrolysis vs. reformation), and what specific policies will help drive hydrogen costs down.

The HSCM calculates hydrogen station costs for seven different station types over a range of sizes. For each station type, the HSCM sizes the required equipment according to the design rules described below. It then computes the total installed station capital cost ($), operation and maintenance costs ($/year) and levelized hydrogen cost ($/kg).

The following station types are considered in this model:

Table 3-1: Station Types and Sizes

Station Type	**Capacity Range (kg/day)**
1. Steam methane reformer	100-1000
2. Electrolyzer, using grid or intermittent electricity	30-100
3. Mobile refueler	10
4. Delivered liquid hydrogen	1000
5. PEM/Reformer energy station	1000
6.. High temp. fuel cell energy station	91[15]
7.. Pipeline delivered hydrogen station	100

To put these station sizes in perspective, one kg of hydrogen has about the same energy content as one gallon of gasoline. A hydrogen fuelling station that delivers 100 kg of hydrogen per day delivers enough energy in a gasoline equivalency to fuel about 5 gasoline SUV's, 10 gasoline hybrids or 20 hydrogen fuel cell vehicles (each carrying 5 kg of hydrogen) per day. Today's typical gasoline stations serve several hundred cars per day.

[15] This size was selected because the costs provided by Fuel Cell Energy for this type of station are for a 91 kg/day unit.

Station Designs and Assumptions

Hydrogen stations have a great degree of flexibility in design (e.g. onsite production vs. delivered hydrogen, compressor type, storage pressure). The model makes the following assumptions regarding equipment, site layout, station design, operation and cost.

Equipment Assumptions:

The stations store hydrogen at 6,250 psi to serve fuel vehicles with 5,000 psi on-board vehicle storage. The model assumes the stations will use the following equipment:

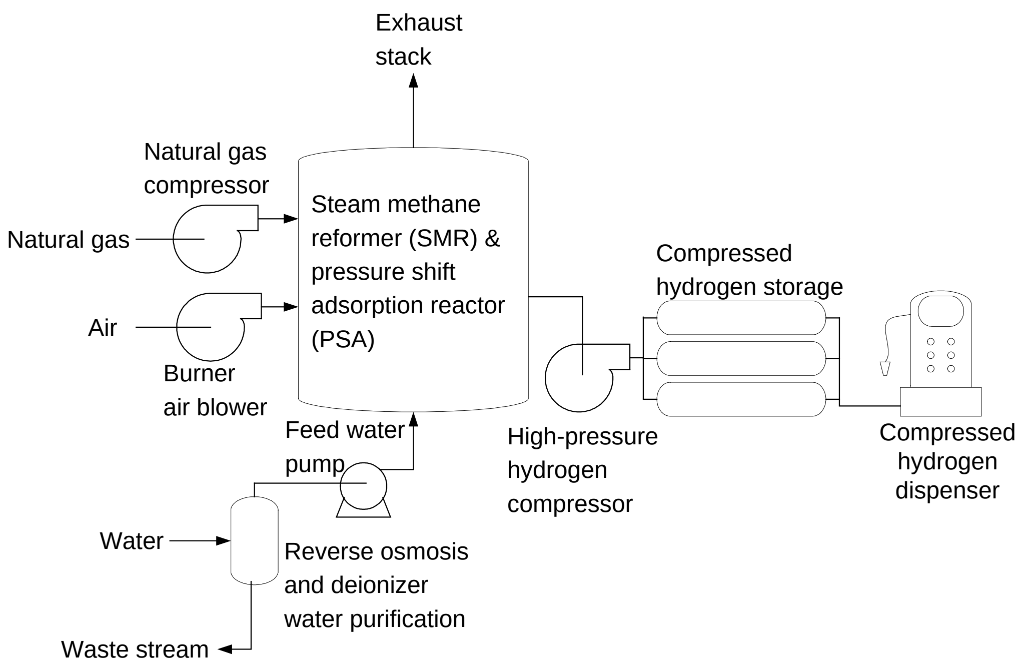
Table 3-2: Station Equipment

<table>
<tr><th>Station Type</th><th>Key Technology</th><th>Additional components</th></tr>
<tr><td>Natural gas reformer</td><td>Steam methane reformer, Pressure Swing Adsorption</td><td rowspan="4">Reciprocating-piston compressor (6,250 psi), cascade storage/dispensing</td></tr>
<tr><td>Electrolyzer</td><td>Alkaline Electrolyzer</td></tr>
<tr><td>Pipeline delivery of hydrogen</td><td>Purifier</td></tr>
<tr><td>Energy station (ES)</td><td>Fuel cell, reformer, shift reactor (for high temp ES), purifier</td></tr>
<tr><td>Delivered LH_2 Tanker Truck</td><td>Cryogenic storage tank, 6,250 psi cryo-pump, Evaporator</td><td>Gaseous cascade storage/dispensing</td></tr>
</table>

Mobile refueler	Integrated refueler trailer	Cascade storage/dispensing (no compressor)

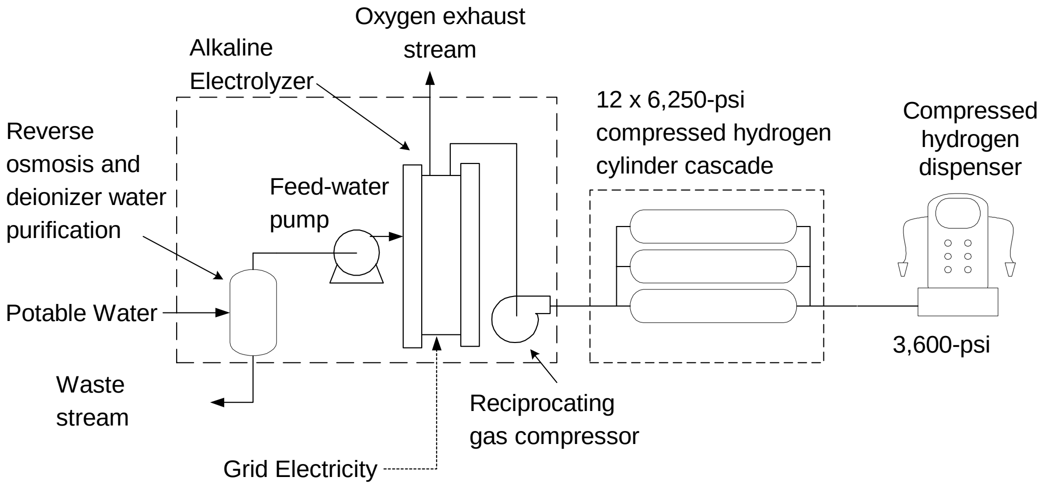
The following figures show how these components are connected together to create a hydrogen station:

Figure 3-1: Reformer Station



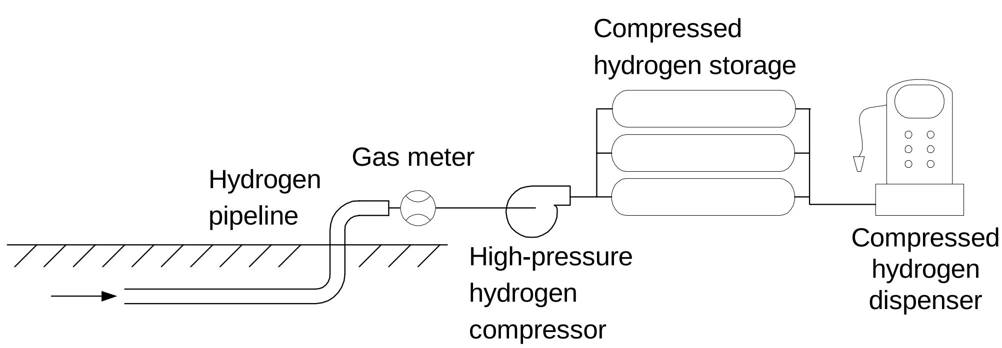
Reformer Station: For this type of station, the natural gas compressor, blower, and water pump are integrated with the SMR and PSA as one unit.

Figure 3-2: Electrolyzer Station



Electrolyzer Station: This station can use either grid power or renewable electricity to produce its hydrogen. For this station, we assume either grid electricity or photovoltaic electricity provides power. We assume the photovoltaics cost $3/$W_{peak}$, and the solar array is sized to provide ~17% of the total electricity to make hydrogen when the station operates at 50% capacity.[16] The rest of the electricity comes from grid power.

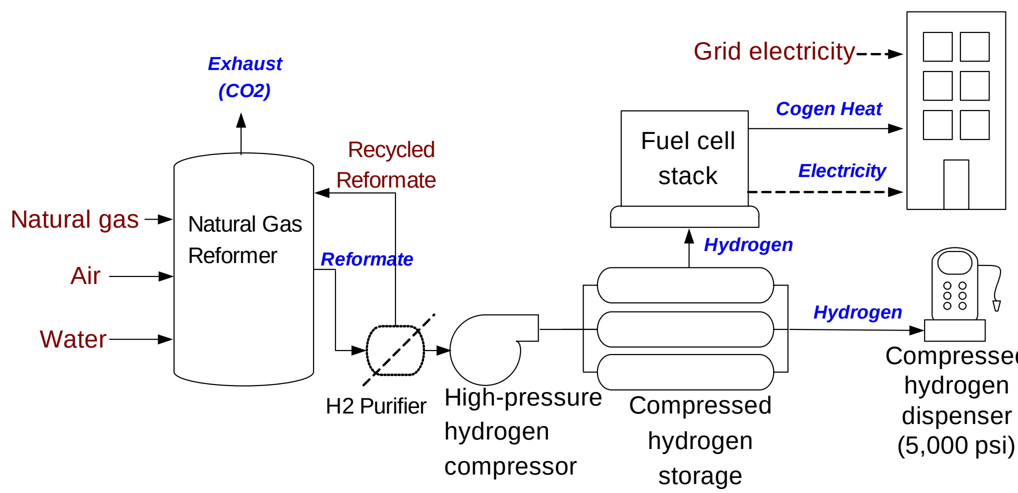
Figure 3-3: Pipeline Hydrogen Station



[16] These assumptions are from TIAX, LLC and are based on an assumed an average insolation of 1 kW/m^2 and $3000/kW capital cost for the photovoltaics system.

Pipeline Station: Stations built near an existing hydrogen pipeline have the advantage of a reliable low-cost source of hydrogen and eliminate the need for on-site production or truck delivery. A hydrogen pipeline already exists between Torrance and Long Beach offering the opportunity to site several stations along this line.

Figure 3-4: Energy Station

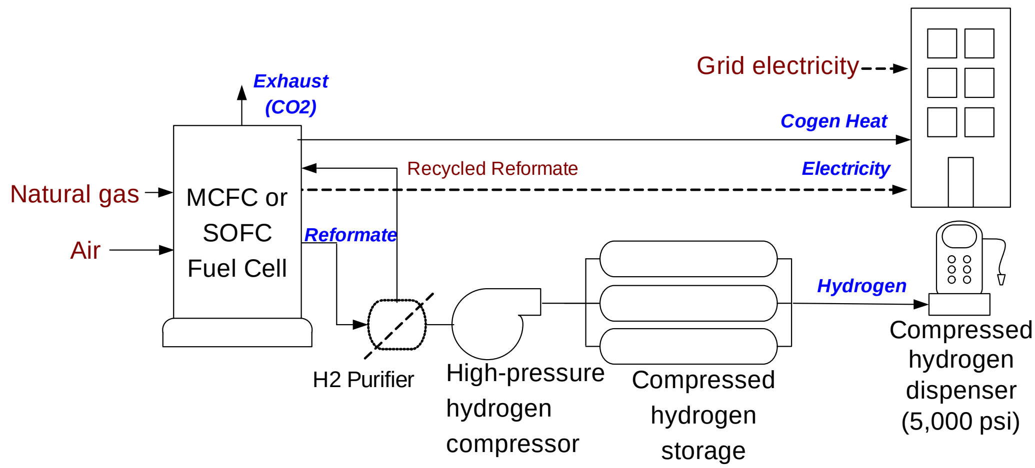


Energy Station: this type of station combines on-site hydrogen fuel production with electricity production using either a fuel cell or H2 ICE. By doing so, the station co-produces hydrogen fuel, electricity, and heating/cooling, yielding three sources of revenue. This type of station is best sited at a facility with large or premium (uninterruptible) electricity loads, such as a hospital, or manufacturing facilities with a steady merchant hydrogen demand.

Evaluating the economics of an energy station is a complex due to the many possible ways to operate the station. For the PEM/Reformer energy station, we assume the fuel cell provides some peak-shaving capability and runs whenever available hydrogen is not required for vehicle fueling. We also assume the reformer runs at 100% capacity factor and that any hydrogen not sold to vehicles is converted into electricity and heat for the building. The fuel cell is sized to be able to process all excess hydrogen from the reformer when hydrogen demand for vehicles is at its lowest. If there are relatively few vehicles using the station, the fuel cells runs a greater fraction of the time.

We assume the electricity produced by the fuel cell sells at a 25% premium ($0.125/kWh vs. $.1/kWh) since it will be used for demand reduction and emergency back-up. For the equipment sizes selected, there will be ample hydrogen available for electricity demand reduction (peak-shaving) if needed. While there are alternative ways to operate an energy station, we have chosen these assumptions for simplicity. The cost of the fuel cell includes a subsidy of $1500/kW from the California Public Utilities Commission (CPUC).

Figure 3-5: High-temperature Fuel Cell Energy Station

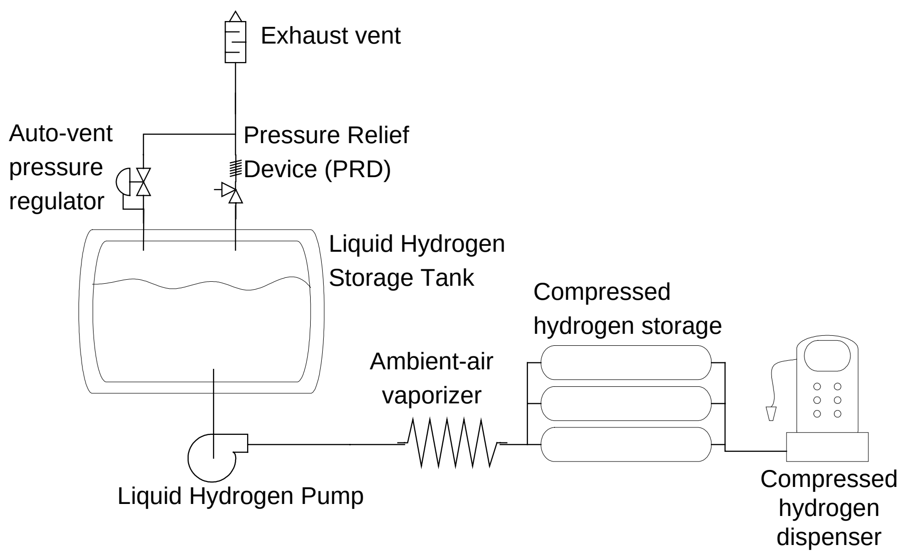


The figure above shows a different energy station configuration considered in the analysis, a high-temperature fuel cell (HTFC) energy station. The main difference between the two is that this energy station uses a HTFC instead of a PEMFC. This eliminates the need for a separate reformer since the fuel cell internally reforms natural gas into hydrogen.

This station was analyzed as a 'best-case scenario', low-cost station option. Optimistic assumptions are made for this station that give it an unfairly low hydrogen cost compared to the other six station types. The model assumes the HTFC energy station operates at a constant output with a 100% capacity factor. This assumption is made because it is more difficult to turn down this equipment and because we also assume there is a steady industrial demand for the hydrogen produced. In both energy stations, the hydrogen demand for power production allows for much higher utilization of the energy station asset. In the case of high-temp fuel cell energy stations, these stations would be sited at either commercial and/or industrial locations with an existing industrial hydrogen demand.

The hydrogen generated by the energy station would be used primarily to displace bottled hydrogen used at the facility, with a dispensing station available to fuel vehicles when and if needed. "Since the costs of producing hydrogen using this technology (~$5.60/kg) is lower than the bottled hydrogen costs (~$6-7.00/kg) it displaces, this specialty station has the potential of being self-funded from the revenues produced by the sale of electricity, hydrogen and heat to the host facility."[17] Although the high-temperature fuel cell option looks promising economically, this type of unit has not yet been built and tested as an integrated system[18]. Thus, the costs presented in the report are expected costs and not field-tested costs.

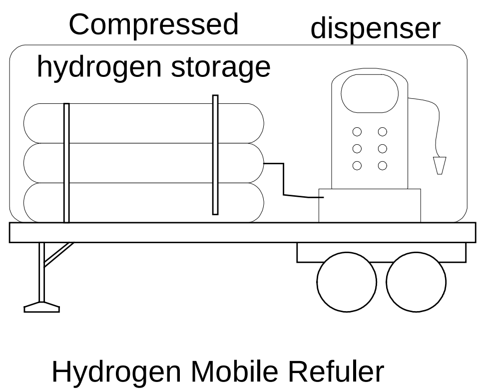
Figure 3-6: Liquid Hydrogen Station



Liquid Hydrogen Station: These types of stations use a cryogenic hydrogen pump to conserve compression energy by pumping a liquid rather than compressing a gas.

[17] Torres, S., (2004) Fuel Cell Energy Co.
[18] According to Fuel Cell Energy, building this type of system involves the integration of two already commercially available technologies (fuel cell itself and PSA H2 purification system)

Figure 3-7: Mobile Refueler Station



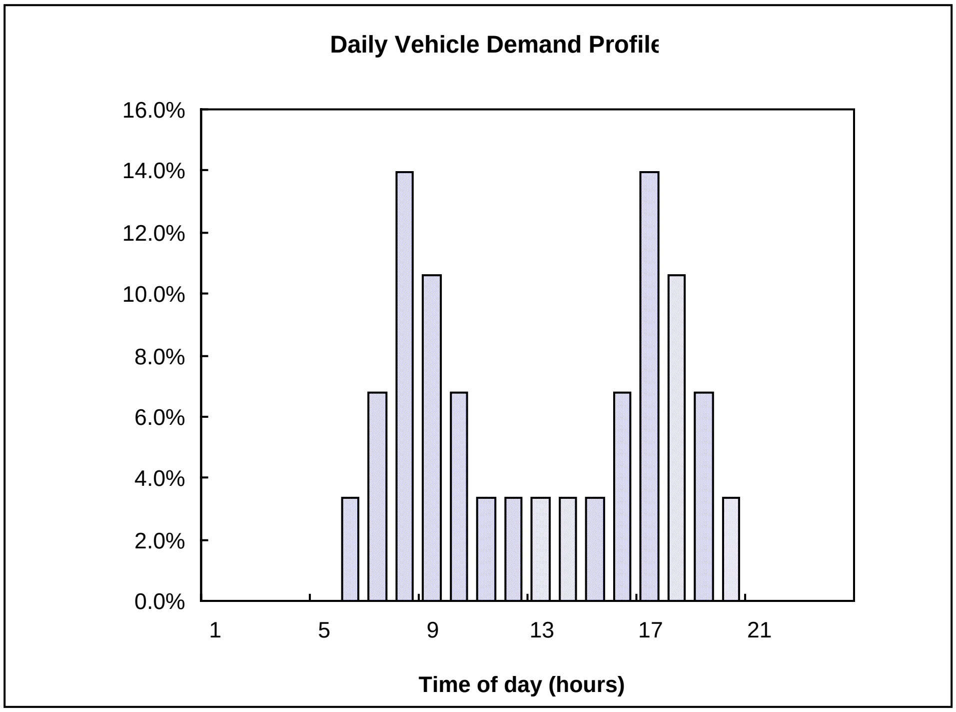
Mobile Refueler Station: This is the simplest type of station. It consists only of high-pressure gaseous hydrogen storage and dispenser. If equipped with photovoltaics and a battery, these units require no site connection and can be completely mobile and self-sustaining.

Demand profile for dispensing hydrogen

In sizing equipment, it is assumed that the station dispenses hydrogen according to an hourly demand profile shown in the figure below. This is based on the vehicle demand profile used by the DOE's Hydrogen Analysis group (H2A)[19]. Refueling takes place during the day, with peaks in the morning and late afternoon/early evening.

[19] Lasher, S. (2004) DOE Hydrogen Analysis Team (H2A), presentation at the National Hydrogen Association Annual Conference

Figure 3-8: Vehicle Demand Profile



Equipment Sizing

Based on the demand profile above, the compressor and storage equipment are sized to be able to a) fuel 40% of the daily-expected vehicle load in 3 hours[20] and b) store the output of the production equipment overnight since reformers must operate continuously. We use rules for sizing compressors and storage systems for hydrogen stations based on studies by TIAX LLC (see Appendix H for complete calculations).

The production systems for stations with on-site generation are sized assuming a constant hydrogen output rate. For example, a system that required 100 kg/day of vehicle fuel is sized for a capacity of 4.17 kg/hr. The compressor size must match the production

[20] Lasher, S. (2004) "Forecourt Hydrogen Station Review", DOE Hydrogen Analysis Team (H2A), presentation at the National Hydrogen Association Annual Conference

equipment capacity since there is no storage buffer between these two systems. The storage system must be large enough to store hydrogen generated throughout the night while still meeting daily vehicle demand.

For stations with delivered hydrogen, there is more flexibility in choosing compressor size, however there is a trade-off between compressor and storage size. Using a larger compressor allows for smaller storage and vice-versa. The table below shows the compressor and storage size for each station type.

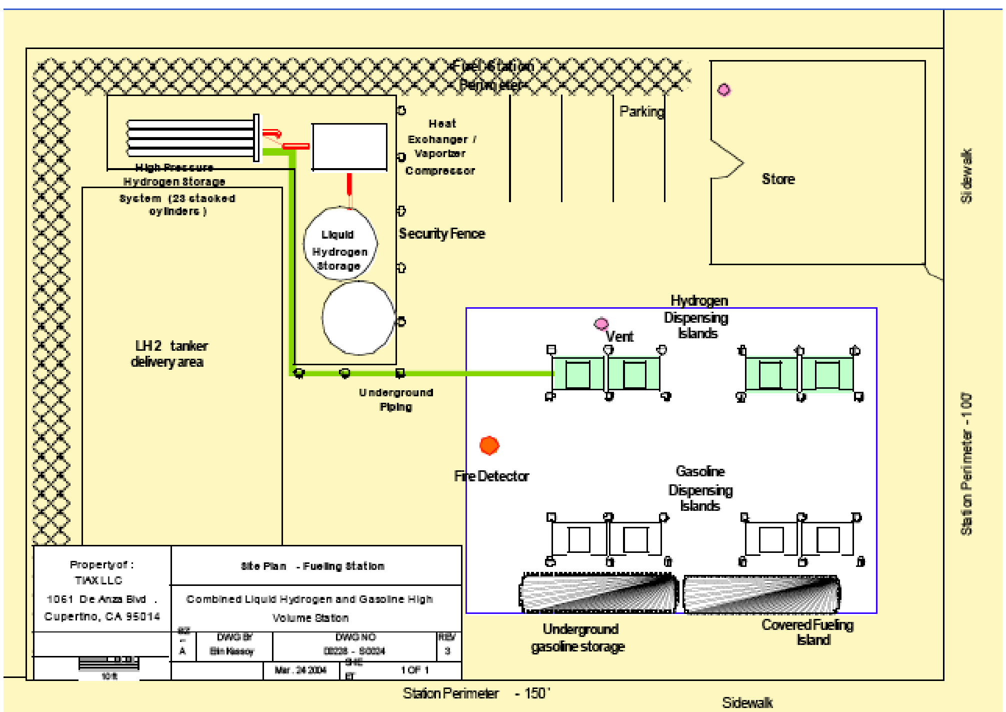
Table 3-3: Storage and Compressors Sizes By Station Type

Station Type	**Capacity Range (kg/day)**	**Storage (kg)**	**Compressor Size (kg/hr)**
1. Steam methane reformer	100-1000	135-1354	4.2-42
2. Electrolyzer, using grid or intermittent electricity	30-100	39-130	1.3-4.2
3. Mobile refueler	10	75	n/a
4. Delivered liquid hydrogen	1000	667 (gaseous)	100
5. PEM/Reformer energy station	100	32	4.2
6. High temp. fuel cell energy station	91	96	3.8
7. Pipeline delivered hydrogen station	100	35	13

Refueling Station Siting Assumptions

The model can take into account several options for siting a station (e.g. co-locate with gasoline station, bus-yard, or office building with vehicle fleet). For the purposes of the H2Hwy Net analysis, the model assumes H_2 stations are integrated into existing gasoline stations with 8 dispensers total. Small stations (≤100 kg/d) use one gaseous H_2dispenser and large stations (1000 kg/d) use three gaseous H_2 dispensers. The following diagram provides an example of LH2/gasoline station layout.

