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An Assessment of the Near-Term Costs of Hydrogen Refueling Stations and Station Components

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Final Report

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ABBREVIATIONS AND ACRONYMS

CaFCP = California Fuel Cell Partnership
CH_4 = methane
CHREC = Compendium of Hydrogen Refueling Equipment Costs
CNG = compressed natural gas
CPUC = California Public Utilities Comission
CRF = capital recovery factor
DOE = U.S. Department of Energy
D&I = delivery & installation
DTI = Directed Technologies Inc.
ES = energy station
FCV = fuel cell electric vehicle
ft^2 = square foot or feet
GJ = gigajoule or gigajoules
H2A = hydrogen analysis (group)
H2Hwy = Hydrogen Highway
HD = Heavy-duty (vehicles)
HHV = higher heating value
HSCM = Hydrogen Station Cost Model
HTFC = High-Temperature Fuel Cell
H_2 = hydrogen
ICE = internal-combustion engine
kg = kilogram or kilograms
kW = kilowatt or kilowatts
LD = Light-duty (vehicles)
m^2 = square meter or meters
MCFC = molten carbonate fuel cell
MCF = thousand cubic feet
MM$ = million dollars
MMBTU = million British thermal units
N = years
NAS = National Academy of Sciences
NRC = National Research Council
NREL = National Renewable Energy Laboratory
O&M = operation and maintenance
PAFC = phosphoric acid fuel cell
PEM = proton-exchange membrane
PSA = pressure swing adsorption
psi = pounds per square inch
PV = photovoltaic
PV = production volume (in tables only)
R&D = research and development
SCAQMD = South Coast Air Quality Management District
scf = standard cubic foot or standard cubic feet
SMR = steam methane reforming

ABSTRACT

Interest in hydrogen as a transportation fuel is growing 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 in the planning and financing of this network is determining the costs of the stations. The purpose of this report is to examine the near-term costs of building hydrogen stations of various types and sizes.

The costs for seven different station types are analyzed with respect to size, siting factors, and operating factors. The first section of the report reviews the existing body of knowledge on hydrogen station costs. In the second section, we present hydrogen station cost data from the Compendium of Hydrogen Refueling Equipment Costs (CHREC), a database created to organize and analyze data collected from equipment suppliers, existing stations and literature. The third section of the report presents the Hydrogen Station Cost Model (HSCM), an engineering/economic model developed to analyze the cost of stations.

Based on the hydrogen station cost analysis conducted here, we conclude the following:

- Commercial scale hydrogen station costs vary widely, mostly as a function of station size, and with a range of approximately $500,000 to over $5 million for stations that produce and/or dispense 30 kg/day to 1,000 kg/day of hydrogen. Mobile hydrogen refuelers represent less expensive options for small demand levels, with lower capital costs of about $250,000.
- Existing hydrogen station cost analyses tend to under-estimate true station costs by assuming high production volume levels for equipment, neglecting station installation costs, omitting important station operating costs, and assuming optimistically high capacity factors.
- Station utilization (i.e. capacity factor) has the most significant impact on hydrogen price.
- Hydrogen fuel costs can be reduced by siting stations at strategic locations such as government-owned fleet yards and facilities that use hydrogen for industrial purposes.
- Hydrogen fuel costs ($/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.

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EXECUTIVE SUMMARY

Interest in hydrogen as a transportation fuel is growing 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 in the planning and financing of this network is determining the costs of the stations. The purpose of this report is to examine the near-term costs of building hydrogen stations of various types and sizes.

The costs for seven different station types are analyzed with respect to size, siting factors, and operating factors. The first section of the report reviews the existing body of knowledge on hydrogen station costs. In the second section, we present hydrogen station cost data from the Compendium of Hydrogen Refueling Equipment Costs (CHREC), a database created to organize and analyze data collected from equipment suppliers, existing stations and literature. The third section of the report presents the Hydrogen Station Cost Model (HSCM), an engineering/economic model developed to analyze the cost of stations.

The following section summarizes the cost results for seven types of individual hydrogen fueling stations. These results are presented in greater depth in the second and third section of the report. 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 ES-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 ES-1: Station Types and Sizes

Station Type	Capacity Range (kg/day)
1. Steam methane reformer	100-1,000
2. Electrolyzer, using grid or intermittent electricity	30-100
3. Mobile refueler	10
4. Delivered liquid hydrogen	1,000
5. PEM/Reformer energy station	1,000
6. High temp. fuel cell energy station	91[1]
7. Pipeline delivered hydrogen station	100

[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.