Figure 3-9: Integrated hydrogen/gasoline station layout[21]



21 Diagram provided by Erin Kassoy of Tiax, LLC

Additional Assumptions

Economic Assumptions: The table below presents the key economic assumptions used in the model. These assumptions can be modified when conducting sensitivity and scenario analyses.

Table 3-4: Model Economic Variables

Natural Gas Price ($/MMBtu)	$7.0
Electricity Price ($/kWh)	$0.10
Capacity Factor (%)	47%
Equipment Life	15 yrs
Return on Investment	10%
% of labor allocated to fuel sales	50%
Real Estate Cost ($/ft^2/month)	$0.50
Contingency (% of total capital cost)	10%

Energy Prices: The natural gas price is based on the Energy Information Administration's projected price of $7.09/MCF for California industrial users in 2010.[22] The electricity price is based on a California Energy Commission projection of $0.0948/kWh for California industrial users in 2010.[23] The 50% of labor allocated to fuel sales is based on a Tiax estimate.[24]

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22 www.eia.doe.gov/oiaf/aeo/index.html
23 www.energy.ca.gov/electricity/rates_iou_vs_muni_nominal/industrial.html
24 Personal communication with Stefan Unnasch, August 2004.

Capacity Factor is defined as actual average consumption divided by the rated output of the station. For example, a reformer is sized to be able to produce 100 kg/day, however, average hydrogen consumption at the station is 47 kg/day, yielding a 47% capacity factor. A 47% capacity factor is used throughout the analysis unless specified otherwise. 47% is based on the H2Hwy Team's demand scenario C which calls for 250 stations and 20,000 vehicles. While other hydrogen cost studies use high capacity factors (e.g. H2A uses 70%, NAS uses 90%), 47% is chosen as baseline capacity factor for this analysis. 47% represents what is realistically achievable for hydrogen stations in the near term based on industry experiences with natural gas stations. Few natural gas stations have yet to achieve a 47% capacity factor, and some stations are much lower.[25]

Equipment Life denotes the useful life of the equipment. It is assumed that at the end of *N* years, the equipment has no salvage value. *N* is also the recovery period of the investment.

Return on Investment is the assumed interest rate on the borrowed capital for installation and equipment. It takes into account the opportunity cost of the borrowed capital. ROI and Equipment life is used to calculate the capital recovery factor (or "fixed charge rate"). The formula for calculating this is:

$$CRF = \frac{ROI}{1-(1+ROI)^{-N}}$$

[25] Pratt, M. (2004), Personal communication.

When calculating the levelized cost of the station ($/yr), the capital cost of the station is amortized over 15 years with 10% return on investment (ROI) based on 15-year plant life (*N*).

Real Estate Cost includes costs associated with the use of buildings and the land occupied by the station. We assumed a real estate cost value of $0.5/ft2/mo.[26] These costs include the rental cost of the land, retail outlet, landscaping and upkeep for the facility. These real estate costs were allocated to be proportional to the space occupied by the hydrogen fueling equipment. This space allocation included a proportional share of the fueling station site depending on the number of dispensers plus additional area for hydrogen storage or production equipment. This cost allocation can also factor in an offset due to retail sales (food, beverages, etc.) if co-located at a gasoline station.

Contingency includes unexpected costs that arise during the station construction process. Contingency is typically a function of capital cost and is therefore represented in the model as a percentage of total capital equipment costs. We assume a value of 10% based on conversations with refueling station developers.[27]

Station Labor Cost is divided between hydrogen, gasoline, and non-fuel sales using a factor of 1/8 or 3/8 (depending on small or large station). This is appropriate for

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[26] This value is comparable to the cost allocated to fuel sales in the CAFCP Scenario Study. Knight, R., Unnasch, S. et al., "Bringing Fuel Cell Vehicles to Market: Scenarios and Challenges with Fuel Alternatives," Bevilacqua, Knight for California Fuel Cell Partnership, October 2001. A similar apporach is used by the DOE H2A group (See ‘Lasher, S.’ reference).

[27] This assumption was vetted with representatives from Chevron Texaco, Oct 2004.

hydrogen stations co-located at an existing gasoline station. One could use other estimates for other station siting locations.

Methodology

Calculating Station Cost:

Station costs are calculated by determining the size and type of equipment needed for a given station, estimating this equipment's cost using data from industry, and estimating how much it will cost to install and operate this equipment.

To determine the cost of the seven different station types listed above, the following steps were employed:

1. Industrial Cost Data Collection:

Suppliers of hydrogen equipment provided data on the capital, installation, and operating costs of their equipment. See Appendix F: "Industry Cost Data" for these data and Appendix G: "Sources" for the list of companies that contributed information. These data are compiled in the CHREC database presented in Chapter 2. Costs for minor station components (e.g. safety equipment, mechanical/piping) were provided by Tiax LLC.

2. Cost Data Adjustment for Size and Production Volume:

In this step, cost data for units of different size and production volumes are normalized and aggregated. Because the costs collected from industry represented a wide variety of sizes and production volumes, the data were scaled to a uniform size and production volume level based on assumed scaling factors and progress ratios. Since there was a larger amount of data available on storage and compressors, these costs are determined from a regression of the equipment costs vs. size data. Dispenser cost data, since independent of size, are simply averaged. These data are presented in Chapter 2.

Scale Adjustment

Data collected from industry were scaled to a uniform size based on the ten station sizes selected. For example, the reformers were scaled to 4.17 and 41.7 kg/hr to correspond to the 100 kg/day and 1000 kg/day station sizes. The formula used to scale each industry cost estimate is:

$$Cost_f = Cost_i \times \frac{Size_f}{Size_i}^{ScalingFactor}$$

Where "f" designates the size and cost of the scaled equipment in kg/day and $, respectively, and "i" designates the original estimate.

The table below presents the scaling factors assumed for each major piece of equipment.

Table 3-5: Scaling Factors

Equipment	***Scaling Factors***[28]	***Eqmt size over which scaling factor valid (kg/hr)***
Reformer	0.6	~11[29]
Electrolyzer	0.46	0.05-0.12
Purifier	0.5	~11

Scaling factors for storage and compressors are derived by curve-fitting the data. Appendix E shows the results of the scaling adjustment for production and purification equipment. The scaling factor for electrolyzers concurs with the scaling factor obtained empirically by the author based on industrial quotes for electrolyzers of various size. The author obtained a value of 0.44 based on equipment from 1-5.4 kg/hr.

Production Volume Adjustment

To calculate cost reduction from production volume increase, progress ratios are estimated for the equipment. The equipment is clustered into 3 categories to reflect its maturity (as of 2004) and potential for cost reduction. Each cluster has an associated progress ratio. The table below shows the clusters categories and their assumed progress ratios:

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[28] Thomas, S.E., (1997) "Hydrogen Infrastructure Report", p.E-5. Thomas indicates that scaling factor values were chosen intuitively based on an assessment of how component cost may vary with size. He notes that higher scaling values may be appropriate.

[29] I assume reformer and purifier scaling factors are valid over a station size range of 100-1000kg/day

Table 3-6: Progress Ratios for Equipment

Cluster	Equipment	Progress ratio[30]
1. Nascent technology, "one-of" production volume levels	Reformers, electrolyzers, purifiers, fuel cells	0.85
2. Mature equipment, predominantly used for H2 stations	Compressor, dispenser, mobile refueler, non-capital station construction costs	0.90
3. Mature equipment, high Prod Vol levels	Storage	0.95

Different progress ratios were selected since the equipment in each cluster is at different levels of maturity and production volume today. For instance, an increase in ASME storage vessel production will have a negligible effect on price since they are already produced in volume and have been so for many years. Alternatively, only a limited amount of small scale reformers have yet been built, thus there is a higher potential for cost reduction with this equipment. The progress ratios take these differences into consideration.

The following table shows the production volume assumptions and calculated discount factors for each piece of equipment using an assumed future production volume.

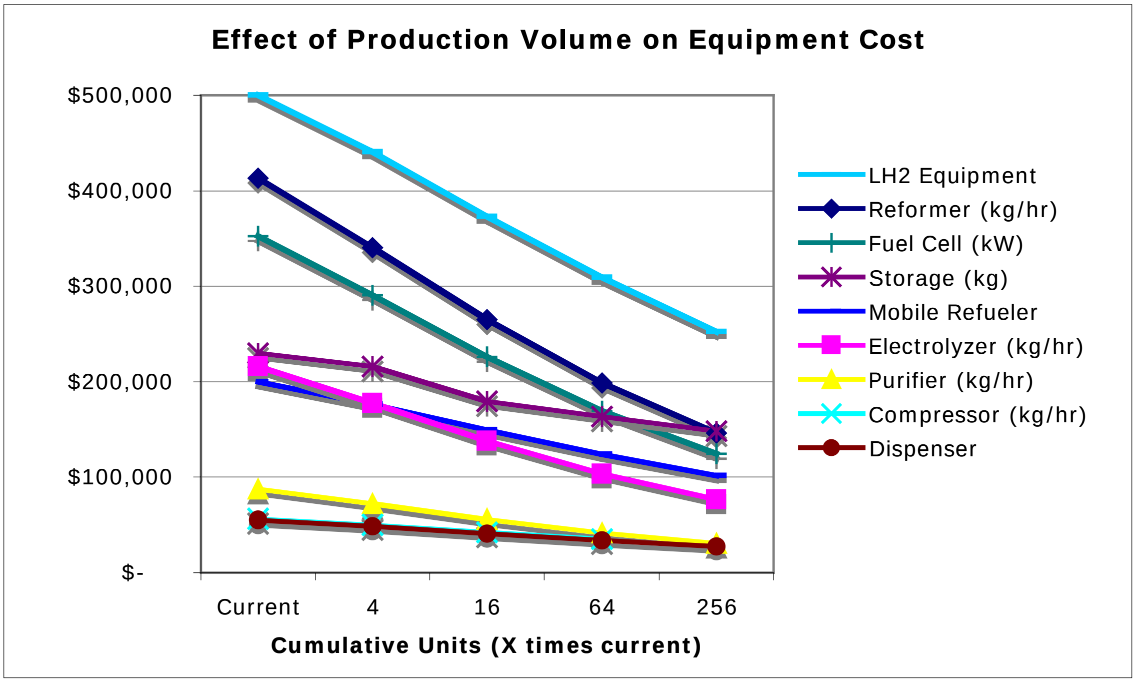
[30] ibid. p.F-3. Not all equipment was given a progress ratio in this report. The author denoted a progress ratio for a reformer (0.85), PSA (0.85), H2 compressor (0.85), H2 Storage (0.95) and dispensers (0.85). I increased the compressor and dispenser PR to 0.90 since production of these units has increased since the time of the original study (1997).

Table 3-7: Production Volume Assumptions

Equipment	***Type***	**Current Cumul. Prod Vol. (units)**	**Future Cumul. Prod Vol. (units)**	**Progress Ratio (Learning Factors)**	**Prod Vol Discount Factor**
Reformer	SMR, Pressurized, 10 atm	4	24	0.85	0.77
Electrolyzer	Alkaline	10	114	0.85	0.68
Purifier	Pressure Swing Absorption	10	79	0.85	0.73
Compressor	Reciprocating	100	280	0.90	0.91
Storage	6,250 psi carbon steel tanks, cascade system, avg vessel size 1.5 m^3	300	926	0.95	0.95
Dispenser	Cafcp protocol	17	215	0.90	0.77
Fuel Cell	PEM/MCFC	5	32	0.85	0.76
Mobile Refueler	includes storage, compressor, and dispenser	10	80	0.90	0.81
LH2 Equipment	Includes Dewar and Vaporizer	5	12	0.90	0.93
Station Construction (non-capital Costs)		15	265	0.9	0.74

The figure below show how the cost for various pieces of equipment change for different scenarios:

Figure 3-10: Effect of Production Volume on Equipment Cost



Note: LH2 Equipment includes the storage tank and vaporizer.

The table below shows the actual cumulative production numbers for each of the cases in the above figure.

Table 3-8: Production Volume Assumptions (Cumulative Units)

Equipment	***Size***	**Current Prod. Vol (units)**	**x 4**	**x 16**	**x 64**	**x 256**
Reformer (kg/hr)	4.2	4	16	64	256	1024
Electrolyzer (kg/hr)	1.3	10	40	160	640	2560

Purifier (kg/hr)	4.2	10	40	160	640	2560
Compressor (kg/hr)	4.2	100	400	1600	6400	25600
Storage (kg)	135	300	1200	4800	19200	76800
Dispenser	1	17	68	272	1088	4352
Fuel Cell (kW)	64	5	20	80	320	1280
Mobile Refueler	n/a	10	40	160	640	2560
LH2 Equipment (gal)	1500	5	20	80	320	1280
Stations		15	60	240	960	3840

The following graphs show the relationship between cost and size for fueling station equipment under three cumulative levels of production.

Figure 3-11: Reformer Cost vs. Size

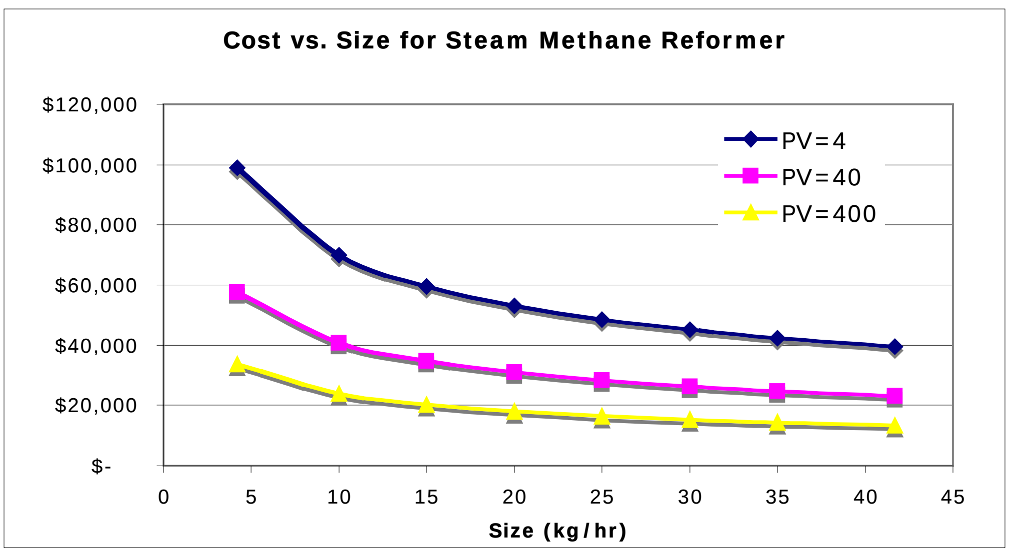


Figure 3-12: Electrolyzer Cost vs. Size

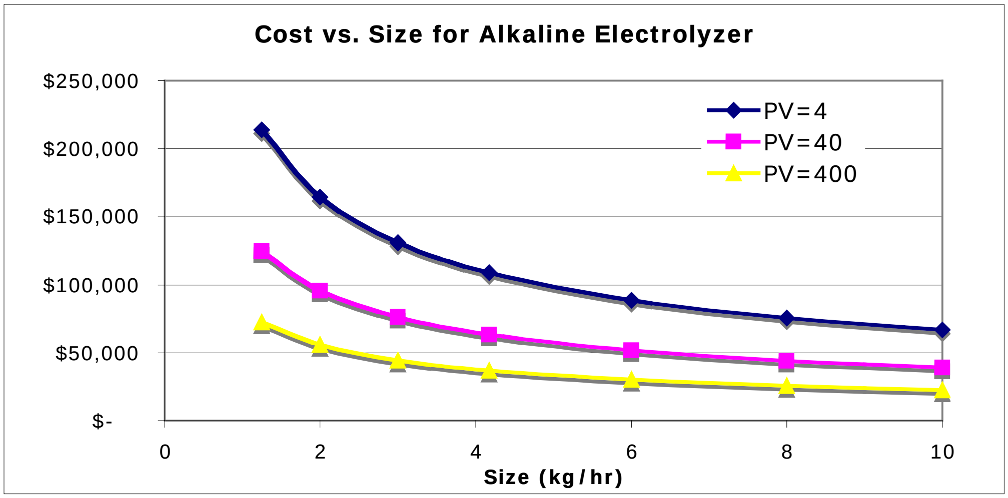


Figure 3-13: Purifier Cost vs. Size

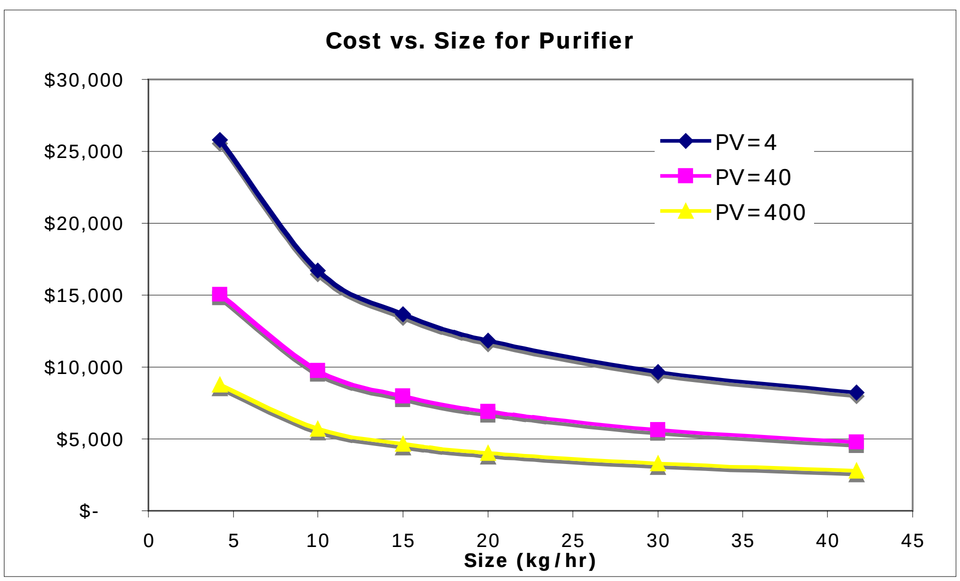


Figure 3-14: Compressor Cost vs. Size

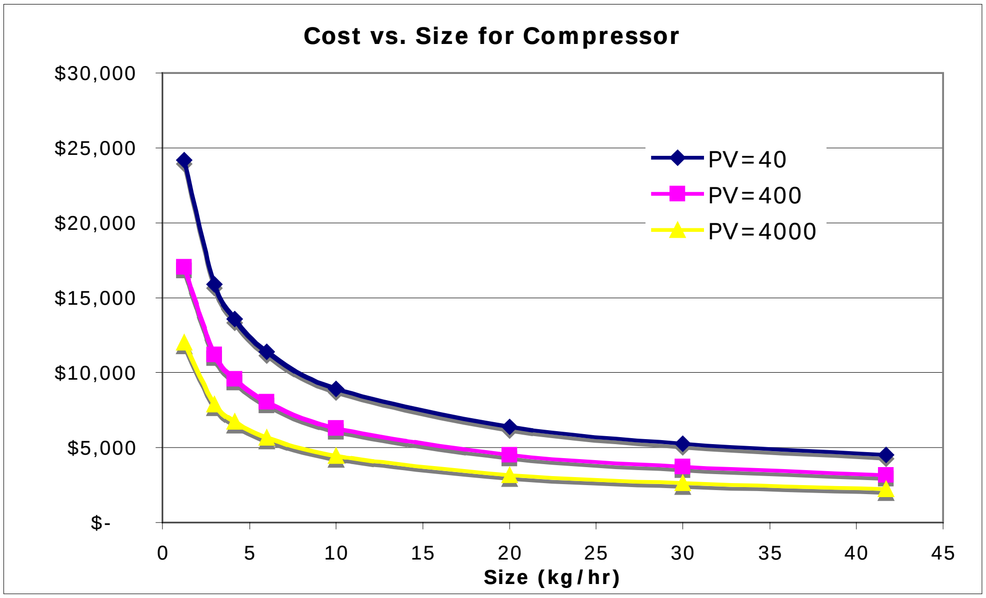
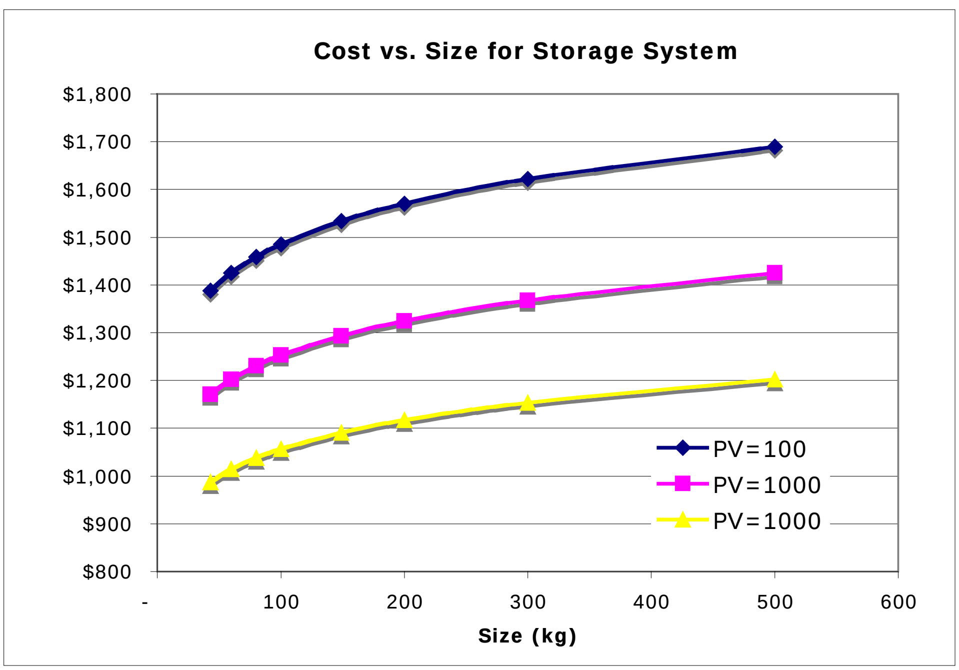


Figure 3-15: Storage Cost vs. Size



The figure indicates that storage actually gets more expensive as capacity increases. The cost curve based on original manufacturer data has a positive exponent (Cost = 1,026 x Size$^{1.08}$). One possible explanation for this is that the cost quotes for small systems just included the cost of the tanks, while the quotes for larger systems included total system expenses like piping and controls. This could artificially bias a higher cost for larger systems.

3. Application of Adjusted Costs in Model

Once the aggregated price for each piece of equipment is calculated, it is then used in the model. Aggregated price refers to the price of a component calculated by scaling each cost quote to a uniform size and production volume, then taking the average value of these scaled quotes. Appendix F shows the costs quotes from suppliers before they are scaled and aggregated, and after. The scaled aggregated costs are used in the model.

The list below shows the various station costs that are added together to determine the total levelized cost of hydrogen:

Equipment Costs:

8. Hydrogen production equipment (e.g. electrolyzer, steam reformer) or storage equipment (if delivered)
9. Purifier: purifies gas to acceptable vehicle standard

10. Compressor: compresses gas to achieve high-pressure 5,000 psi fueling and minimize storage volume
11. Storage vessels (liquid or gaseous)
12. Safety equipment (e.g. vent stack, fencing, bollards)
13. Mechanical equipment (e.g. underground piping, valves)
14. Electrical equipment (e.g. control panels, high-voltage connections)

Installation Costs:

6. Engineering and Design
7. Site preparation
8. Permitting
9. Installation
10. Commissioning (i.e. ensuring the station works properly)
11. Contingency

Operating Costs:

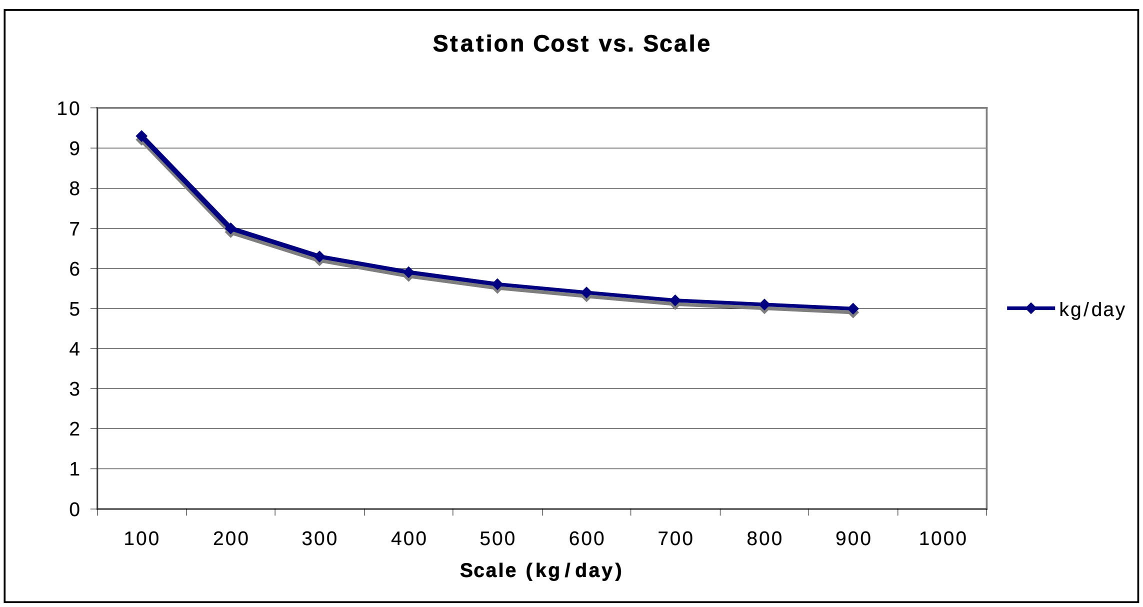
6. Feedstock Costs (natural gas, electricity)
7. Equipment Maintenance
8. Labor (station operator)
9. Real Estate
10. Insurance

The operating cost for the PEM/Ref energy station is determined by subtracting the electricity revenue from the feedstock costs.

Example Results:

The model can be used to determine total station cost over a range of capacities. Figure 3-16 shoes the cost of hydrogen at a reformer-type station between 100 and 900 kg/day. It is assumed that 10 stations have been built.[31]

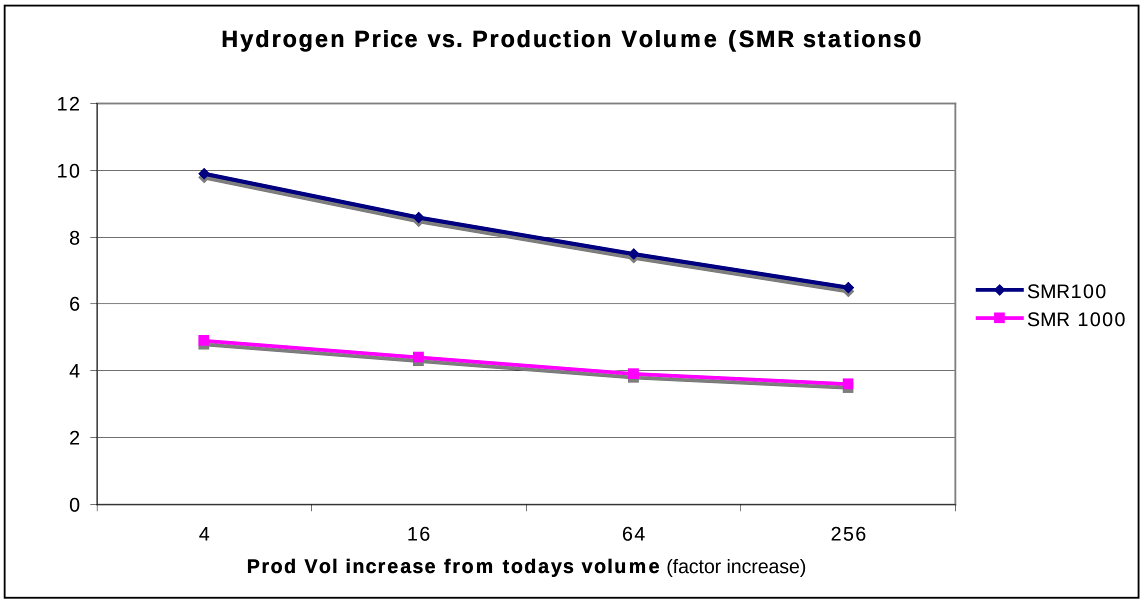
Figure 3-16: Hydrogen Cost vs. Station Size for Reformer Station



[31] Figure 3-16 and 3-17 only demonstrate the functional capabilities of the model. The results ($/kg) should not be referenced since they are dependent on assumptions that are not mentioned.

The next figure shows how the model can be used to calculate the effects of production volume on hydrogen cost. As expected, the price of hydrogen decreases with production volume for a given station type.

Figure 3-17: Cost vs. Production Volume for the Reformer Station



Model Validation

To validate the results of the HSCM, the author compared assumptions and results from other studies on hydrogen station costs. First, the assumptions used in this model were compared to the assumptions used in other reports such as NAS/NRC report[32], Tiax[33],

[32] National Academy of Science/National Research Council, (2004) "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs",

[33] Unnasch, S. (Tiax) and Powars, C., (2004) "Requirements for Combining Natural Gas and Hydrogen Fueling", Consultant report for the California Energy Commission.

GM Well to Wheels Study[34]. They were also reviewed by other members of the Economics Team and by Tiax during the California Hydrogen Highway Network process (see Chapter 4). An example of this comparison is provided in the table below. See Appendix C & D for a complete list of assumptions.

Table 3-9: Assumption Comparison

Parameter	**Study**	**On-site NG Reformation**	**Electrolysis**
Total Electric Consumption (kWh/kg)	***This study***	***3.0***	***60***
	Lasher/ADL	3.41	53.45
	GM/LBST	2.16	53.84
	Simbeck/SFA Pacific	2.19	54.8
Natural Gas Consumption (J/J)	***This study***	***1.35***	-
	Lasher/ADL	1.32	-
	Simbeck/SFA Pacific	1.43	-

To ensure the model uses the assumptions accurately, the model has undergone peer review within the H2Hwy Net Economics Team. Tiax also compared the model against the Hydrogen Analysis (H2A) team's economic model of forecourt station economics[35].

34 Ludwig Bolkow Systemtechnik, (2002) "GM Well-to-Wheels Analysis of Energy Use and Greenshouse Gas emissions of Advanced Fuel/Vehicle Systems", www.lbst.de/gm-wtw
35 Lasher, S. (2004), "H2A Forecourt Hydrogen Station Cost Analysis", Presentation at the National Hydrogen Asociation Conference, Los Angeles CA.

Model Comparison

To show how the analysis compares against other hydrogen station cost analyses, the HSCM model results are compared with results from studies by H2Gen[36] and the National Academy of Sciences Report[37] for an on-site reformer station. In general, costs from the HSCM are higher than those by earlier authors since they assumed mass production of components and low installation costs while I assume more first-of-a-kind station costs. In this comparison, I modified my assumptions (where possible) to match the assumptions used in the other two studies. Table 3-10and 3-11 show the assumptions and results for this comparison. Since NAS presents both current and future costs, I present results using two different production volume levels (40 and 4000 units) to represent near-term and future scenarios.

H2Gen vs. HSCM: Results from the HSCM are first compared with H2Gen costs for an on-site reformer-type station. These results are shown in the figure and table below.

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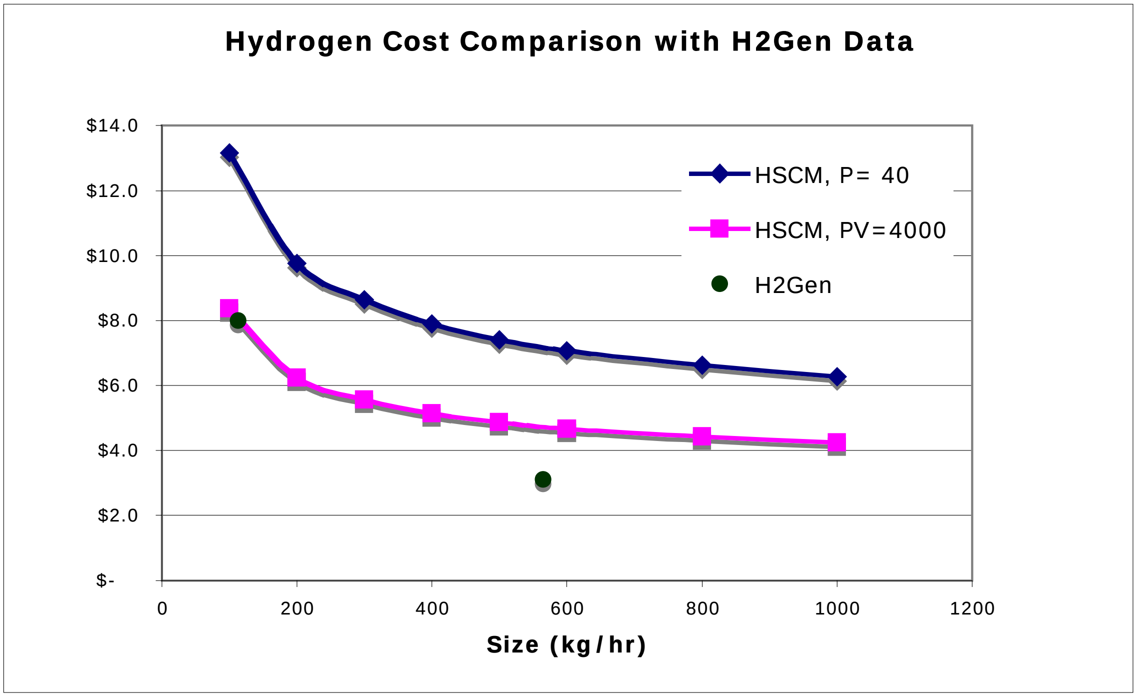
[36] Thomas, C.E. (2004) The numbers in the study were emailed to the author by Sandy Thomas directly.
[37] National Academy of Science/National Research Council, (2004)

Figure 3-18: Hydrogen Cost Comparison for Reformer Station, H2Gen Data



The figure indicates that the results match only when the HSCM is adjusted for a cumulative production volume of 4000 units. The large H2Gen unit is even lower than the HSCM "4000th unit" cost for a similar size reformer station. The table below provides a more detailed look at this comparison.

Table 3-10: Cost Comparison for Reformer Station, H2Gen

	HSCM (2010)	HSCM (2010)	H2Gen HGM-2000	H2Gen HGM-10000
SMR Capacity (kg/day)	113	565	113	565

Capacity Factor	47%	47%	47	47
Annual Capital Recovery Factor	13.15%	13.15%	13.15	13.15
Natural Gas Cost ($/MMBTU, HHV)	7	7	7	7
Electricity Cost (cents/kWh)	10	10	10	10
Production Volume	**40**	**40**		
Storage Capacity	153	765	50	250
Production Efficiency (reformer, %), (El'sis, kWh/kg includes compr)	70%	70%		
Capital Cost	$750,862	$2,435,765	$435,000	$737,000
Delivery and Installation Cost	$328,585	$653,295	$21,500	$25,500
Hydrogen Cost				
Natural Gas Cost ($/kg)	$1.1	$1.1	$1.1	$1.2
Electricity Cost ($/kg)	$0.4	$0.4	$0.4	$0.4
O&M ($/kg)	$3.4	$1.3	$2.6	$0.5
Capital Charge ($/kg)	$5.1	$3.3	$3.8	$1.00
Delivery and Installation Cost ($/kg)	$2.2	$0.9	$0.2	$0.03
Total H2 Cost ($/kg)	**$12.3**	**$7.0**	**8.0**	**3.1**

The biggest discrepancy between HSCM results and the results of H2Gen is in the delivery and installation (D&I) costs. In the HSCM model, D&I costs are over an order of magnitude higher than H2Gen’s estimates. The author collected data on D&I costs from several recently built stations and thus believes they are more indicative of true costs. While some think these costs will decline as more stations are built, experience in the natural gas fueling industry does not support this notion.[38] Costs have remained high because the station technology continues to evolve (e.g. higher pressure equipment) along with an evolving set of codes and standards. These evolutions require new equipment and new designs. New station designs and a lack of uniform codes and standards make siting and permitting costs higher than expected. Since a similar evolution in station design is expected with today's hydrogen stations, the author assumes high D&I costs and a conservative progress ratio (0.9) for these costs over time.

Capital costs are also considerably higher in the HSCM. This is due in part to the larger hydrogen storage capacity used in the HSCM stations vs. H2Gen stations. The author assumes 153 kg are needed vs. H2Gen's assumption of 50kg for a 113 kg/day station. H2Gen's estimates for capital costs are also lower than the NAS model. Feedstock costs are similar throughout all studies.

NAS vs. HSCM: The results from the HSCM are compared against the results from the NAS report, again for on-site reformer-type stations. Figure 3-19 shows where NAS costs fall between HSCM costs for two production volume scenarios. Table 3-13 compares the HSCM to NAS results for reformer station costs.

[38] Personal communications with Mitchell Pratt of Clean Energy and Roger Conyers of IMW Industries Ltd.

Figure 3-19: Hydrogen Cost Comparison for Reformer Station, NAS

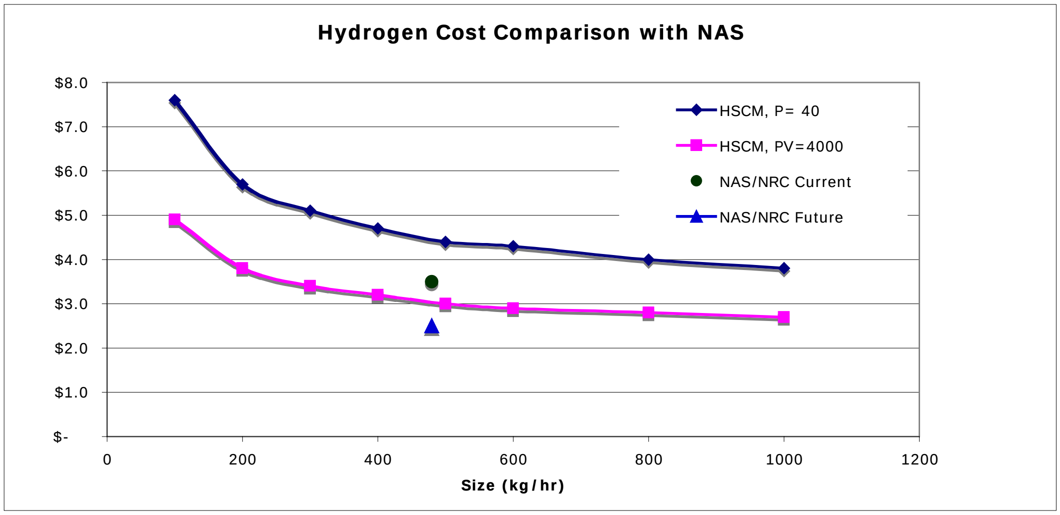


Table 3-11: Cost Comparison for Reformer Station, NAS

	HSCM Current SMR 480	HSCM Future SMR 480	NAS-current[39] Onsite SMR	NAS-future[40] Onsite SMR
SMR Capacity (kg/day)	480	480	480	480
Capacity Factor (%)	90	90	90	90
Annual Capital Recovery Factor (%)	14	14	14	14
Natural Gas Cost ($/MMBTU, HHV)	6.5	6.5	6.5	6.5
Electricity Cost (cents/kWh)	7	7	7	7
Production Volume	40	4000		

[39] NAS, p.E-35
[40] NAS, p.E-36

Storage Capacity	650	650	108	108
Production Efficiency (reformer, %), (El'sis, kWh/kg includes compr)	70%	75%	70%	75%
Total Capital Cost	$2,144,847	$1,224,094	$1,276,000	$660,000
Reformer	$743,080	$273,106	$990,000	$528,000
Compressor	$101,310	$52,668	$154,000	$33,000
Storage	$1,005,165	$729,464	$121,000	$88,000
Dispenser	$87,270	$45,369	$22,000	$11,000
Delivery and Installation Cost	$596,000	$234,168	$572,000	$297,000
Hydrogen Cost				
Natural Gas Cost ($/kg)	$1.1	$1.0	1.37	1.17
Electricity Cost ($/kg)	$0.2	$0.2	0.15	0.12
O&M ($/kg)	$0.8	$0.5	0.35	0.18
Capital Charge ($/kg)	$1.9	$1.1	$1.14	$0.59
Delivery and Installation Cost ($/kg)	$0.5	$0.2	$0.52	$0.26
Total H2 Cost ($/kg)	**$4.5**	**$3.0**	**$3.5**	**$2.3**

Capital costs calculated by the HSCM are higher than results from both the current and future NAS model for the near term case. The biggest reason for the larger capital costs in the HSCM is that it assume a larger storage capacity is required (650 kg vs. 108 kg for 480 kg/day station). The reason HSCM's estimated storage capacity is much higher is that it accounts for the storage required for storing reformer output in addition to storage for fueling vehicles. Because of this high storage capacity estimate, the high cost of storage dominates while the HSCM actually assumes a lower reformer and compressor cost. The D&I costs from both models are actually quite similar in the near term cases. The HSCM also assumes two dispensers are needed for a 480 kg/day station whereas the NAS model assumes one. Operations and maintenance (O&M) costs from NAS are lower than both HSCM and H2Gen.

The table below presents a comparison in results for the costs of an electrolysis station using two different models.

Table 3-12: Hydrogen Cost Comparison for Electrolysis Station, NAS

	NAS Model v.3 NAS-current	NAS Model v.3 NAS-future	HSCM, Elec Current	HSCM, Elec Future
Electrolyzer Capacity (kg/day)	480	480	100	100
Capacity Factor (%)	90	90	90	90
Annual Capital Recovery Factor (%)	14	14	14	14
Natural Gas Cost ($/MMBTU, HHV)	6.5	6.5	6.5	6.5
Electricity Cost (cents/kWh)	7	7	7	7
Production Volume (cum units)			40	4000
Storage Capacity (kg)	108	108	149	149
Production Efficiency (kWh/kg includes compr)	54.8	50.2	54.8	50.2
Capital Cost	$1,760,000	$396,000	$593,748	$340,609
Hydrogen Equipment	$1,287,000	$143,000	$256,448	$94,253

Storage System	$176,000	$33,000	$176,768	$128,283
Compressor	$275,000	$209,000	$44,799	$23,290
Dispenser	$22,000	$11,000	$43,635	$22,684
Delivery and Installation Cost	$774,000	$181,500	$340,059	$155,932
Hydrogen Cost				
Natural Gas Cost ($/kg)	$-	$-	$-	$-
Electricity Cost ($/kg)	$3.8	$3.3	$4.9	$4.5
O&M ($/kg)	$0.5	$0.1	$1.8	$1.4
Capital Charge ($/kg)	$1.6	$0.4	$2.5	$1.4
Delivery and Installation Charge ($/kg)	$0.7	$0.2	$1.4	$0.7
Total H2 Cost ($/kg)	**$6.6**	**$3.9**	**$10.7**	**$8.0**

The NAS model analyzes a much bigger electrolyzer (480 vs 100 kg/day), hence the results cannot be directly compared. A larger electrolyzer results in cheaper hydrogen cost per kg of output since electrolyzers have a significant scaling factor (0.46). Similar to the reformer station comparison, the hydrogen costs from the HSCM for electrolysis stations are larger than results from the NAS model. Electricity cost is higher in the HSCM because it accounts for the demand charge ($/kW) due to the higher peak load caused by the electrolyzer. Again, part of the higher capital cost can be attributed to the larger storage capacity assumed by the HSCM. O&M costs are higher in the HSCM since they include insurance, real estate, property tax, and labor costs, none of which are included in the NAS model.

The comparison analysis with these two previous studies demonstrates the flexibility in the HSCM. The assumptions in the HSCM were easily modified to allow a meaningful comparison between the studies. The assumptions can also be modified for modeling station costs in other geographical areas as well.

The comparative analysis shows at a production volume level of 4000 units, small-scale reformer-type stations achieve the costs reported from the H2Gen report. This corresponds to a demand of ~250,000 vehicles.[41] At a production volume of ~400, NAS hydrogen costs match HSCM hydrogen costs (25,000 vehicles).

Costs are likely to decrease differently for different station types due to a variety of unknown factors. The potential for technology breakthroughs in small-scale reformation is arguably higher than for small-scale electrolyzers since the latter equipment is more mature. The feedstock price for reformer-type stations (natural gas), however, is more volatile and will only continue to increase.

Sensitivity Analysis

One can perform a sensitivity analysis on the six important station assumptions to determine each assumptions effect on overall hydrogen cost. The table below shows the high and low values used for each variable in the sensitivity analysis for the case of the Hydrogen Highway Network analysis (discussed in more detail in Chapter 4).

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[41] Assumes the average vehicle consumes 0.82 kg/day of hydrogen, stations operate at 50% capacity factor, and all vehicles are served by 100 kg/day reformer type stations. This last assumption is not realistic, but is made for simplicity.

Table 3-13: Sensitivity Analysis Parameters

	Basecase	Bright	Bleak
Natural Gas Price ($/MMBtu)	$7.0	$4.9	$9.1
Electricity Price ($/kWh)	$0.10	$0.07	$0.13
Capacity Factor (%)	24%	31%	17%
Return on Investment	10%	7.0%	13%
Real Estate Cost ($/ft^2/month)	$0.50	$0.35	$0.65
Contingency (% of Total Installed Capital Cost)	20%	14%	26%

Calculating the Cost of a H2 Network of Stations

While the focus of the model is to look at individual station costs, it can also be used to calculate the costs of a network of stations. This is done by multiplying the cost of each station by the number of stations in each scenario. The capacity factor used for each station is determined by the vehicle numbers and station numbers in each scenario. Chapter 4 presents an example of this type of analysis using the proposed California Hydrogen Highway network. Chapter 4 will describe how the HSCM is used to calculate the costs of a specific network, the California Hydrogen Highway network, using the station costs and methodology described in Chapter 2 and 3.

4. Application of the HSCM Model to the California Hydrogen Highway Network

Introduction

In April 2004, Governor Schwarzenegger signed an executive Order S-7-0442 for the creation of the Hydrogen Highway (H2Hwy Net) in order to expand the network of hydrogen fueling stations throughout California. The goals of the H2Hwy Net are to

- Improve California's economy through job creation around the hydrogen/fuel cell industries
- Make California's energy more secure, stable and sustainable
- Improve California's environment and reduce greenhouse gas emissions

The timeframe for this bulk of the station construction is estimated to be between 2005-2010, though construction will likely continue past that timeframe. Appendix J contains the original announcement made by Governor Schwarzenegger. To achieve this task, the Hydrogen Highway Blueprint Team was assembled to determine the most promising way to achieve the governor's vision. The Team, made up of representatives from the hydrogen industry, government, and NGOs, was divided into sub-teams based on expertise.

The Economics Sub-team, which the author served on, had the core purpose of determining the costs of the proposed H2Hwy Net. To accomplish this goal, the author

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[42] The Executive Order can be found at http://www.hydrogenhighway.ca.gov/announce/announce.htm

created the H2SCM as a tool to determine the overall network cost under various station roll-out scenarios. This model was described in Chapter 3. To create this model, the author worked closely with Tiax and other members of the team to ensure completeness and accuracy.

This chapter presents the results of this project, namely, the cost of building a network of 50 to 250 hydrogen fueling stations across California within the next 5 years. The costs of individual stations under are presented first to show how the total cost of the network was determined. These costs are also calculated under different siting and demand assumptions to show their sensitivity to different assumptions. Future cost scenarios are investigated and conclusions are drawn based on the analysis with the aim to reduce station cost.

Scenarios

The following section describes the different scenarios examined for the H2Hwy Net to account for a variety of station supply and vehicle demand levels. It is taken directly from the H2Hwy Net Blueprint Plan since it best describes the scenario selection methodology:

"With guidance from the Advisory Panel, three implementation scenarios were selected: business as expected, maximum envisioned by 2010, and one between these two cases. These three scenarios were labeled A, C, and B. The task for the topic teams became identifying the requirements to achieve various levels of implementation.