Table ES-2: Sample Cost Estimates for Ten Hydrogen Refueling Station Types

(All units in $1,000 except $/kg))	SMR 100	SMR 1000	EL-G 30	EL-PV 30	EL-G 100	MOB 10	LH2 1000	PEME S 100	HTFC 91	PIPE 100
Hydrogen Equipment	$318	$1,266	$147	$147	$250	$163	$510	$318	$365	$100
Purifier	$64	$201	$0		$0			$64		$20
Storage System	$197	$2,372	$51	$51	$189		$1,103	$41	$136	$46
Compressor	$52	$171	$28	$28	$52		$219	$52	$49	$76
Dispenser	$42	$127	$42	$42	$42		$127	$42	$42	$42
Additional Equipment	$72	$77	$67	$67	$72	$10	$87	$107	$123	$72
Installation Costs	$193	$300	$165	$128	$229	$44	$330	$193	$197	$175
Contingency	$110	$621	$49	$63	$89	$25	$302	$131	$147	$52
Fuel Cell / Photovoltaics				$90				$268	$285	
Total Capital Investment	$1,048	$5,137	$550	$616	$923	$243	$2,677	$1,216	$1,345	$583
Hydrogen + Delivery $/yr						$5	$714			$35
Natural gas $/yr	$20	$197	$0					$37	$107	
Electricity $/yr	$6	$63	$43	$27	$143		$19	($38)	($201)	$6
Maint., Labor, Overhead $/yr	$67	$196	$34	$39	$60	$17	$168	$76	$79	$39
Total Operating Cost $/yr	$93	$456	$77	$66	$203	$22	$901	$76	($16)	$79
Annualized Cost $/yr	$230	$1,132	$149	$147	$324	$54	$1,253	$236	$161	$156
Annualized Cost $/kg	$13	$6.5	$29	$28	$19	$31	$7.2	$14	$4.9	$9.0
Capacity kg/day	100	1000	30	30	100	10	1000	100	91	100
Hydrogen Sales 1000kg/yr	17.3	173	5.2	5.2	17.3	1.7	173	17.3	33.2	17,324

Key Assumptions: 13% Capital recovery factor Capacity Factor 47% for all except HTFC 100 (100% CF)

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

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

Additional equipment includes mechanical, electrical, and safety equipment

Pie charts have been created for each station type to illustrate the share each station component contributes to overall hydrogen cost. The figure below presents the pie chart for a reformer-type station.

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

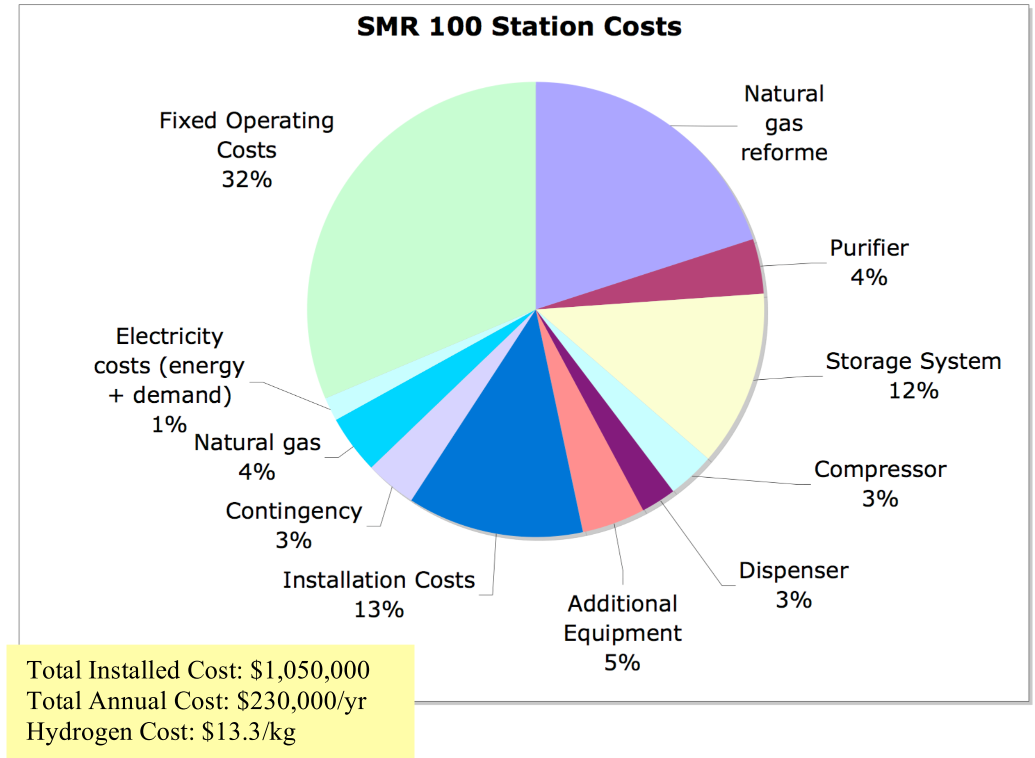
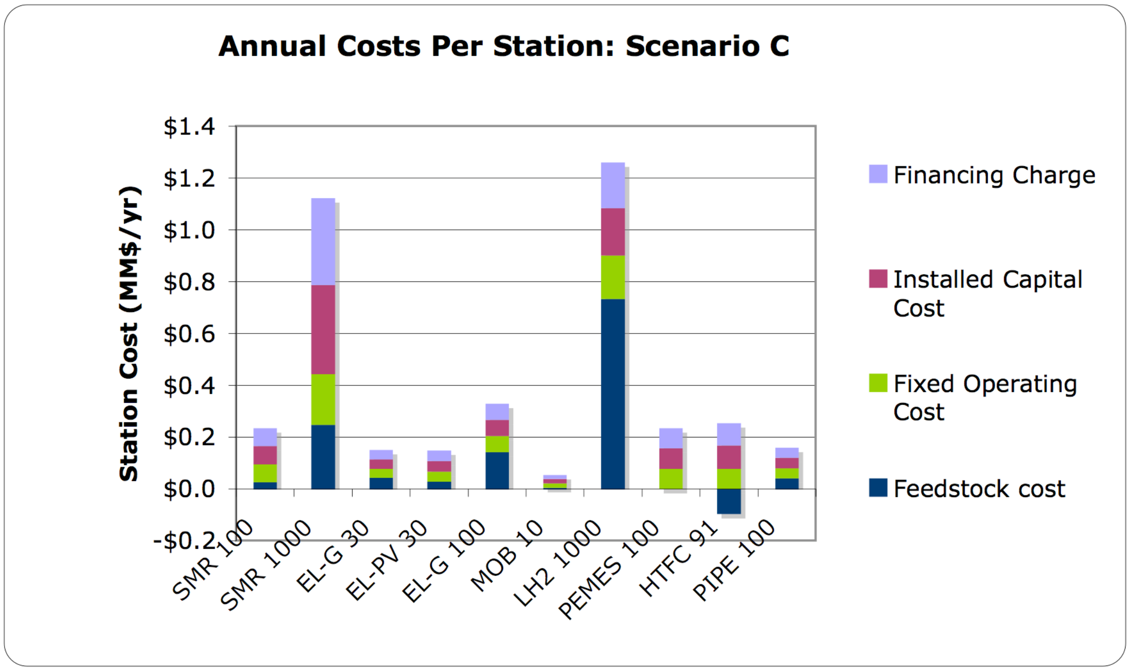


Figure ES-2 below shows annual station costs for the seven different types of stations analyzed in this analysis.

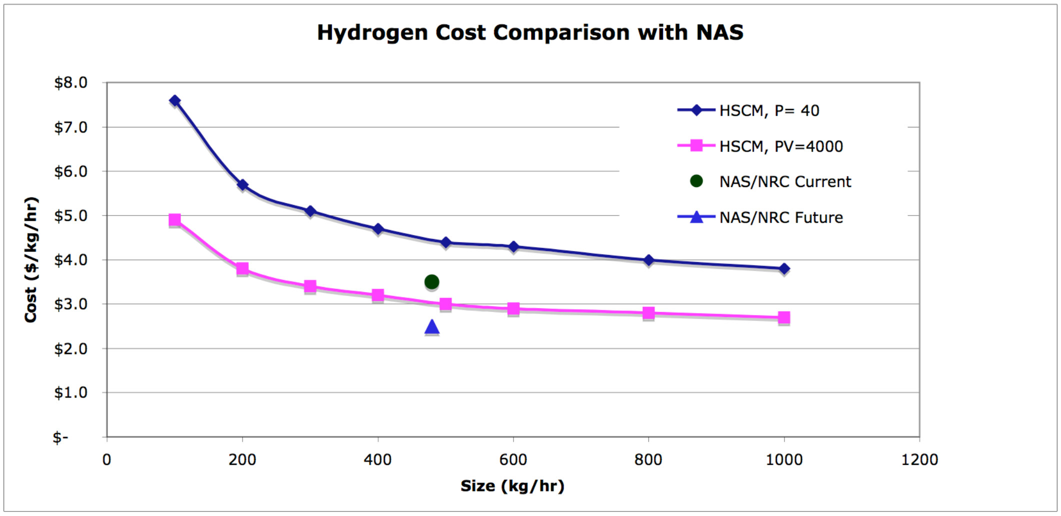
Figure ES-2: Annual Costs per Station[2]