Scenario A was based on on-going efforts in California to deploy hydrogen-fueled vehicles and devices, and the fueling infrastructure to serve them. This includes collaborative efforts by the California Fuel Cell Partnership, the US DOE, the California Stationary Fuel Cell Collaborative, and other projects by state and local agencies such as CEC, ARB, and SCAQMD. Scenario C, which represents the upper end of what is possible in California by 2010, was based on past experience with alternative fuel programs and the introduction of other advanced vehicle technologies. Scenario B values for vehicles and applications were chosen to be between Scenarios A and C.
For each scenario, estimates of numbers of vehicles or applications were made for three end-use sectors: light-duty vehicles, HDVs, and stationary and off-road applications. Light-duty vehicles included hydrogen fueled ICE vehicles and fuel cell vehicles both of which are being developed by automobile companies. Most heavy-duty hydrogen vehicles have been transit or other shuttle buses to date although other vehicle applications are possible. The last end-use category assumed was stationary and off-road applications."[43] Vehicle numbers were estimated to reflect a modest, moderate, and aggressive vehicle roll-out strategy. Capacity factor for the stations is determined by the number of vehicles, number of stations, and size of stations.

Fuel use by vehicles is estimated by assuming the average light duty vehicle (LDV) drives 11,000 miles and has a fuel economy of 45 miles per kg of hydrogen. It assumes one heavy-duty vehicle consumes the same amount of fuel as ten LDVs. The hydrogen produced/yr is the actual amount you expect vehicles to use. Capacity factor is calculated

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[43] H2Hwy Net Executive Order Team, (2004) "Draft Blueprint Plan: California's 2010 Hydrogen Highway Network , v.B1", p.3-1,3-2

by dividing this number by the nameplate capacity of the stations. The parameters of each scenario are presented in the table below.

Table 4-1: Scenario Assumptions

Assumptions:	A	B	C
Total # of Stations	50	250	250
Hydrogen Price to Customer ($/kg)	$3.0	$3.0	$3.0
LD Vehicles	2,000	10,000	20,000
HD Vehicles	10	100	300
Rated Capacity of Stations (kg/yr)	2,496,509	7,580,685	7,580,685
Total Hydrogen Produced/yr (kg/yr)	459,289	2,027,025	3,755,114
Capacity Factor (%)	16%	24%	47%

Station Mix

A mix of different station types was chosen for each scenario. As explained in the H2Hwy Net Blueprint Plan, "The purpose in choosing a portfolio of station forecourt technologies and fuel sources is to determine scenarios for infrastructure costs, environmental benefits, and station siting issues. The goal is not only to support the fueling demand in California but also to support the development of multiple fueling technologies and fuel options."[44]

The table below shows how many of each station are allocated to each scenario.

[44] ibid, p.3-4

Table 4-2: Station Mix Assumptions

Scenario	A	B	C
Total # of Stations	**50**	**250**	**250**
1. Steam Methane Reformer, 100 (SMR 100)	12.0%	8.0%	8.0%
2. Steam Methane Reformer, 1000 (SMR 1000)	0.0%	0.8%	0.8%
3. Electrolyzer, grid, 30 (EL-G 30)	6.0%	6.4%	6.4%
4. Electrolyzer, renewable energy, 30 (EL-PV 30)	18.0%	27.6%	27.6%
5. Electrolyzer, grid, 100 (EL-G 100)	10.0%	7.6%	7.6%
6. Mobile Refueler, 10 (MOB 10)	20.0%	28.0%	28.0%
7. Delivered LH2, 1000 (LH2 1000)	8.0%	2.8%	2.8%
8. & 9. Energy Stations, 100 (PEMES 100, MCFC 91)	18.0%	14.4%	14.4%
10. Pipeline Station, 100 (PIPE 100)	8.0%	4.4%	4.4%

For example, 6 SMR-100 stations (12% of 50) would be built in scenario A and 12 (8% of 250) would be built in Scenario B.

Savings from Existing and Planned Stations:

To accurately reflect California's existing (or soon to be) hydrogen infrastructure, the team assumed that 70% of the stations in scenario A (~35 total) either exist or are planned. Each scenario subtracts the cost of these existing and planned stations within California.

As stated in the Blueprint plan, "Within the constraints of the number of stations for each scenario, the station technology mix portfolio was chosen based on a number of criteria.

The criteria are not prescriptive but provide a methodology for determining the station mix in the scenarios. Table 4-3 describes the criteria and the types of stations that result.

The criteria in Table 4-3 were applied to options for resources, production technology, delivery methods, and station size to determine the three station mix scenarios for 2010."[45]

Table 4-3: Criteria for Station Mixes in the Three Scenarios*[46]*

[45] ibid, p.3-4, 3-5
[46] ibid, p.3-5

Criteria	Explanation	Comments
Existing Stations	Station types that currently exist in California are included in scenarios for 2010. There are currently 15 fueling stations in California that are or could be part of the CA H2 Net	Existing stations are mainly on-site generation of H_2 using electrolysis, natural gas steam reforming, or centrally produced liquid H_2 delivery.
Planned Stations	Stations that are planned, either privately or through public/private partnerships must be included in the scenarios. 19 stations planned under DOE cost-shared grants fall under this category. Thirteen stations partially funded by SCAQMD are also included. Some stations have overlapping funding sources.	Planned stations include on-site generation of H_2 using electrolysis, natural gas steam reforming, centrally produced liquid H_2 delivery, and energy stations.
Technology Development & Diversity of Options	The scenarios assume that industry will introduce a diverse set of forecourt designs and fuel sources as companies determine their best technology options to commercialize.	Technologies will include distributed and centralized production of gaseous and liquid hydrogen from various fuel sources
Greenhouse Gas Reductions	The scenarios assume that the station mix will result in overall GHG reductions primarily due to the inclusion of renewable energy	A variety of stations could meet this goal including those using distributed or centralized generation of hydrogen from a several fuel sources
Renewable Energy	The station mix in the scenarios results in increased use of renewable energy in California since the Blueprint recommends that 20% of the hydrogen production come from “new” renewable resources	The stations can include electrolysis from distributed or grid-based renewable energy. Also biomass-based hydrogen can be included in a variety of stations.

Cost	The scenarios should consider annual operating and capital costs. Some stations types may have low operating costs but high capital vice versa. Both situations should be included in the scenarios.	The scenarios do not represent the overall lowest cost options because the station mix must accommodate all other criteria (e.g. GHG reductions, renewable content, with a variety of pathways utilized)

Results

This section presents the costs of individual stations and the cost of the overall Hydrogen Highway Network using current technology. It presents these costs for each of the scenario described above. The complete set of assumptions used in each scenario are in Appendix D.

Equipment cost estimates are based on future cumulative production volume levels. To calculate these levels, we assumed a current production volume for each piece then added the number of units required based on the station mix and station number. For instance, scenario C calls for 250 stations, 20 of which are small reformers. Thus 2010 production volume level adds 20 to the current assumed production volume (3 units) of reformers. This method does not account for production volume increases due to non-H2Hwy stations.

Since the stations will presumably be built over 5 years (2005-2010), we use the average cost of the equipment over the 5 years taking into account the continual reduction in cost due to production volume increase. As more stations of a particular type are built, the cumulative production increases from Pi to Pf. We can estimate an average equipment cost over this time period, using the following equation:

$$R = \frac{P_f}{P_i}$$
$$\alpha = \ln(R)/\ln(2)$$
$$DF = \left(\frac{1}{1+\alpha}\right)\frac{(R^{(\alpha+1)}-1)}{R-1}$$
$$C_f = C_i \times DF$$

The alternative to this approach is to calculate the costs of all stations in 2010 at production volume P_f. This approach would have produced artificially low results and was therefore not used.

Individual Station Costs

The total cost of the H2Hwy Network is determined by aggregating the costs of individual station types. This section presents individual station costs for the seven stations types considered in the analysis.

Station Cost by Category

Station costs are divided into four main categories: financing, installed capital, fixed operating and feedstock. ***Capital*** includes the levelized equipment cost and one-time non-capital installation costs. ***Financing*** (i.e. fixed charge rate) includes the cost of borrowing the capital required to build the station assuming a certain return on the investment over *N* years (10% ROI and 15 yrs is the baseline assumption). ***Fixed Operating*** includes all recurring annual expenses at the station except feedstock costs. ***Feedstock*** includes the cost of fuel to the station (e.g. natural gas, electricity, gaseous hydrogen, liquid hydrogen). The segmented station costs from Scenario A & C are presented in both $/kg and MM$/yr in the following figures below:

Figure 4-1: Hydrogen Cost, Scenario B

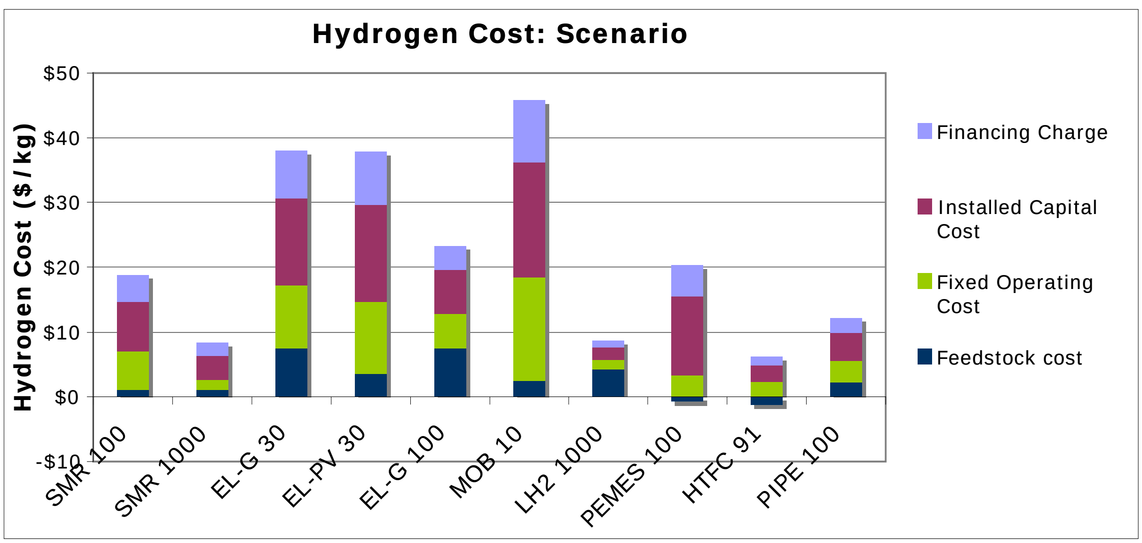
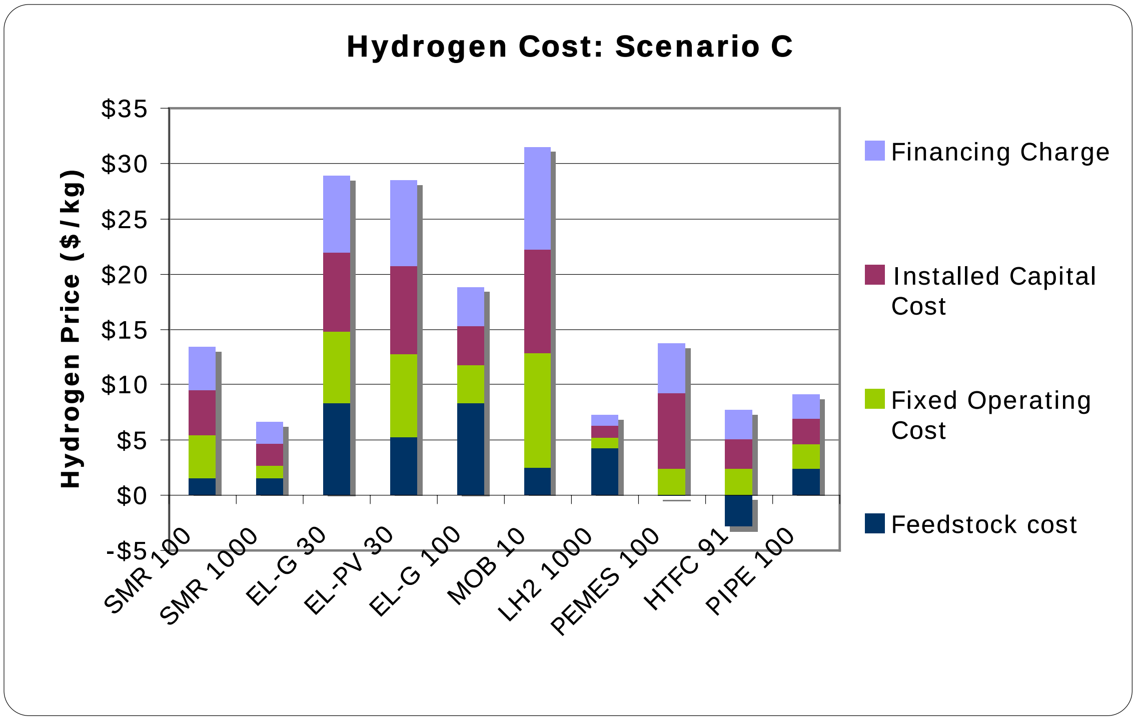


Figure 4-2: Hydrogen Cost, Scenario C



The top two bars together represent the total levelized capital cost. The financing charge is:

$$FC = (CRF - \frac{1}{N}) * CapitalCost$$

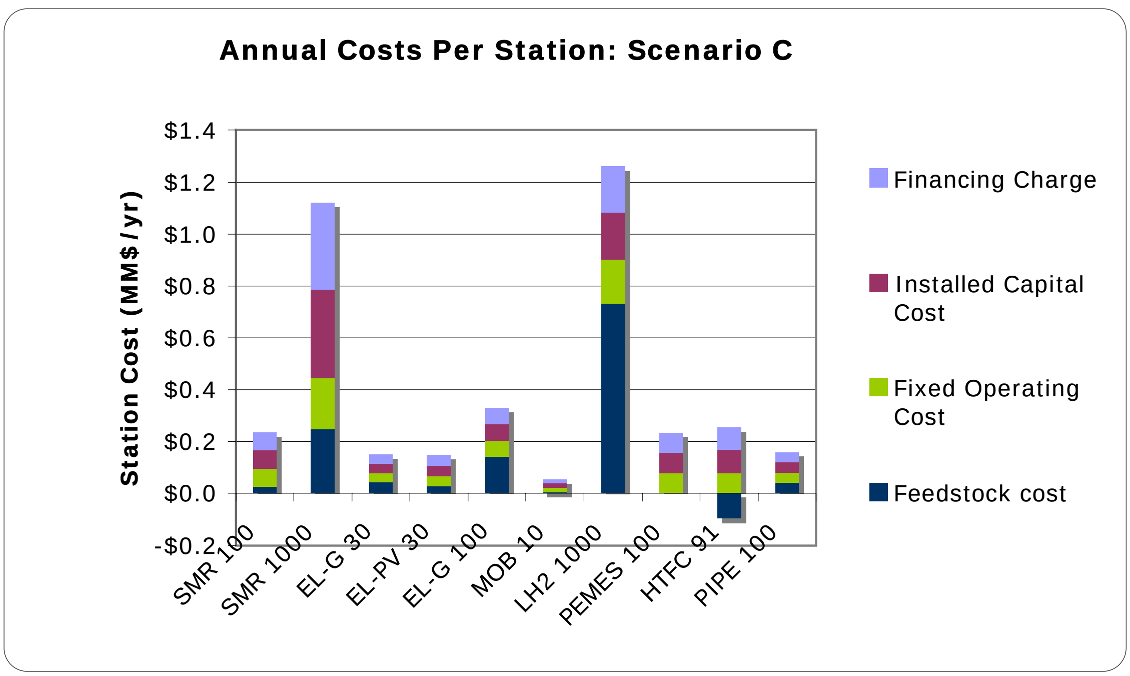
Financing is only applied to the capital invested. This does not imply the station operator makes a return on operating the station. If the ROI is 0%, the blue bar below disappears.

To illustrate how these costs compare to gasoline and conventional vehicles on a cost per mile and per fill-up basis, the following table provides an example calculation:

Table 4-4: Comparison of Hydrogen Costs to Gasoline Costs

	Hydrogen	Gasoline
mpg(equiv)	50	30
Fuel Cost ($/kg, $/gal)	$3.35	$2.00
Fuel Tank size (kg, gal)	4	12
Range (miles)	200	360
Cost Per Fill-up	$13.4	$24.0
Cost per mile	$0.067	$0.067

Figure 4-3: Annual Costs per Station: Scenario C

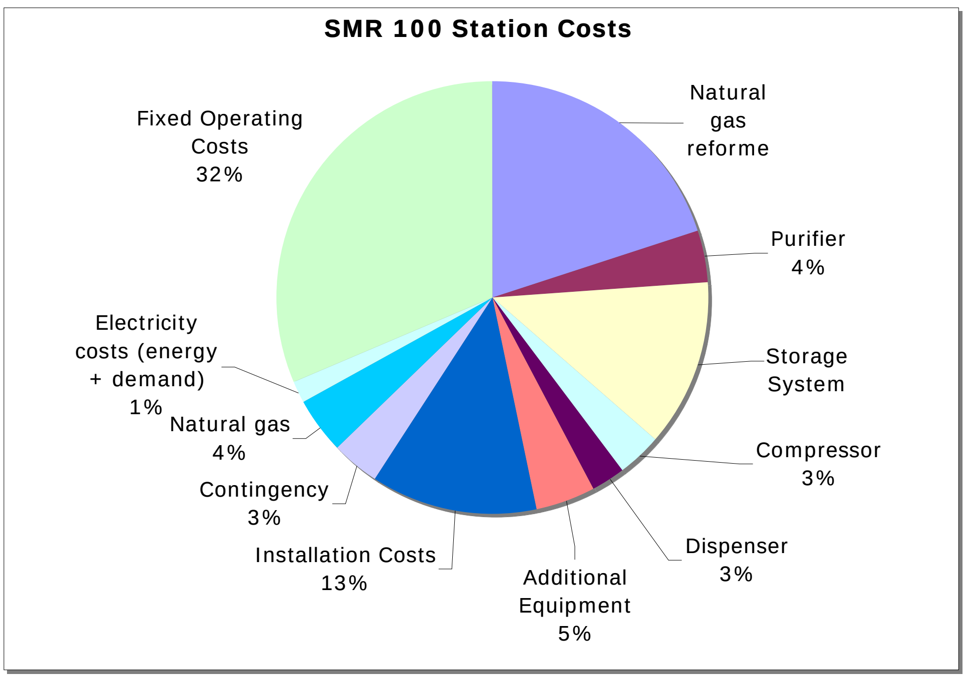


Note: Since annual station costs are very similar between scenario A and C, only Scenario C is shown.

Station Cost by Component:

Pie charts have been created for each station type to illustrate what costs are considered for each individual station and the amount each cost item contributes to overall hydrogen price. The figure below presents the pie chart for a reformer-type station.   Appendix B provides a table summarizing these data for all stations and pie charts for the other stations considered in this analysis.

Figure 4-4: Reformer Station Costs (100kg/day)



Fixed operating costs include equipment maintenance expenses, labor, rent, and insurance. *Installation Costs* includes non-capital costs of building the station such as engineering, permitting, construction, etc. *Additional Equipment* includes mechanical, electrical, and safety equipment. For a complete list of the costs for the SMR 100 station, see Appendix C.

Hydrogen Cost by Scenario

The following figures show the cost of hydrogen for each station type and their total annual levelized cost (MM$/yr) for three supply/demand scenarios.

Figure 4-5: Hydrogen Costs for 10 Stations under 3 Scenarios

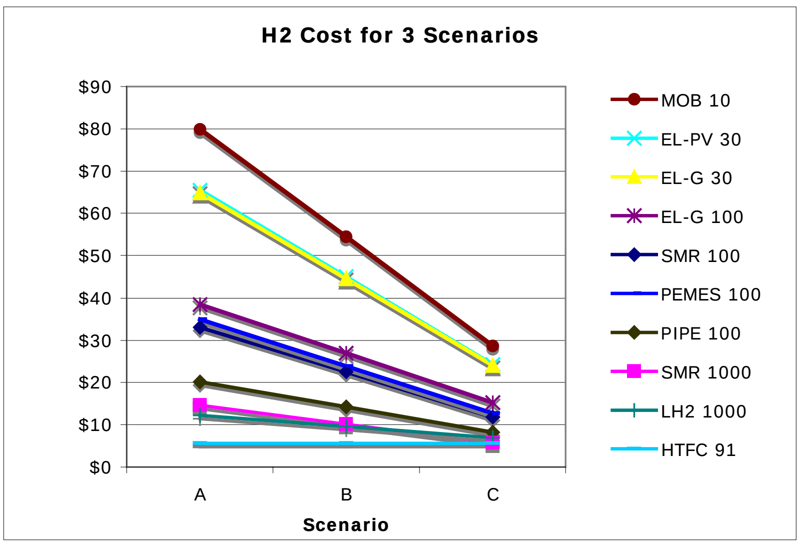


Figure 4-6: H2 Cost for 10 Stations (adjusted scale)

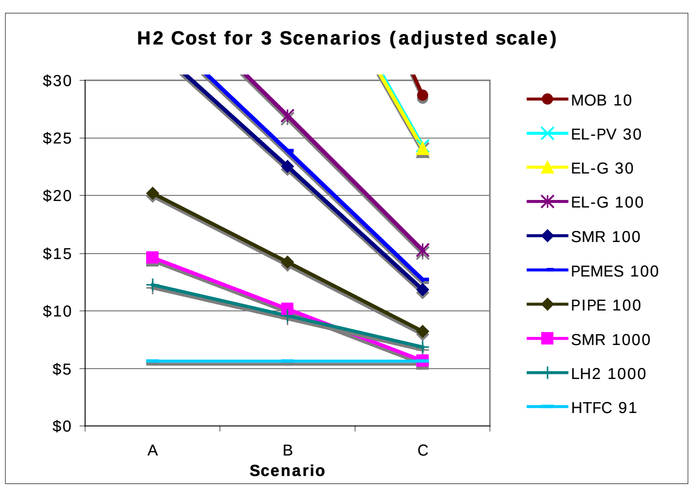


Figure 4-7: Annual Station Costs for 10 Stations, 3 Scenarios

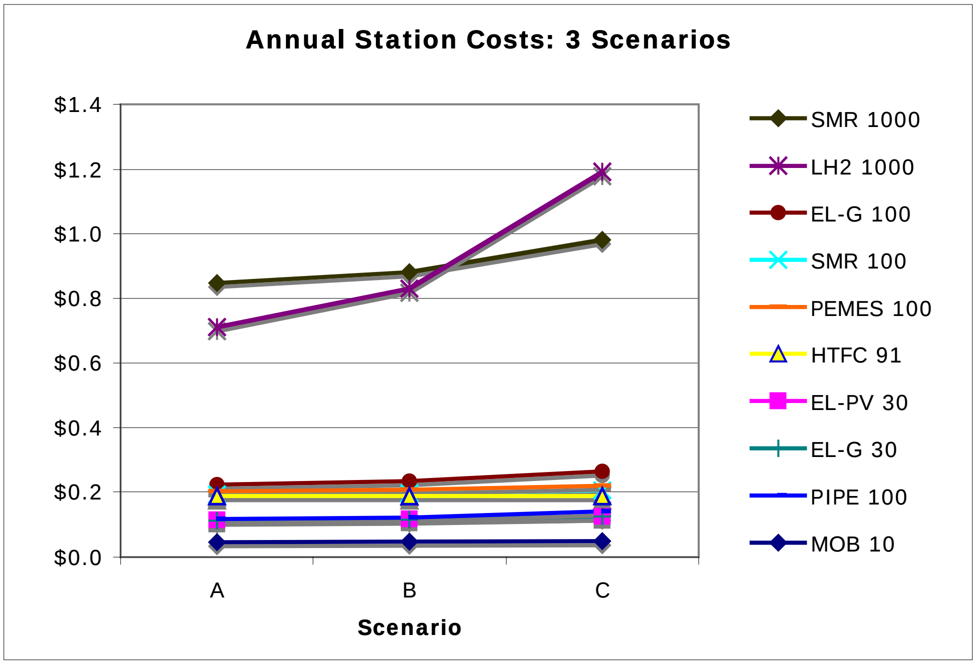
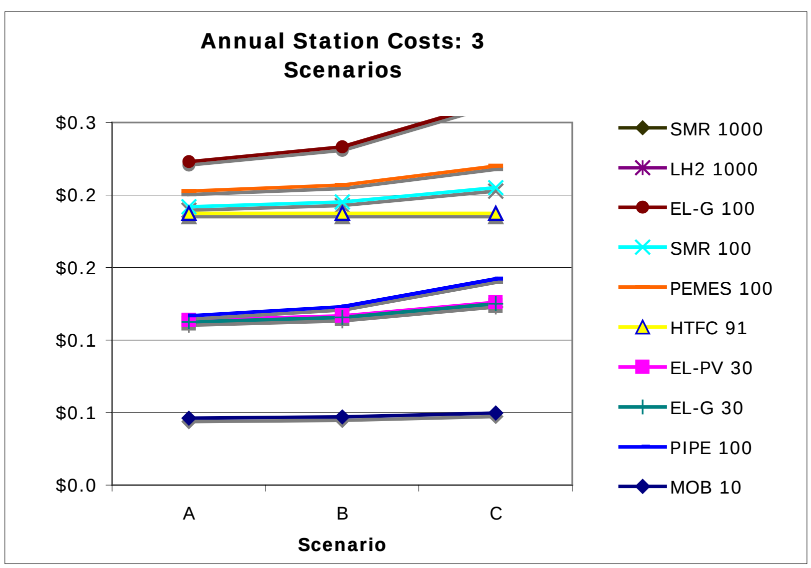
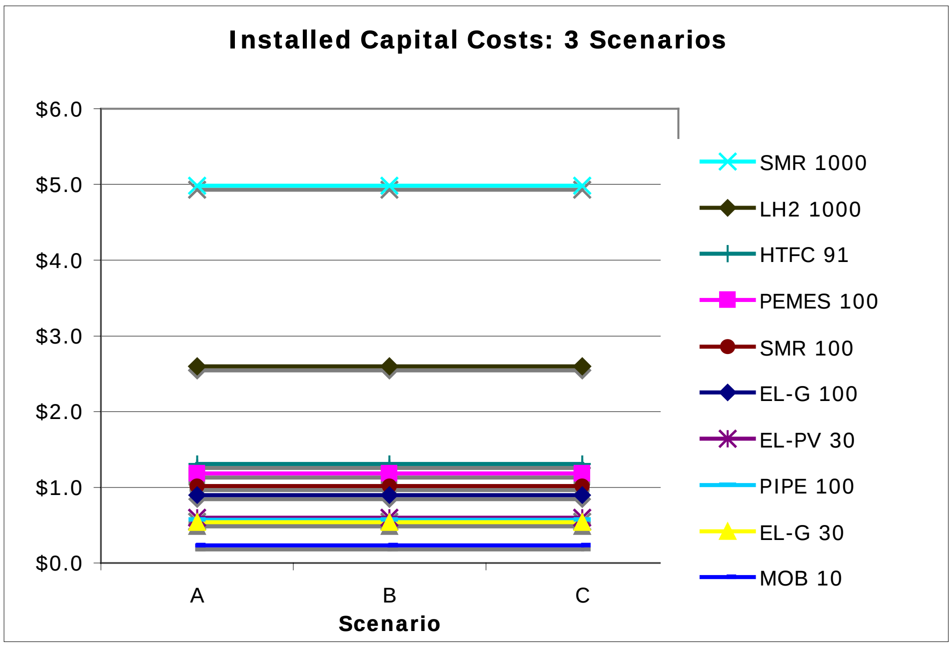


Figure 4-8: Annual Station Costs for 10 Stations (adjusted scale)



Installed Station Cost (ISC) represents the initial capital investment required to build a station. This includes both equipment and non-capital installation expenses. The following figures show installed station costs.

Figure 4-9: Installed Capital Cost for 10 Stations, 3 Scenarios



Hydrogen Highway Network Costs

I used the HSCM to estimate the cost of building the proposed H2Hwy Network of fueling stations for three scenarios. For Scenario C, the cost to build a network of 250 stations is estimated to be **$31 million/yr +/- $5 million** (includes only capital and installation cost). The following figure shows the annual cost of the network for the three scenarios. Annual Cost accounts for the capital, installation, and operating costs, and is calculated using the following equations:

$$AC = OC + (CIC * CRF)$$

Where,

AC = Annual Cost ($/yr)

OC = Operating Cost ($/yr)

CIC= Capital + Installation Cost ($)

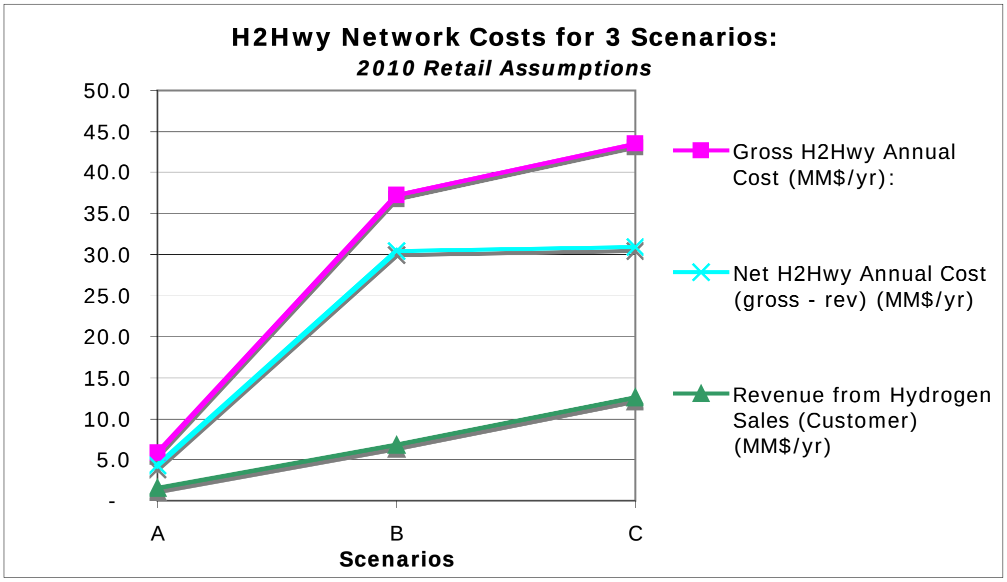
CRF = Capital Recovery Factor (%)

The assumptions for each scenario are provided in Table 1.

Table 4-5: H2Hwy Net Economic Assumptions

Natural Gas Price ($/MMBtu)	$7.0
Electricity Price ($/kWh)	$0.10
Capacity Factor (%)	70%
Equipment Life	15 yrs
Return on Investment	10%
% of labor allocated to fuel sales	50%
Real Estate Cost ($/ft^2/month)	$0.50
Contingency (% of total capital cost)	20%

Figure 4-10: H2Hwy Net Costs for 3 Scenarios



Gross Annual Cost (Million $/yr) represents the levelized annual costs to build and operate the H2Hwy network over 15 yrs. The ***Net Annual Cost*** subtracts the ***Revenue*** gained by selling hydrogen to customers at $3/kg[47] from the gross cost.

NAC = GAC – Rev

Where,

NAC = Net Annual Cost (MM$/yr)

GAS = Gross H2Hwy Annual Cost (MM$/yr)

Rev = Total hydrogen produced x Revenue from Hydrogen Sales

[47] The $3/kg selling price was chosen to be competitive with current gasoline price ($2/gal) on a cost/mile basis.

Each scenario subtracts the cost of 15 stations that are already assumed to be built. For Scenario A, this represents 30% of the total stations. For scenario B and C, it represents only 6% of stations. In both cases, the stations built amount to an offset of roughly $3.5 million/yr (capital cost of 15 stations).

The average cost of hydrogen and overall network cost per vehicle for each station scenario is presented in the table below.

Table 4-6: Hydrogen Cost and Station Network Cost Per Vehicle[48]

Scenario	**A**	**B**	**C**
Hydrogen Cost ($/kg)	$12.68	$18.36	$11.59
Hydrogen Cost per vehicle ($/veh/yr)	$2,774	$3,383	$1,892

This represents the average cost ($/kg) to make hydrogen from a mix of ten different station types (see Table 2). It is calculated by dividing the total annual H2Hwy cost (MM$/yr) by the total hydrogen produced per year (kg/yr). Hydrogen cost rises between scenario 1 and 2 because in Scenario A, the capital cost of 70% of the stations are already paid for.

[48] These results are based on 2010 retail siting assumptions.

The average cost for the H2Hwy per vehicle per year calculated by dividing the net annual H2Hwy cost by the number of vehicles the network will serve (see Table 1) in each scenario. The costs in the figures above are based on the following assumptions:

Table 4-7: Station Assumptions

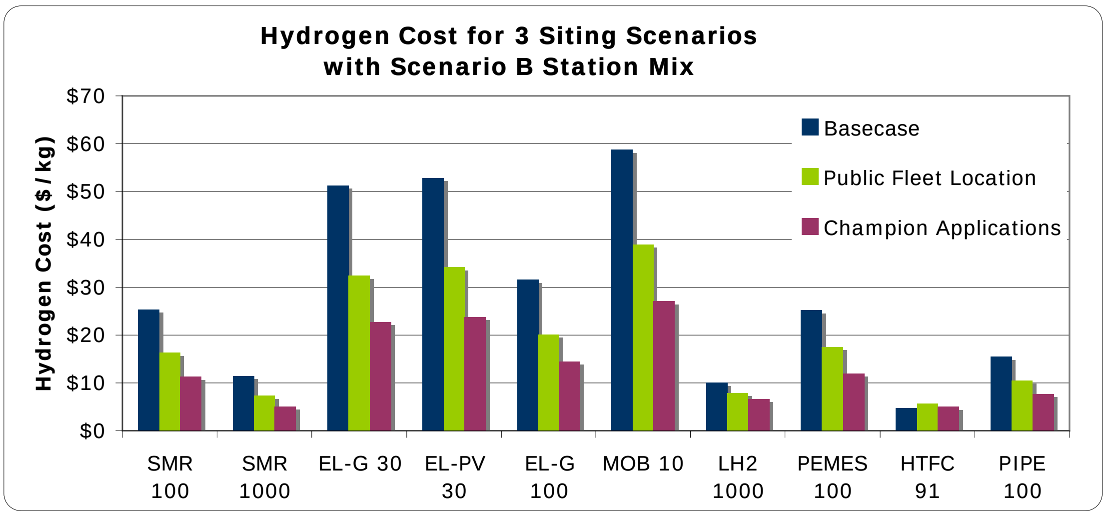
Station Assumptions		
Natural gas ($/MMBtu)	7	/MMBTU
Electricity ($/kWh)	0.1	/kWh
Demand charge ($/kW/month)	$13	/kW
Capacity Factor	16%A, 24%B, 47%C	
After-tax rate of return	10%	=d
recovery period in years	15	=n
% of labor allocated to fuel sales	50%	
Real Estate Cost ($/ft^2/month)	0.5	/ft^2/month
Contingency	20%	of total installed capital cost (TIC)
Property Tax	1%	(% of TIC)

<u>Siting Scenarios</u>

In addition to running station-vehicle scenarios, we have developed three siting scenarios for analyzing station costs: “Base Case 2010 Retail Station”, “Public Fleet Location”, and

"Champion Applications". The characteristics of each scenario are described in more detail in the analysis section. Each siting scenario uses Scenario B's station number, station mix, and vehicle demand. The figure below indicates that hydrogen costs decrease for each station under the three scenarios.

Figure 4-11: Hydrogen Cost for 3 Siting Scenarios, Scenario B Mix



The assumptions under each scenario are presented in the table below. Note that the low capacity factors assumed are not realistic for reformer-type stations. These stations are designed for high capacity factor operation due to start-up/shut-down limits of steam methane reformers.

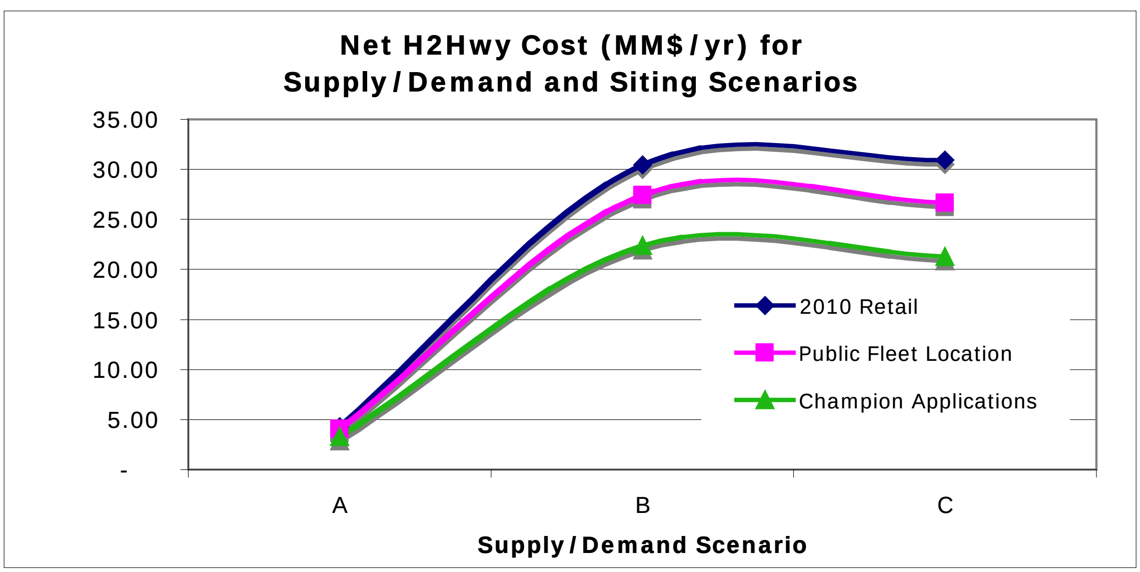
Table 4-8: Siting Scenario Assumptions

Scenario:	***Basecase***	***Public Fleet Location***	***Champion Applications***
Station Assumptions	Scenario 1	Scenario 2	Scenario 3
Natural gas ($/MMBtu)	$7.00	$6.00	$5.00

Electricity ($/kWh)	$0.10	$0.06	$0.05
Demand charge ($/kW/mth)	$13	$13	$13
Capacity Factor	24%	34%	44%
After-tax rate of return	10%	8%	6%
recovery period in years	15	15	15
% of labor allocated to fuel sales	50%	30%	20%
Real Estate Cost ($/ft^2/month)	$0.50	$0.50	$-
Contingency	20%	15%	10%
Property Tax	1%	1%	1%

Combining the supply/demand scenarios with the siting scenarios yields the following figure. This provides an upper and lower bound on the H2Hwy Network cost estimate for scenarios A, B, and C.

Figure 4-12: H2Hwy Net Cost Range for Demand/Supply and Siting Scenarios



Analysis

The following section explores how the costs of stations and the overall H2Hwy Network change under different scenarios and assumptions. It looks at the effects of particular variables to determine the most important factors in hydrogen station cost.

Scenario Analysis

The model can be used to determine how hydrogen cost is affected when several key variables change at once, or, when a station is built under a new scenario. This is useful in determining the affects of strategic station siting. For example, hydrogen costs are evaluated under three siting scenarios: Base case 2010 Retail Station, Public Fleet Location, and Champion Application (leveraging state-owned land, public-private partnerships). The characteristics and assumptions of each scenario are described below:

1. Base-case Scenario: see Chapter 3 description of siting assumptions.

2. Public Fleet Location: this scenario involves siting the station at a public fleet vehicle site such as a bus yard or near a pool of government vehicles. This will enable higher throughput and therefore higher capacity factors since the location ensure a steady reliable demand. This type of facility may also be able to achieve a lower utility rate through inventives and if it is able to qualify for industrial classification.

3. Champion Application: this scenario involves siting the station at "champion" facilities involving partners committed to the projects success in order to minimize expenses and maximize the capacity factor. Leveraging public-private partnerships may enable attractive financing schemes and facilitate stronger local authority cooperation with permitting. Co-locating the station at an existing industrial gas user or distributed generation application will raise capacity factor. Cost improvements resulting from the aforementioned factors will enable more stations to be built, thus creating higher equipment production volumes.

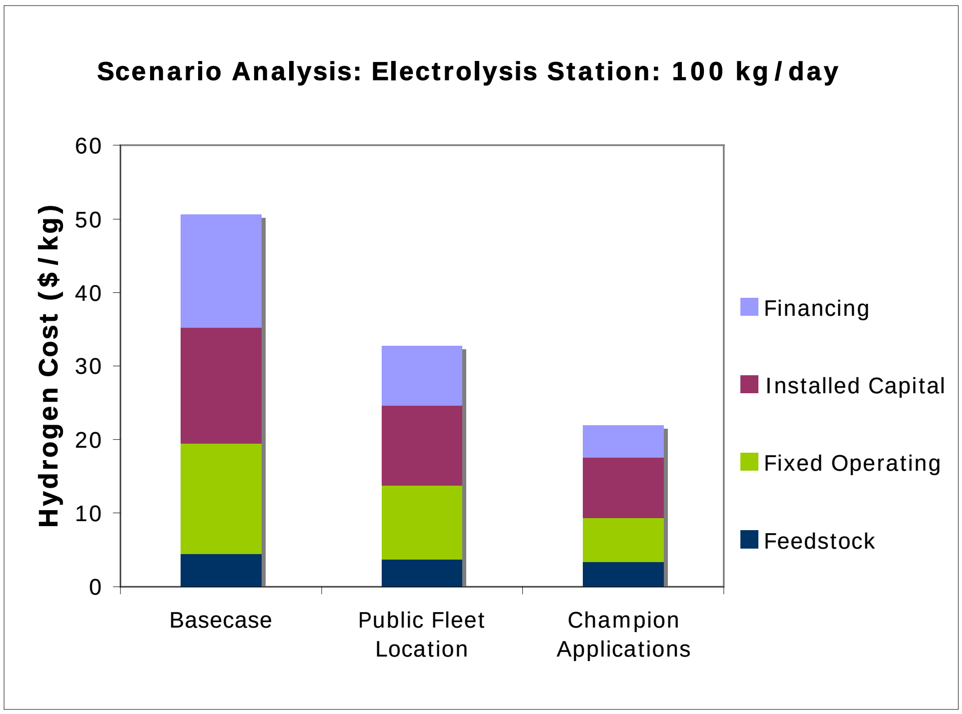
The assumptions under each scenario are presented in the table below:

Table 4-9: Scenario Assumptions

Scenario:	***Basecase***	***Public Fleet Location***	***Champion Applications***
Station Assumptions	Scenario 1	Scenario 2	Scenario 3
Natural gas ($/MMBtu)	$7.00	$6.00	$5.00
Electricity ($/kWh)	$0.10	$0.06	$0.05
Demand charge ($/kW/mth)	$13	$13	$13
Capacity Factor (depends on demand scenario)	(24% base) 0% increase	(24% base) 10% increase	(24% base) 20% increase
After-tax rate of return	10%	8%	6%
recovery period in years	15	15	15
% of labor allocated to fuel sales	50%	30%	20%
Real Estate Cost ($/ft^2/month)	$0.50	$0.50	$-
Contingency	20%	15%	10%
Property Tax	1%	1%	1%

The figure 4-8 above shows how hydrogen costs decrease for each station under the three siting scenarios using Station Mix B (250 stations, 10,000 vehicles, 24% capacity factor). The following figures show the changes in cost components under three scenarios for the electrolysis station. These figures are provided for the other six station types in Appendix I.

Figure 4-13: Electrolysis (30\kg/day) Scenario Analysis



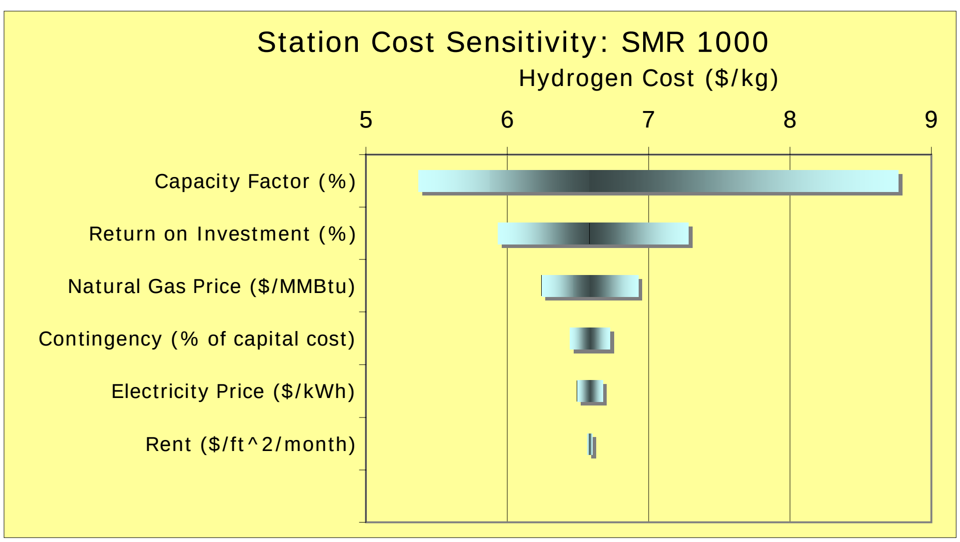
Sensitivity Analysis

A sensitivity analysis was conducted on the 10 major variables in the model to determine each variable's effect on overall hydrogen cost. (see "Sensitivity" sheet). The table below shows the high and low values used for each variable in the sensitivity analysis. The figure bellows shows an example of the results of the analysis for the reformer-type station.

Table 4-10: Sensitivity Values

	Basecase	Bright	Bleak	Actual % change Bright	Actual % change Bleak
Natural Gas Price ($/MMBtu)	$7.0	$4.9	$9.1	30%	30%
Electricity Price ($/kWh)	$0.10	$0.07	$0.13	30%	30%
Demand Charge ($/kW)	$13	$9	$17	30%	30%
Capacity Factor (%)	47%	62%	33%	31%	30%
Return on Investment (%)	10%	7.0%	13%	30%	30%
Recovery period	15	19.5	10.5	30%	30%
Rent ($/ft^2/month)	$0.50	$0.35	$0.65	30%	30%
Contingency (% of capital cost)	20%	14%	26%	30%	30%

Figure 4-14: Sensitivity Analysis for Reformer Station (1000 kg/day)



As can be seen from the above, hydrogen price is most sensitive to capacity factor. This is also true for the nine other station types. The following figure shows the effect station capacity factor has on the price of hydrogen.

Figure 4-15: The Effect of Capacity Factor on Hydrogen Cost

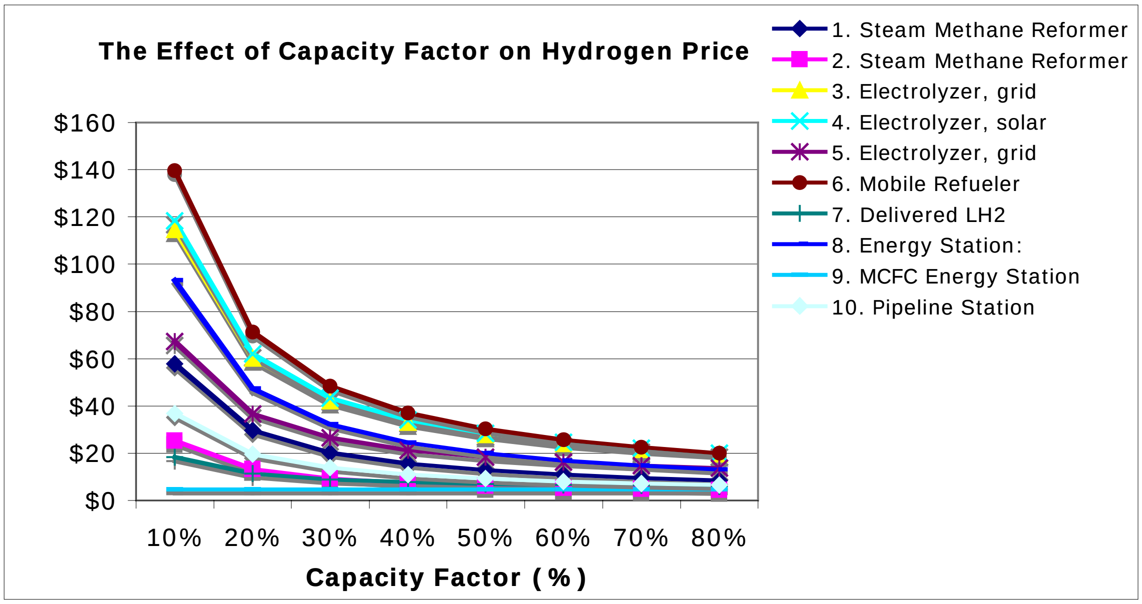
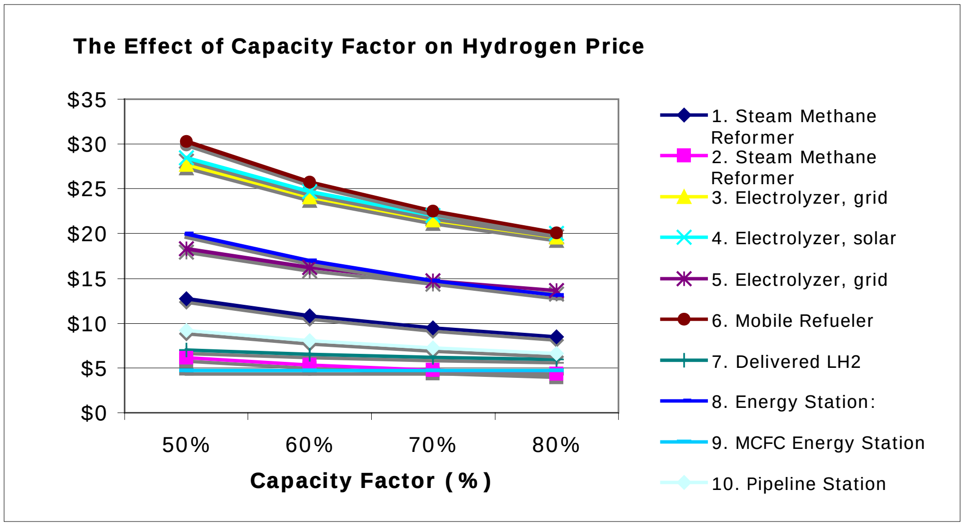


Figure 4-16 is provided to better illustrate the cost effects at high capacity factors.

Figure 4-16: The Effect of Capacity Factor on Hydrogen Cost

(high capacity factors)



Electrolysis Economics: the Effect of Scale and Electricity Price

Electrolyzer costs are highly dependent on scale. The following quote provided by Stuart Energy, an electrolyzer manufacturer, describes this relationship: "For an electrolyser-based hydrogen station of the scale contemplated by the California Hydrogen Highway analysis, variable costs related to the cost of energy make up greater than 40% of the cost of hydrogen. Residential prices for electricity in California, at more than $.10/kWhr, contribute greater than $6.00 /kg of hydrogen produced. In California today, time of use (TOU) and interruptible service rates available for large customers (>500 kW) can yield electricity rates between $.05-.07 /kWhr with capacity factors in excess of 80% (for example, SCE Schedule I-6, LAWDP A-3). With the demand management capabilities of electrolysis, these rates can be leveraged for hydrogen production.

To date, the hydrogen highway model has considered stations between 30 and 1000 kg for the delivery of hydrogen fuel. As an example of the improving economics with scale, consider the unit cost benefit of increasing from a 100 kg/day electrolysis based system, the largest considered by the current analysis, to a 200 kg/day electrolysis based system: [49]

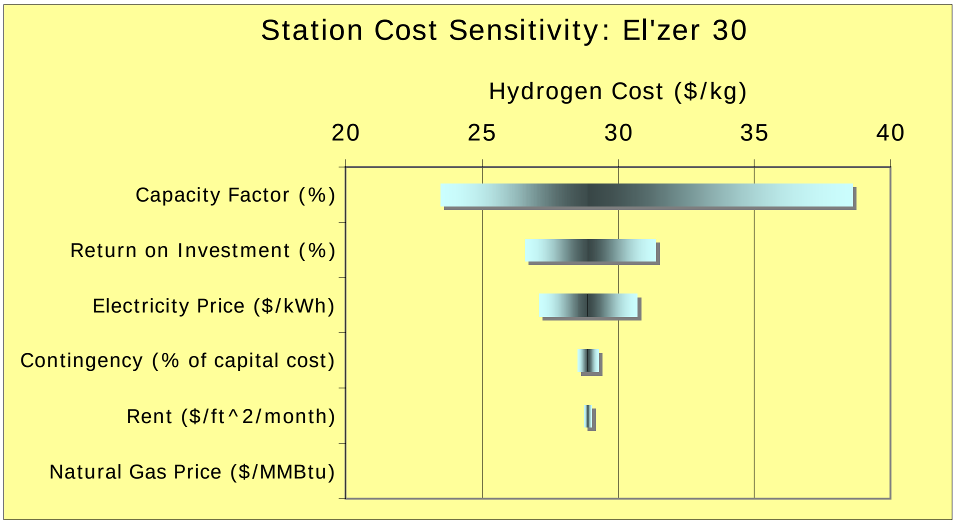
Table 4-11: Electrolyzer Cost vs. Scale

	Electrolyser 30 kg/day	Electrolyser 100 kg/day	Electrolyser 200 kg/day
Analysis	Existing CaHH	Existing CaHH	Additional
Electrolyser Price	$310k	$450k	$600k
Electricity Price	$0.10 /kWhr (Residential)	$0.10 /kWhr (Residential)	$0.065 /kWhr (TOU, Interrupt)
Station Annual Cost	$197 k	$403 k	$493 k
Hydrogen Cost	$25.70	$15.80	$9.64

The following figure shows the effect a drop in electricity price to $0.07/kWh has on hydrogen cost for electrolysis type station.

Figure 4-17: Electrolyzer Station Cost Sensitivity (30 kg/day)

[49] Merer, Rupert of *Stuart Energy* (2004).



At low capacity factors, the effect of an electricity price change is small since the cost of capital dominates. At higher capacity factors, where operating cost dominates, hydrogen price will be more sensitive to electricity price.

The hydrogen costs presented in this section are all much higher than those in the NAS and H2Gen models, especially for electrolyzer stations. This is due to the following factors:

- The HSCM includes station installation costs such as site preparation and permitting
- The HSCM assumes a larger gaseous hydrogen storage capacity
- The 30 kg/day electrolyzer is a small-scale plant.

5. CONCLUSION

The author has reviewed the existing body ot literature on hydrogen fueling station costs and from this, developed two tools for determining the costs of hydrogen fueling stations. These tools have been and applied to the specific case of California's Hydrogen Highway Network. The CHREC is a tool to collect and compare data on the costs of hydrogen station equipment and installation costs. The HSCM is a model to calculate the costs of seven types of hydrogen station of varying size under a variety of assumptions (i.e. production volume, feedstock cost, etc.). Through the development and applications of these tools, the author has made the following conclusions:

1. Existing analyses on the economics of hydrogen stations under-estimate the costs of building hydrogen stations in the near-term. They often omit important installation costs such as permitting and site development, and overlook operating costs such as liability insurance and maintenance. Many analyses also use equipment costs associated with higher production volumes than what industry is experiencing today.
2. In order to achieve hydrogen costs competitive with current gasoline prices, production volumes for stations will need to reach levels in the 1000's. This is equivalent to about 6% of gasoline stations in California.[50]

[50] This assumes units are made from a single manufacturer.

3. Capacity factor, or station utilization, has the biggest impact on hydrogen cost. Station operators should try to maintain high station utilization in order to achieve low hydrogen cost.
4. The strategic location of stations and vehicles is critical to station economics. The scenario analysis showed that "Champion Applications" resulted in the lowest cost hydrogen. This involves building stations on state-owned land to reduce real-estate costs and installation costs (easier permitting process), and taking advantage of fleet vehicle clusters to increase capacity factor.
5. Large stations (1000 kg/day) like the reformer station and liquid hydrogen station exhibit the lowest costs since they are able to spread their installation and capital costs over a large volume of hydrogen sales. These large stations also show the result of equipment scale economies on reducing cost.
6. Electrolyzer refueling stations yield high hydrogen costs due to low throughput (30-100 kg/day) and high electrolyzer capital costs at small scale. At low capacity factors (<30%), capital costs dominate and thus electricity price does not substantially affect hydrogen cost.
7. Mobile refuelers yield the most expensive hydrogen due to their small size (10kg/day) and the high cost to refill them.
8. Energy stations have the potential for lower cost hydrogen due to increased equipment utilization (hydrogen is produced for cars and stationary power). Costs for these station types are the most uncertain since only a few PEM/Reformer energy station have been built and no HTFC energy stations have yet been built.

9. Station sited near an industrial demand for hydrogen can share the hydrogen use and thus take advantage of scale-economies and high capacity factors.
10. Pipeline stations have potential for low cost at low flow rates when sited near existing pipelines.
11. The HSCM is a flexible tool for comparing different analyses on hydrogen station cost. This tool was used to compare the results of H2Gen and the NAS report by using their assumptions and identifying where the results differed.
11. The HSCM, though applied in this report to California's Hydrogen Highway Network, is flexible enough to model the construction of hydrogen stations in any region.

The cumulative production volumes that will result from the H2Hwy Net do not appear to be high enough to achieve hydrogen costs projected by the NAS. This is due in part to the higher capital costs being experienced in industry today compared to the projections in the report. It is also due to the higher installation costs, insurance, and operating costs not necessarily accounted for in the NAS report.

At present, station costs are higher than reported in the available literature. In addition to the costs being higher than expected, hydrogen cost from the H2Hwy Net stations will not decrease significantly throughout the length of the project. The analysis shows that building 50-250 stations for the H2Hwy alone will not be enough to bring costs down to NAS levels. Cost levels seen in the NAS reports may not be achieved for many years (production volumes in the 1000s are required).

Despite the high cost in the near term, however, there is unaccounted value in demonstrating hydrogen station technologies. The anticipated scale of the H2Hwy demonstration will impact California's local hydrogen/fuel cell industry and send a signal to automakers investing in fuel cell vehicle technology. Building stations also helps establish uniform codes and regulations by providing a real-world example for officials to reference. It also helps in demonstrating the safety of hydrogen stations and in sending the message to the public. The long-term impacts of this project on the state's economy and air quality could be enormous.

With the HSCM model, I look at how many stations needed to get down to NAS levels. For reference, there are 180,000 gas stations in US. Building 4000 stations, the level needed for low cost hydrogen, represents 0.2% of total gas stations. Achieving low cost hydrogen will require time and building stations (to get production volumes higher). In the interim while companies and governments are building theses stations, they should note the various ways to reduce station costs, namely: larger stations, higher capacity factor, and sharing the station with specialty hydrogen applications.

Next Steps/Future Work

The author intends to use this model for further hydrogen station cost analysis. This work will be merged with models created by other researchers to examine the trade-offs between accessibility, emissions, and cost for a network of stations in a given region. The model will also be used with GIS tools to examine the trade-offs between station size, station number, and location. With some adjustment of the assumptions in the model, the HSCM can also be applied to determining station network costs in other regions and countries. Shanghai is one place in particular where the model will be applied.

REFERENCES

1. Dale Simbeck and Elaine Chang (Jul-02) “Hydrogen Supply: Cost Estimate for Hydrogen Pathways - Scoping Analysis” SFA Pacific, Mountain View, CA

2. Lipman, T., Kammen, D. (Nov-02) “Economic Analysis of Hydrogen Energy Station Concepts”, RAEL, University of California Berkeley, CA

3. Duane B. Myers,Gregory D. Ariff, Brian D. James, John S. Lettow, C.E. (Sandy) Thomas, & Reed C. Kuhn (Apr-02) “Cost and Performance Comparison Of Stationary Hydrogen Fueling Appliances” DTI, Arlington, VA

4. C. E. (Sandy) Thomas, John P. Reardon, Franklin D. Lomax, Jr., Jennifer Pinyan & Ira F. Kuhn, Jr. (2001) “Distributed Hydrogen Fueling Systems Analysis” DTI, Arlington, VA

5. Amos, W. (Nov-98) “Costs of Storing and Transporting Hydrogen” NREL, Golden, CO

6. Thomas G. Kreutz, Joan M. Ogden (2000) “Assessment of Hydrogen Fueled Proton Exchange Membrane Fuel Cells for Generation and Cogeneration” Center for Energy and Environmental Studies Princeton University Princeton, NJ 08544

7. Padró, C.E.G. and Putsche, V. (Sep-99) “Survey of the Economics of Hydrogen Technologies” NREL, Golden, CO

8. Unnasch, Stefan (2002) “Energy stations for Federal Buildings”, NREL Proceedings 2002

9. Melaina, M. (2003) “Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US”, IJHE v.28 pp.743-755

10. Timothy E. Lipman,Jennifer L. Edwards,Daniel M. Kammen, (2002) *“Fuel cell system economics: comparing the costs of generating power with stationary and motor vehicle PEM fuel cell systems”* Energy Policy, Renewable and Appropriate Energy Lab (RAEL), Energy and Resources Group, University of California

11. Rastler, D. (2000) “Challenges for fuel cells as stationary power resource in the evolving energy enterprise”, Journal of Power Sources v.86, pp.34-39

12. Ianucci, Eyer, Horgan, and Schoenung (1998) “Economic and Technical Analysis of Distributed Utility benefits for Hydrogen Refueling Stations” Distributed Utility Associates, Livermore, CA and Longitude 122 West (Schoenung)

13. Raman, V. (2001), “Research and Development of a PEM Fuel Cell, Hydrogen Reformer, and Vehicle Refueling Facility”, Proceedings of the 2002 DOE Hydrogen Program Review, Air Products and Chemicals Inc.

14. Venkatesh, S. et al, (Tiax LLC) (2004), “Failure Modes and Effects Analysis for Hydrogen Fueling Options”, Consultant report prepared for the California Energy Commission.

14. Powars, C. et al, (Tiax LLC) (2004), “Hydrogen Fueling Station Guidelines”, Consultant report prepared for the California Energy Commission.

15. Sepideh, S. (2003) “The Costs of Hydrogen Technologies” (final draft of PhD Dissertation Thesis), Personal communication, Imperial College, London, United Kingdom.

APPENDICES

Appendix A: Summary of Costs for 10 Station Types

	SMR 100	SMR 1000	EL-G 30	EL-PV 30	EL-G 100	MOB 10	LH2 1000	PEMES 100	HTFC 91	PIPE 100
Hydrogen Equipment	$317,981	$1,265,904	$147,301	$147,301	$250,191	$162,804	$510,049	$317,981	$365,075	$100,000
Purifier	$63,715	$201,486		$-		$-	$-	$63,715	$-	$20,000
Storage System	$196,865	$2,372,295	$51,348	$51,348	$188,693	$-	$1,102,748	$40,692	$136,186	$45,600
Compressor	$51,652	$171,113	$27,611	$27,611	$51,652	$-	$218,507	$51,652	$49,235	$75,603
Dispenser	$42,377	$127,130	$42,377	$42,377	$42,377	$-	$127,130	$42,377	$42,377	$42,377
Additional Equipment	$72,098	$77,458	$66,738	$66,738	$72,098	$10,000	$87,458	$107,098	$122,658	$72,098
Installation Costs	$193,455	$300,373	$165,408	$128,021	$228,837	$44,227	$329,858	$192,566	$196,942	$175,027
Contingency	$109,784	$621,443	$49,442	$62,710	$89,192	$25,475	$301,611	$131,460	$147,497	$52,435
Fuel Cell / Photovoltaics	$-	$-	$-	$90,000	$-	$-	$-	$268,210	$284,978	$-
Total Investment	$1,047,927	$5,137,202	$550,225	$616,105	$923,039	$242,506	$2,677,362	$1,215,751	$1,344,947	$583,141
Hydrogen $/yr	$-	$-	$-	$-	$-	$4,331	$713,757	$-	$-	$34,648
Delivery	$-	$-	$-	$-	$-	$806	$-	$-	$-	$-
Natural gas $/yr	$19,708	$197,080	0	$-	$-	$-	$-	$37,370	$106,511	$-
Electricity $/yr	$6,289	$63,205	$42,884	$27,254	$142,945	$-	$19,059	$(37,961)	$(200,605)	$5,977
Maint., Labor, Overhead $/yr	$66,597	$195,993	$33,731	$38,831	$59,613	$16,984	$168,190	$76,349	$78,507	$38,833
Total Operating Cost	$92,594	$456,278	$76,615	$66,085	$202,558	$22,121	$901,007	$75,758	$(15,586)	$79,459
Annualized Cost	$230,369	$1,131,685	$148,955	$147,086	$323,914	$54,005	$1,253,010	$235,598	$161,239	$156,126
Sales Revenue $3/kg/yr	$51,973	$519,726	$15,592	$15,592	$51,973	$5,197	$519,726	$51,973	$99,645	$51,973
Annual Funding Need	$178,396	$611,959	$133,363	$131,495	$271,941	$48,807	$733,284	$183,625	$61,594	$104,154
Annualized Cost/Kg	$13.30	$6.53	$28.66	$28.30	$18.70	$31.17	$7.23	$13.60	$4.85	$9.01
Annual Funding Need/Kg	$10.30	$3.53	$25.66	$25.30	$15.70	$28.17	$4.23	$10.60	$1.85	$6.01
Capcity Kg/day	100	1000	30	30	100	10	1000	100	91	100
Capacity Utilization	47%	47%	47%	47%	47%	47%	47%	47%	100%	47%
Hydrogen Sales Kg/yr	17,324	173,242	5,197	5,197	17,324	1,732	173,242	17,324	33,215	17,324
Natural Gas Cost/kg	$1.14	$1.14	$-	$-	$-	$-	$-	$2.16	$3.21	$-
Electricty Cost/Kg	$0.36	$0.36	$8.25	$5.24	$8.25	$-	$0.11	$(2.19)	$(6.04)	$0.35
Fixed Operating/Kg	$3.84	$1.13	$6.49	$7.47	$3.44	$12.77	$5.09	$4.41	$2.36	$4.24
Capital Charge /Kg	$5.65	$3.20	$8.48	$10.76	$4.59	$13.11	$1.55	$6.77	$3.96	$2.70
Delivery and Installation Charge /Kg	$2.30	$0.70	$5.44	$4.82	$2.41	$5.29	$0.48	$2.46	$1.36	$1.73

Key Assumptions: 13% Capital recovery factor

Assumes a scenario of 20,000 vehicles and 250 stations sited in 2010

Additional equipment includes mechanical, electrical, and safety equipment

Labor and Overhead costs are maintenance, rent, labor, insurance, property tax

Installation Costs includes engineering and design, permitting, site development and safety & hazops analysis, installation, delivery, start-up & commissioning

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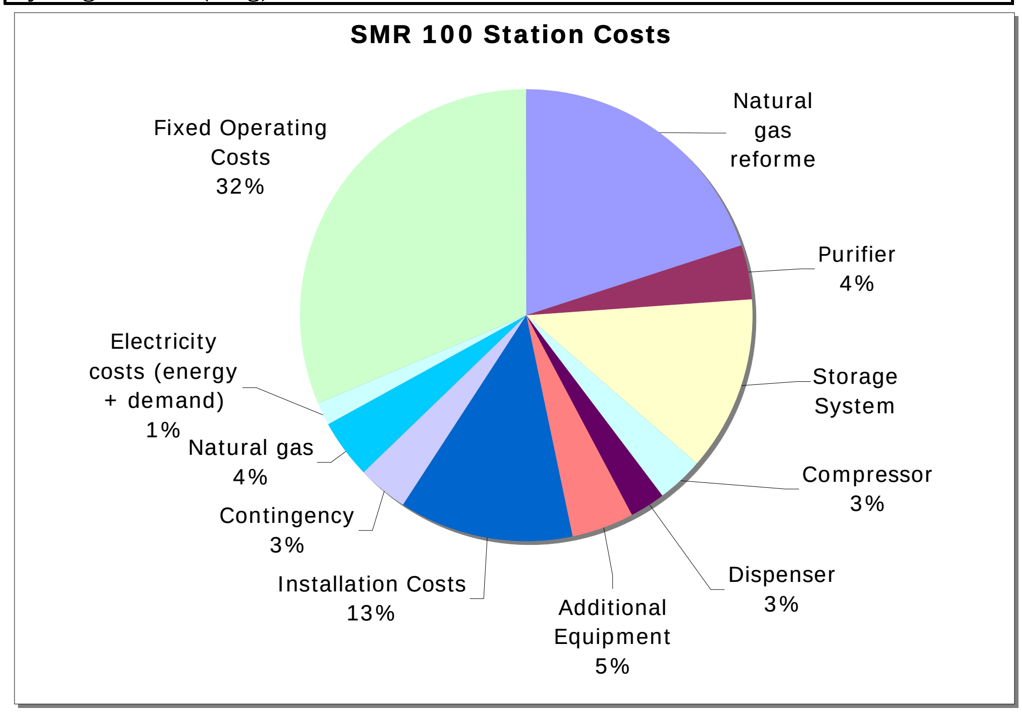
Appendix B: Station Costs by Type

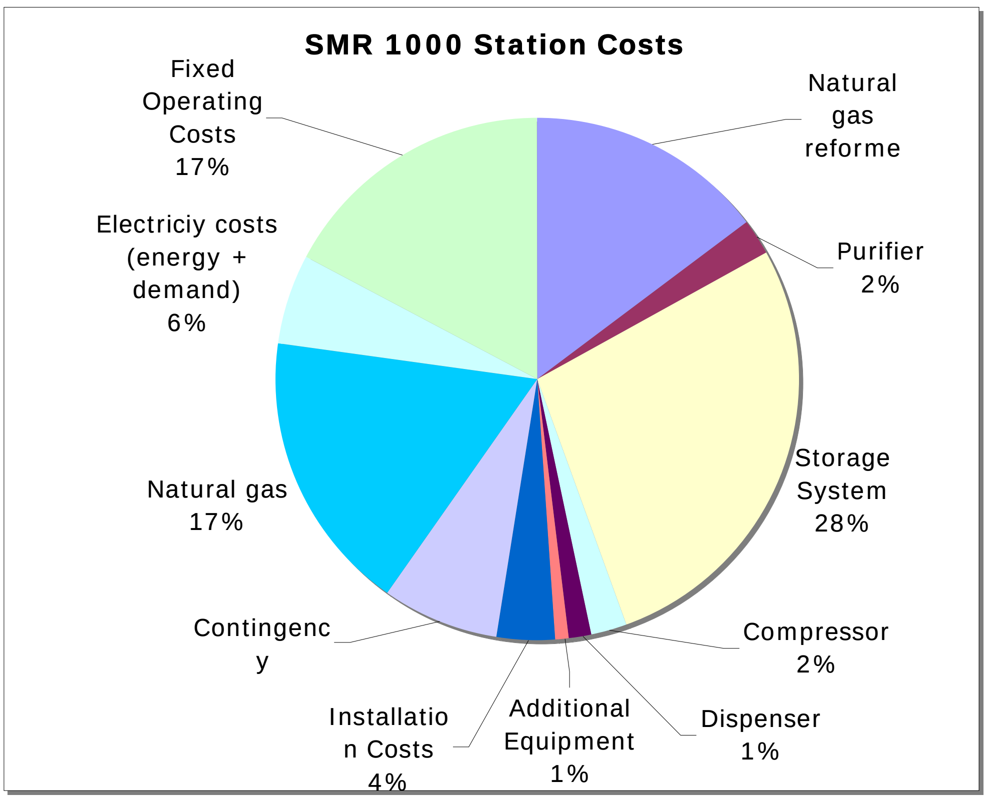
The following cost results are based on a capacity factor of 47% and the other base-case assumptions in Appendix C).

Station 1: Steam Methane Reformer, 100 kg/day		$	$/yr
Natural gas reformer	18.1%	$317,981	
Purifier	3.6%	$63,715	
Storage System	11.2%	$196,865	
Compressor	2.9%	$51,652	
Dispenser	2.4%	$42,377	
Additional Equipment	4.1%	$72,098	
Installation Costs	11.4%	$193,455	
Contingency	6.3%	$109,784	
Natural gas	8.6%		$19,708
Electricity costs (energy + demand)	2.7%		$6,289
Fixed Operating Costs	28.9%		$66,597
Total	100%	**$1,047,927**	**$92,594**
Annual Cost ($/yr)	$230,369		
Hydrogen Price ($/kg)	$13.30		

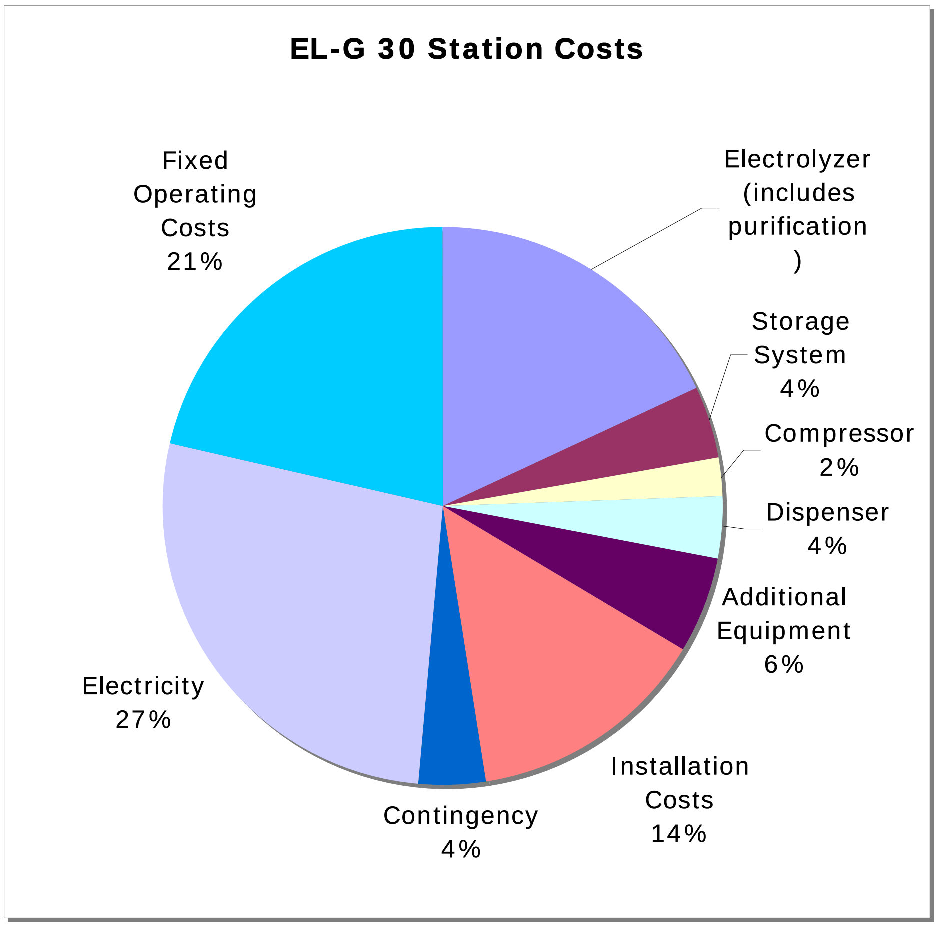


Station 2: Steam Methane Reformer, 1000 kg/day

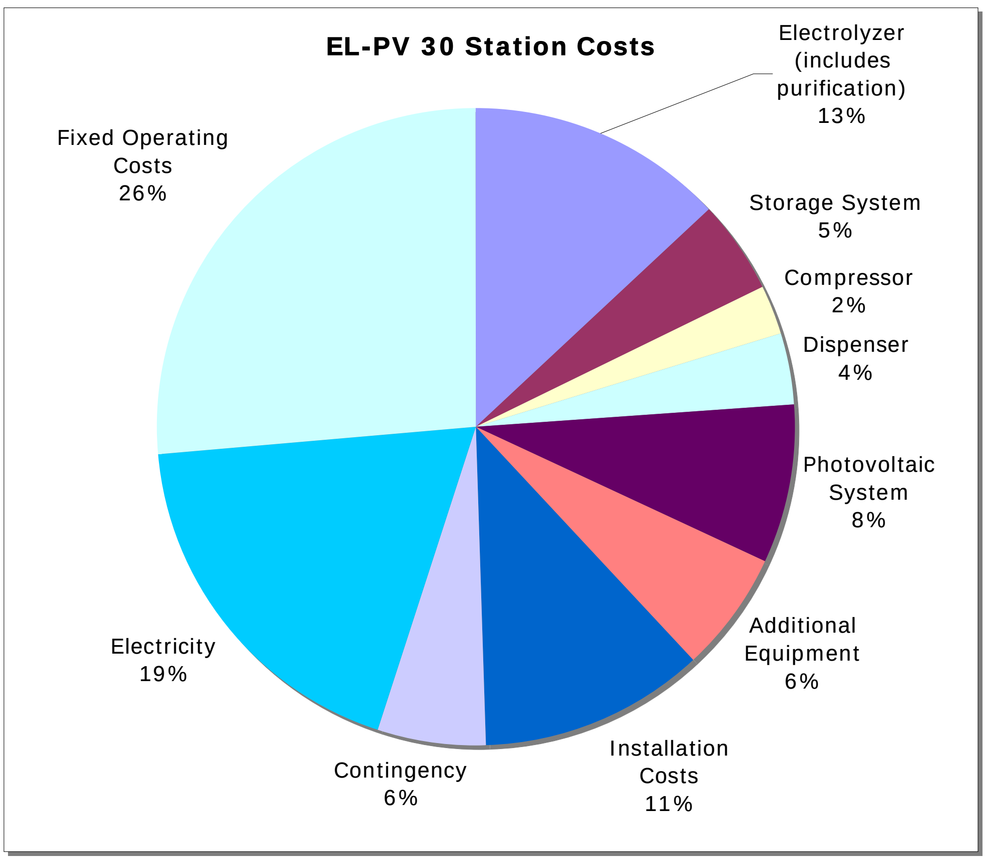
Natural gas reformer	14.7%	$1,265,904	
Purifier	2.3%	$201,486	
Storage System	27.6%	$2,372,295	
Compressor	2.0%	$171,113	
Dispenser	1.5%	$127,130	
Additional Equipment	0.9%	$77,458	
Installation Costs	3.6%	$300,373	
Contingency	7.2%	$621,443	
Natural gas	17.4%		$197,080
Electriciy costs (energy + demand)	5.6%		$63,205
Fixed Operating Costs	17.3%		$195,993
Total	100%	**$5,137,202**	**$456,278**
Annual Cost ($/yr)	$1,131,685		
Hydrogen Price ($/kg)	$6.53		



Station 3: Electrolyzer-grid, 30 kg/day			
Electrolyzer (includes purification)	19.0%	$147,301	
Storage System	4.5%	$51,348	
Compressor	2.4%	$27,611	
Dispenser	3.7%	$42,377	
Additional Equipment	5.9%	$66,738	
Installation Costs	14.6%	$165,408	
Contingency	4.4%	$49,442	
Electricity	28.8%		$42,884
Fixed Operating Costs	22.6%		$33,731
Total	106%	**$550,225**	**$76,615**
Annual Cost ($/yr)	$148,955		
Hydrogen Price ($/kg)	$28.66		

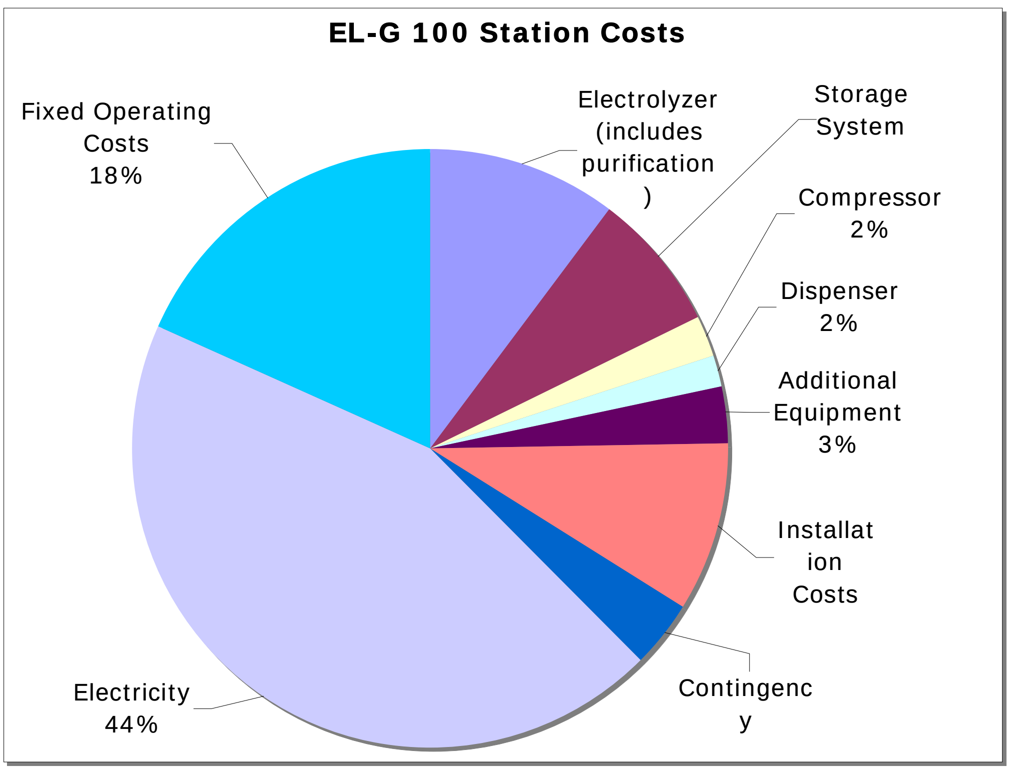


Station 4: Electrolyzer-solar, 30 kg/day			
		$	**$/yr**
Electrolyzer (includes purification)	13.2%	$147,301	
Storage System	4.6%	$51,348	
Compressor	2.5%	$27,611	
Dispenser	3.8%	$42,377	
Photovoltaic System	8.0%	$90,000	
Additional Equipment	6.0%	$66,738	
Installation Costs	11.4%	$128,021	
Contingency	5.6%	$62,710	
Electricity	18.5%		$27,254
Fixed Operating Costs	26.4%		$38,831
Total	100%	**$616,105**	**$66,085**
Annual Cost ($/yr)	$147,086		
Hydrogen Price ($/kg)	$28.30		



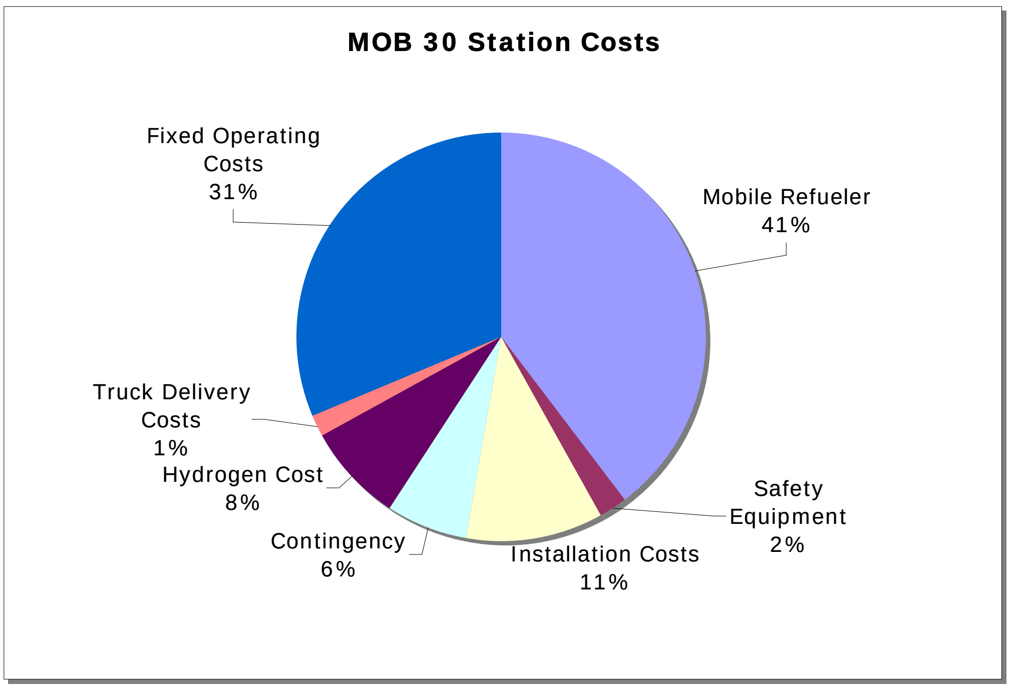
Station 5: Electrolyzer-grid, 100 kg/day

		$	$/yr
Electrolyzer (includes purification)	10.2%	$250,191	
Storage System	7.7%	$188,693	
Compressor	2.1%	$51,652	
Dispenser	1.7%	$42,377	
Additional Equipment	2.9%	$72,098	
Installation Costs	9.3%	$228,837	
Contingency	3.6%	$89,192	
Electricity	44.1%		$142,945
Fixed Operating Costs	18.4%		$59,613
Total	100.0%	**$923,039**	**$202,558**
Annual Cost ($/yr)	$323,914		
Hydrogen Price ($/kg)	$18.70		



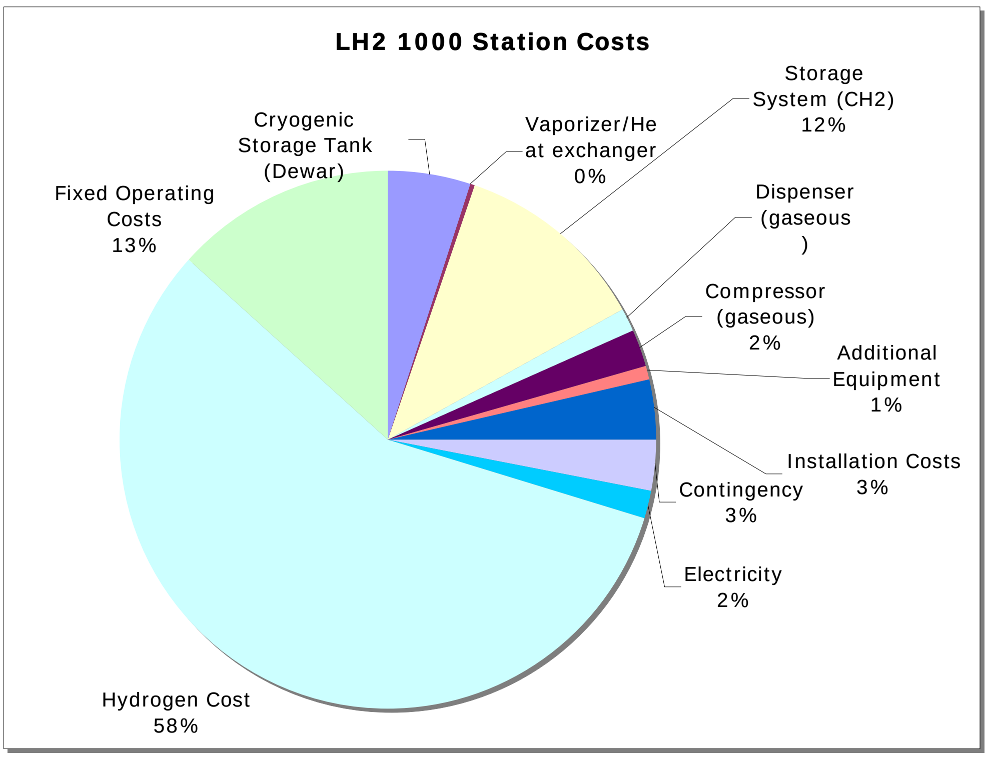
Station 6: Mobile Refueler, 10 kg/day

			$/yr
Mobile Refueler	39.6%	$162,804	
Safety Equipment	2.4%	$10,000	
Installation Costs	10.8%	$44,227	
Contingency	6.2%	$25,475	
Hydrogen Cost	8.0%		$4,331
Truck Delivery Costs	1.5%		$806
Fixed Operating Costs	31.4%		$16,984
Total	100.0%	**$242,506**	**$22,121**
Annual Cost ($/yr)	$54,005		
Hydrogen Price ($/kg)	$31.17		

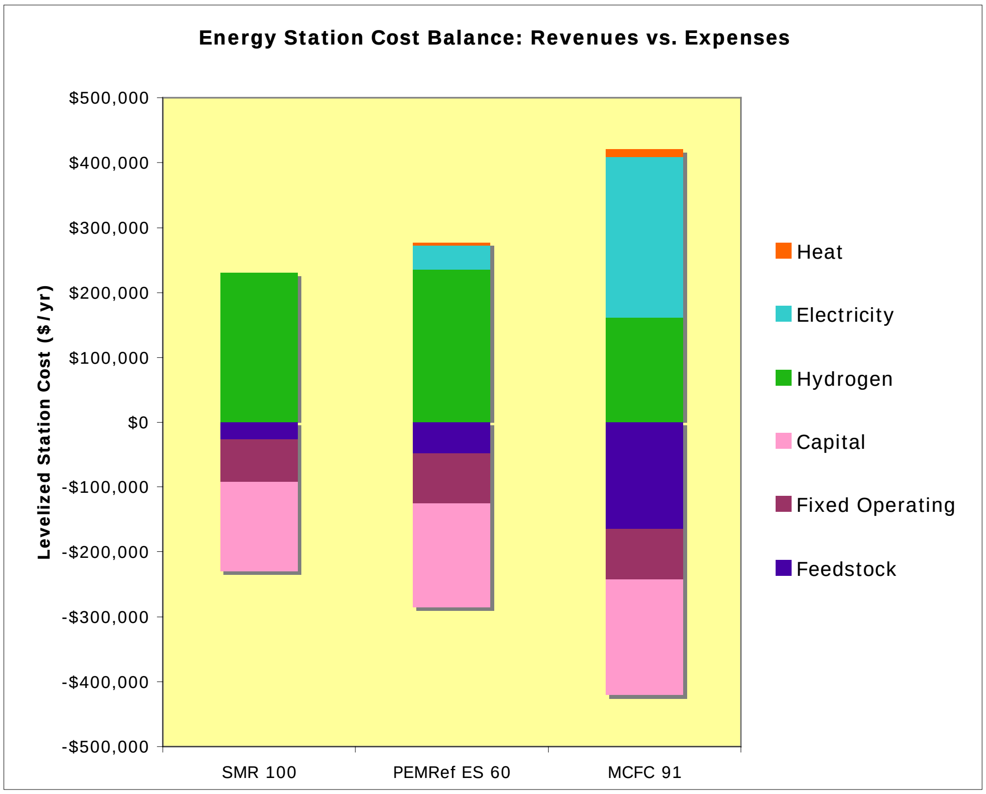


Station 7: Liquid Hydrogen Station, 1000 kg/day

		$	**$/yr**
Cryogenic Storage Tank (Dewar)	4.9%	$463,681	
Vaporizer/Heat exchanger	0.5%	$46,368	
Storage System (CH2)	11.6%	$1,102,748	
Compressor (gaseous)	2.3%	$218,507	
Dispenser (gaseous)	1.3%	$127,130	
Additional Equipment	1%	$87,458	
Installation Costs	3%	$329,858	
Contingency	3%	$301,611	
Electricity	2%		$19,059
Hydrogen Cost	57%		$713,757
Fixed Operating Costs	13.4%		$168,190
Total	100%	**$2,677,362**	**$901,007**
Annual Cost ($/yr)	$1,253,010		
Hydrogen Price ($/kg)	$7.23		



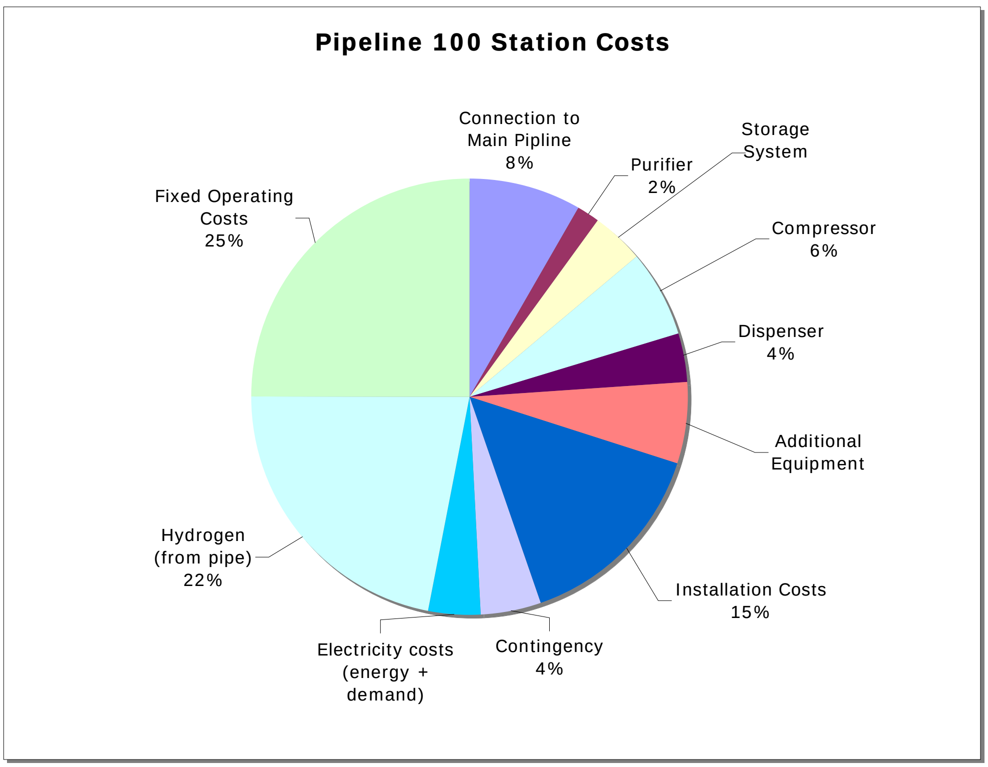
Station 8: PEM/Reformer Energy Station, 100 kg/day			
		$	**$/yr**
Natural gas reformer	17.7%	$317,981	
Purifier	3.6%	$63,715	
Storage System	2.3%	$40,692	
Compressor	2.9%	$51,652	
Dispenser	2.4%	$42,377	
PEM Fuel Cell	15.0%	$268,210	
Additional Equipment	6.0%	$107,098	
Installation Costs	10.7%	$192,566	
Contingency	7.3%	$131,460	
Electricity costs (energy + demand)	-16.1%		$(37,961)
Natural gas	15.9%		$37,370
Fixed Operating Costs	32.4%		$76,349
Total	100.0%	**$1,215,751**	**$75,758**
Annual Cost ($/yr)	$235,598		
Hydrogen Price ($/kg)	$13.599		



Option 9: MCFC Energy Station, 100 kg/day			
		$	**$/yr**
Natural gas reformer	29.8%	$365,075	
Purifier	0.0%	$-	
Storage System	11.1%	$136,186	
Compressor	4.0%	$49,235	
Dispenser	3.5%	$42,377	
MC Fuel Cell	23.2%	$284,978	
Additional Equipment	10.0%	$122,658	
Installation Costs	16.1%	$196,942	
Contingency	12.0%	$147,497	
Electricity costs (energy + demand)	-124.4%		$(200,605)
Natural gas	66.1%		$106,511
Fixed Operating Costs	48.7%		$78,507
Total	100.0%	**$1,344,947**	**$(15,586)**
Annual Cost ($/yr)	$161,239		
Hydrogen Price ($/kg)	$4.84		

Station 10: Pipeline Station, 100 kg/day

		$	$/yr
Connection to Main Pipline	8.4%	$100,000	
Purifier	1.7%	$20,000	
Storage System	3.8%	$45,600	
Compressor	6.4%	$75,603	
Dispenser	3.6%	$42,377	
Additional Equipment	6.1%	$72,098	
Installation Costs	14.7%	$175,027	
Contingency	4.4%	$52,435	
Electricity costs (energy + demand)	3.8%		$5,977
Hydrogen (from pipe)	22.2%		$34,648
Fixed Operating Costs	24.9%		$38,833
Total	100.0%	**$583,141**	**$79,459**
Annual Cost ($/yr)	$156,126		
Hydrogen Price ($/kg)	$9.01		



Appendix C: Station Assumptions

Basecase Station Assumptions

Natural gas ($/MMBtu)	7	/MMBTU
Electricity ($/kWh)	0.1	/kWh
Demand charge ($/kW/month)	$13	/kW
Capacity Factor	47%	
After-tax rate of return	10%	=d
recovery period in years	15	=n
% of labor allocated to fuel sales	50%	
Real Estate Cost ($/ft^2/month)	0.5	/ft^2/month
Contingency	20%	of total installed capital cost (TIC)
Property Tax	1%	(% of TIC)

Equipment Assumptions

Equipment	***Type***	***Scaling Factors***
Reformer	SMR, Pressurized, 10 atm	0.6
Electrolyzer	Alkaline	0.44
Purifier	Pressure Swing Absorption	0.5
Compressor	reciprocating	
Storage	carbon steel tanks, cascade system, max vessel size 3 m^3	
Dispenser		
Fuel Cell	PEM/MCFC	
Mobile Refueler	includes storage, compressor, and dispenser	
LH2 Equipment	Dewar vessel and vaporizer	

Station Construction (non-capital Costs)	Inc. engineering/design, permitting, site development, installation, Safety and Haz Ops, equipment delivery, installation, start-up and commissioning, & contingency.		
Compression energy	3	kWh/kg	
Outlet Pressure	5000	psi	
Percent of vehicles fueled in:	3	hours =	40%

Appendix D: Hydrogen Highway Assumptions

Production Volume Assumptions for H2Hwy Case Scenario **A,B,C**

Equipment	**Current Cumm. Prod Vol. (units)**	**2010 Projected Prod Vol. (units)**	**Progress Ratio**	**Prod Vol Discount Factor**
Reformer	4	24	85%	77%
Electrolyzer	10	114	85%	68%
Purifier	10	79	85%	73%
Compressor	100	280	90%	91%
Storage	300	934	95%	95%
Dispenser	17	215	90%	77%
Fuel Cell	5	32	85%	76%
Mobile Refueler	10	80	90%	81%
LH2 Equipment	5	12	90%	93%
Station Construction (non-capital Costs)	15	265	90%	74%

H2Hwy Network Assumptions

Scenario	A	B	C
# of Stations	50	250	250
LD Vehicles	2000	10000	20000
HD Vehicles	10	100	300
H2 Demand, kg/yr	459,289	2,027,025	3,755,114
Capactiy Factor	**16%**	**24%**	**47%**
% of stations			
1. Steam Methane Reformer, 100	12.0%	8.0%	8.0%
2. Steam Methane Reformer, 1000	0.0%	0.8%	0.8%
3. Electrolyzer, grid, 30	6.0%	6.4%	6.4%
4. Electrolyzer, renewable energy, 30	18.0%	27.6%	27.6%
5. Electrolyzer, grid, 100	10.0%	7.6%	7.6%
6. Mobile Refueler, 10	20.0%	28.0%	28.0%
7. Delivered LH2, 1000	8.0%	2.8%	2.8%
8 & 9 Energy Stations, 100	18.0%	14.4%	14.4%
10. Pipeline Station, 100	8.0%	4.4%	4.4%
	100.0%	100.0%	100.0%
# of stations	A	B	C
1. Steam Methane Reformer	6	20	20
2. Steam Methane Reformer	0	2	2
3. Electrolyzer, grid	3	16	16
4. Electrolyzer, renewable energy	9	69	69
5. Electrolyzer, grid	5	19	19
6. Mobile Refueler	10	70	70
7. Delivered LH2	4	7	7
8 & 9 Energy Stations	9	36	36
10. Pipeline Station	4	11	11
	50	**250**	**250**

Appendix E: Production Volume and Scaling Adjustments

Scaling and Production Volume Adjustment of Industrial Data

=industry data
= adjusted data
= assumption

Industry Data on SMR Reformers

			kg/hr	units/yr	kg/hr	units/yr
			4.2	4	42	1
Capacity (kg/hr)	Production Volume (units/yr)	Total Cost ($2004)	Total Cost: (Size Scaled)	Total Cost (PV Scaled)	Total Cost: (Size Scaled)	Total Cost (PV Scaled)
1.5	2	$372,000	$686,691	583,687	2,733,767	1,874,465
4.16	2	$400,000	$400,384	340,327	1,593,959	1,092,932
6.25	2	$200,000	$156,811	133,289	624,274	428,047
9	2	$1,116,000	$703,059	597,600	2,798,929	1,919,145
		AVERAGE	486,736	**413,726**	1,937,732	**1,328,647**
		Standard Deviation		$221,155		$710,222

Industry Data on Alkaline Electrolyzer

			kg/hr	units/yr	kg/hr	units/yr
			1.25	10	4.17	10
Capacity (kg/hr)	Production Volume (units/yr)	Total Cost ($2004)	Total Cost: (Size Scaled)	Total Cost (PV Scaled)	Total Cost: (Size Scaled)	Total Cost (PV Scaled)
3.43	2	$686,044	$440,011	301,703	747,623	512,623
1	2	$161,116	$177,738	121,870	301,995	207,069
1.3	1	$370,000	$357,856	208,565	608,033	354,374
2.7	1	$450,000	$320,823	186,982	545,111	317,702
5.4	1	$670,000	$352,107	205,215	598,265	348,681
1.3	10	$250,000	$241,794	241,794	410,833	410,833
2.7	10	$310,000	$221,011	221,011	375,521	375,521
5.4	10	$450,000	$236,490	236,490	401,820	401,820
		AVERAGE	$293,479	**$215,454**	$498,650	**$366,078**
		Standard Deviation		$51,168		$86,939

Industry Data on Purifiers

			kg/hr	units/yr	kg/hr	units/yr
			4.17	10	41.7	10
Capacity (kg/hr)	Production Volume (units/yr)	Cost (2004$)	Total Cost: (Size Scaled)	Total Cost (PV Scaled)	Total Cost: (Size Scaled)	Total Cost (PV Scaled)
3	2	$100,000	$117,898	80,839	372,827	255,637
9	2	$200,000	$136,137	93,345	430,504	**295,184**
		AVERAGE		**87,092**		**275,410**
		Standard Deviation		$8,843		$27,964

Appendix F: Sources of Industry Cost Data

Tiax
Air Products
BOC
BP
Cal State University LA
Chevron Texaco
Clean Energy
Dynetek
FIBA
Fuel Cell Energy
Fueling Technologies Inc.
H2Gen
Harvest Technologies
Hydrogenics
HydroPac
ISE Research
Nippon Oil
PDC Machines
Praxair
Pressure Products Industries
Proton Energy
Quantum Technologies
SCAQMD
Stuart Energy
Toyota
Ztek

Appendix G: Compressor and Storage Sizing Calculations

TIAX LLC Copyright 2004 Station	ON SITE PRODUCTION Station 1: Steam Methane Reformer, 100 kg/day	ON SITE PRODUCTION Station 2: Steam Methane Reformer, 1000 kg/day	ON SITE PRODUCTION	ON SITE PRODUCTION Station 3: Electrolyzer-grid, 30 kg/day	DELIVERED Station 5: Electrolyzer-grid, 100 kg/day	DELIVERED Station 7: Liquid Hydrogen Station, 1000 kg/day	DELIVERED Station 10: Pipeline Station, 100 kg/day
Refueling System	**cH2, on-site NG SR**	**cH2, on-site NG SR**	**cH2, on-site NG SR, intensifier**	**cH2, on-site electrolyzer**	**cH2, on-site electrolyzer**	**cH2, LH2 Delivery, compresser**	**cH2, pipeline, compresser**
Vehicle	Passenger Car	Passenger Car	Passenger Car	Passenger Car	Passenger Car	Passenger Car	Passenger Car
Fuelings/day	**25**	**250**	**25**	**7.5**	**25**	**250**	**25**
Fill per car (kg/car/d)	4.00	4.00	4.00	4.00	4.00	4.00	**4**
Total fuel per day (kg)	100.0	1000.0	100.0	30.0	100.0	1000	100
Dispensers	2	1	3	1	1	1	1
# of compressors	1	1	1	1	1	1	1
Comp/Cascade ratio	0.5					**0.50**	**0.65**
Compressor Flow Rate (kg/hr)	**4.17**	**41.67**	**4.17**	**1.25**	**4.17**	**66.67**	**8.67**
(Nm3/hr)	**50.5**	**505.4**	**50.5**	**15.2**	**50.5**	**808.6**	**105.1**
Refill Time (min)	10	10	10	10	10	10	10
Average Flow Rate (kg/hr) (no storage)	4.17	41.7	4.167	1.25	4.17	41.67	4.17
Storage Pressure Capacity	6250	6250	4500	6250	6250	6250	6250
Vehicle Storage Pressure	5000	5000	5000	5000	5000	5000	5000
Storage type	Cascade	Cascade	Cascade/accumulator	Cascade	Cascade	**Cascade**	**Cascade**
Vehicle demand storage credit (hours)	**6.0**	**6.0**	**7**	**7**	**7**	3.0	1.6
Production storage (hours)	18	18	17	17	17	--	--

Storage constraint calculations (kg fuel)							
Storage due to production rate	75.0	750.00	70.8	21.3	70.8	--	--
kgs for peak fill period->	40.0	400.0	40.0	12.0	40.0	400.0	40.0
Fueling Cascade Storage	91.7	916.7	27.5	27.5	91.7	**666.7**	**35.0**
Additional storage	43.8	437.5	38.5	11.6	38.5		
Actual storage	135.4	1354.2	66.0	39.1	130.2	666.7	35.0
Fuel production (kg/hr)	4.2	41.7	4.2	1.3	4.2	66.7	8.7
# of Vehicles to fill in 3 hours (40%)	**10**	**100**	**10**	**3**	**10**	**100**	**10**
Cascade Efficiency	30%	30%	**100%**	30%	30%	30%	**40%**
Storage Efficiency	80%	80%	80%	80%	80%	80%	80%
Cylinders/bank	4	10	10	4	4	3	10
Storage volume, WC m3	4.56	45.63	2.92	1.32	4.39	22.46	35.00
Cylinder volume, m3/cyl	1.14	4.56	0.29	0.33	1.10	7.49	3.50
% of total vehicles to fill in"A23" hours	40%		booster				
	22.60	kg/m^3					

Explanation of Variables:

Storage Credit= hours of production output that will not require storage in stationary storage tanks. This assumes there will be X hours of steady vehicles demand, therefore the cars will take the reformer output directly, eliminating the need for Y kg of storage capacity).
Production Storage= hours of production output that will require storage in stationary storage tanks.
Storage due to production rate= storage capacity (kg) required to handle the production output
Kgs for peak fill period= amount of hydrogen required to fuel X% of the daily vehicles in Y hours (X=40%, Y=2hrs)
Fueling Cascade Storage= amount of actual hydrogen storage capacity required to fill X% of cars in Y hours considering cascade efficiency

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Additional storage = If the “storage due to production rate” is larger than the “Kg required for peak fill period”, subtract the latter from the former and divide by cascade efficiency to find the additional storage capacity required.

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Actual Storage= Fueling cascade storage + additional storage

The calculations for the above table are provided below for Station 1:

		ON SITE PRODUCTION
	Station	='Station Costs'!A40
Row number	**Refueling System**	**cH2, on-site NG SR**
5	Vehicle	Passenger Car
6	Fuelings/day	**25**
7	Fill per car (kg/car/d)	4
8	Total fuel per day (kg)	=C7*C6
9	Dispensers	2
10	# of compressors	1
11	Comp/Cascade ratio	0.5
12	Compressor Flow Rate (kg/hr)	**=C8/24**
13	(Nm3/hr)	
14	Refill Time (min)	10
15	Average Flow Rate (kg/hr) (no storage)	=C8/24
16	Storage Pressure Capacity	6250
17	Vehicle Storage Pressure	5000
18	Storage type	Cascade
19	Vehicle demand storage credit (hours)	**6**
20	Production storage (hours)	=24-C19
21	**Storage constraint calculations (kg fuel)**	
22	Storage due to production rate	=(C6*C7-C28*C19)
2	<-hrs of vehicle fueling/ kgs for peak fill period->	=C29*C7
24	Fueling Cascade Storage	=(C23-A23*C28)/C30
25	Additional storage	=IF(C22>C23,(C22-C23)/C31,0)
26	Actual storage	=C24+C25
28	Fuel production (kg/hr)	=C12
29	Fill Spec. (vehicles)	**=C6*C36**
30	Cascade Efficiency	0.3
31	Storage Efficiency	0.8
32	Cylinders/bank	4
33	Storage volume, WC m3	=C26/E66
34	Cylinder volume, m3/cyl	=C33/C32

Appendix H: Line Item Station Costs

Station 1: SMR 100

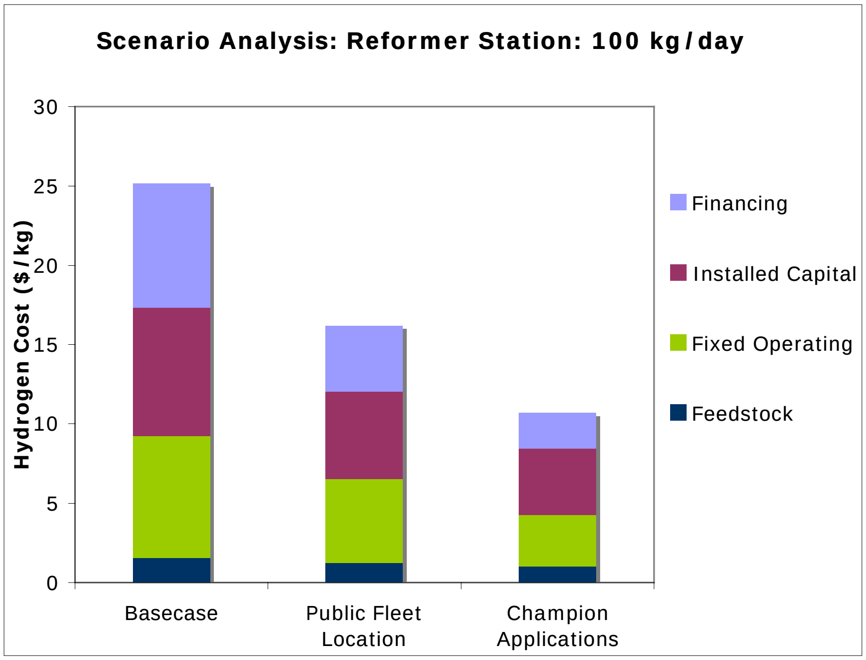
Total capital equipment costs	**$744,688**
Natural gas reformer	**$317,981**
Purifier	**$63,715**
Storage System	$196,865
Compressor	$51,652
Dispenser	$42,377
Electrical Equipment	$42,658
Safety Equipment	$10,000
Mechanical and Piping	$19,440
Total non-capital station costs	**$303,239**
Engineering (incl proj. mgt. & design)	$36,856
Permitting	$42,753
Site Development	$15,811
Safety and Haz-ops Analysis	$22,113
Equipment Delivery	$16,216
Installation	$36,856
Start-up & Comissioning	$22,850
Contingency	$109,784

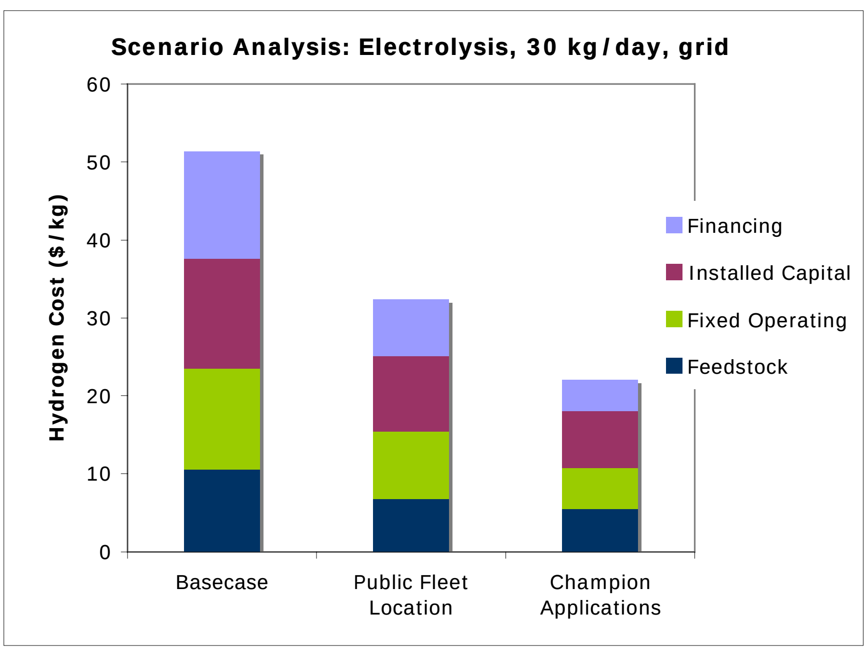
Total Operating Costs ($/yr)	**$92,594**
Total Maintenance	$29,788
Natural gas	$19,708
Electricity costs (energy + demand)	$6,289
Rent for landscape and hardscape	$4,800
Labor (full-service fueling)	$4,563
Insurance	$20,000
Property taxes	$7,447

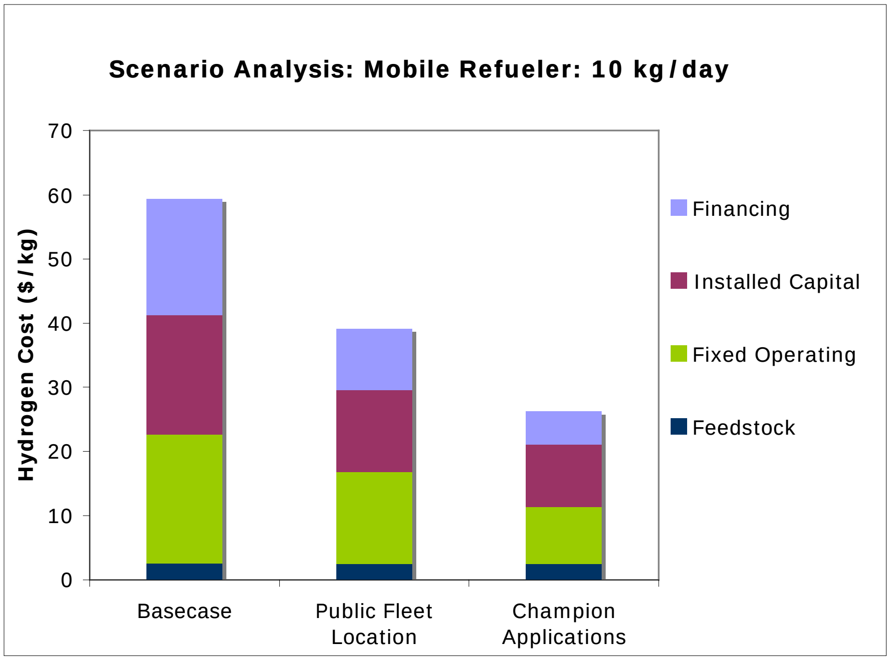
Finanacial Calculations*	
Annual Fixed Expenses ($/yr)	$92,594
Total installed station capital costs	$1,047,927
Annual Cost ($/yr)	$230,369
Hydrogen Price ($/kg)	**$13.30**

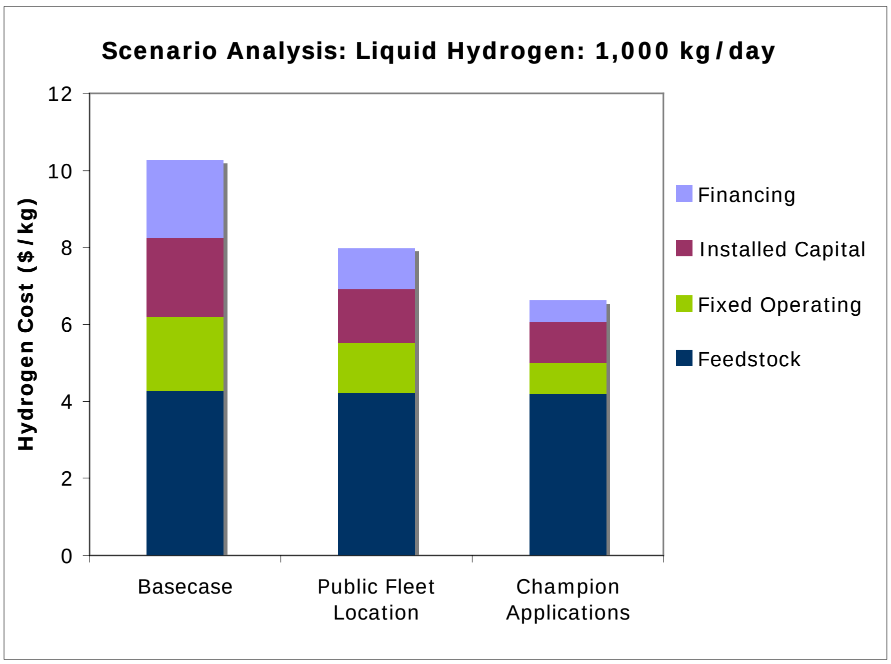
Appendix I: Scenario Analysis for Various Station Types

These results are based on a 24%, 34% (24+10), and 44% (24+20) capacity factor.






Scenario Analysis: Mobile Refueler: 10 kg/day
Hydrogen Cost ($/kg)
70
60
50
40
30
20
10
0
Basecase
Public Fleet Location
Champion Applications
Financing
Installed Capital
Fixed Operating
Feedstock


Scenario Analysis: Liquid Hydrogen: 1,000 kg/day
Hydrogen Cost ($/kg)
12
10
8
6
4
2
0
Basecase
Public Fleet Location
Champion Applications
Financing
Installed Capital
Fixed Operating
Feedstock

Appendix J: Hydrogen Highway Executive Order Transcript

Transcript of Governor Arnold Schwarzenegger's Hydrogen Highways Network Announcement Time: 10 a.m. Date: Tuesday, April 20, 2004 Event: Hydrogen Highways Network Announcement, UC Davis, Davis, CA

GOVERNOR SCHWARZENEGGER:
Thank you very much, Terry, for your wonderful introduction. I have to say that Terry is probably the best Secretary of the EPA that we've ever had in the history of our state. Give him a big hand. He's a great visionary. I would also like to thank our other Secretaries that are here today. Resources Secretary Mike Chrisman -- a big hand for Mike Chrisman. And then we have Business, Transportation and Housing Secretary Sonny McPeak. A big hand for Sonny McPeak, a big hand for Sonny. And then we have here, and we already heard him, the Chancellor of UC Schwarzenegger -- I mean, Davis. You kept the name, uh? The Chancellor of UC Davis, Larry Vanderhoef. A big hand for Larry. Anyway, this is really great, and I want to welcome all of you here. Thank you for coming. As you can see, this looks kind of like a movie set here, right? But of course it will be better, because what you see here today, this is the future of California and the future of our environmental protection.

All Californians deserve clean air and the promise of a healthy environment for generations to come, and this is exactly what we are doing here today. I will sign an executive order creating a public and private partnership that will create hydrogen highways all over the state of California by the year 2010. All across our highway system, hundreds of hydrogen fueling stations will be built, and these stations will be used by thousands of hydrogen-powered cars and trucks and buses.

This starts a new era for clean California transportation. These vehicles produce no emissions and no smog. They will clean the air and get rid of the smog that is hanging over our cities, and reduce the health problems caused by our pollution. Your government will lead by example and start using hydrogen-powered vehicles. And while we invest in a clean California, I will make sure that we get federal funds to support our innovative efforts.

As I have said many times, the choice is not between economic progress and environmental protection. Here in California growth and protecting our natural beauty go hand in hand. It goes together. A healthy environment leads to a healthy economy and a more productive workforce, and a better quality of life for everyone.

And as you know, we now have workers compensation reform. I signed the bill yesterday. That means it will be cheaper to do business in California. And of course this is great news for this effort, because now we are even more attractive for companies on the cutting edge of environmental technology. They will want to expand here, and they will want to do business here in our great state of California.

California will be the research capitol, the business capitol, and the job capitol of innovation and technology. We are the caretakers of our golden state, and the hydrogen highway will help us protect our extraordinary coastlines. It will help us protect our spectacular forests and our wonderful mountains and deserts, and make California a cleaner and healthier place for everyone. Thank you very much. Thank you. And now, let's sign the bill. Let's create some action