To show how these cost estimates compare to those in previous studies, Figure ES-3 below compares the HSCM model results for reformer-type stations to results from a recent report by the National Academy of Sciences (NAS) that is being widely cited and compared with other estimate. The figure shows where NAS costs fall between HSCM costs for two production volume scenarios.

[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 ES-3: Reformer Station Hydrogen Cost Comparison With NAS Estimates



Costs for a network of stations were evaluated under three demand scenarios. The key assumptions for the demand scenarios are listed in Table ES-2.

Table ES-2: Demand Scenario Assumptions

Parameter	**Scenario**		
	A	**B**	**C**
Total # of Stations	50	250	250
Hydrogen Price to Customer ($/kg)	$3.00	$3.00	$3.00
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. The assumptions for each scenario are presented in the table below the figure, and reflect different assumptions about energy prices and other key inputs. Demand scenario B (250 stations, 10,000 vehicles, 24% capacity factor) is used for this case.

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

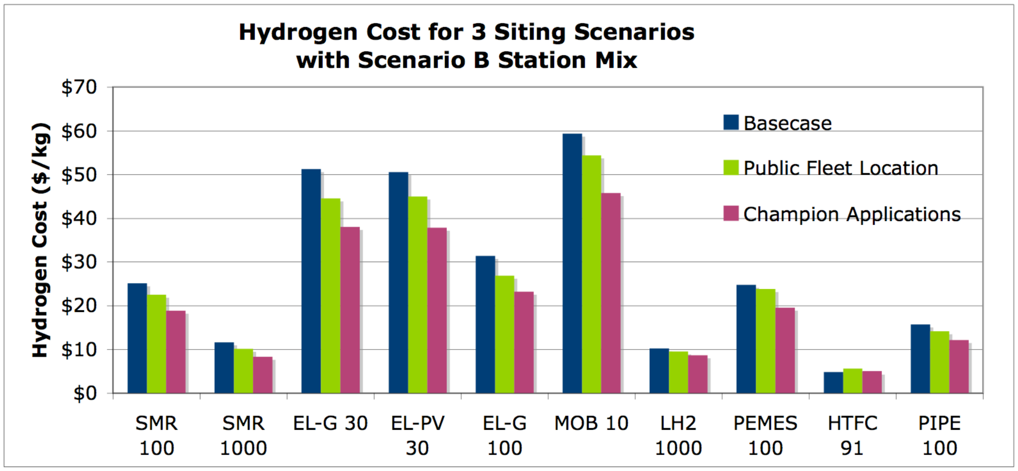


Table ES-3: Siting Scenario Assumptions

Station Assumptions	Scenario		
	Basecase	Public Fleet Location	Champion Applications
Natural gas ($/MMBtu)	$7.00	$6.00	$5.00
Electricity ($/kWh)	$0.10	$0.06	$0.05
Demand charge ($/kW/mo.)	$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/mo.)	$0.50	$0.50	$0.00
Contingency	20%	15%	10%
Property Tax	1%	1%	1%

Conclusions
The following conclusions can be drawn from the analysis conducted here:

1. Commercial scale hydrogen station costs vary widely, mostly as a function of station size, and with a range of approximately $500,000 to over $5 million for stations that produce and/or dispense 30 kg/day to 1,000 kg/day of hydrogen. Mobile hydrogen refuelers represent less expensive options for small demand levels, with lower capital costs of about $250,000.
2. 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.

3. In order to achieve hydrogen costs competitive with gasoline prices of around $2.00 per gallon, production volumes for key station components will need to reach levels of 1,000 or more units per year. This is equivalent to about 6% of gasoline stations in California.
4. 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.
5. 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.
6. Large stations (~1,000 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.
7. 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.
8. Mobile refuelers yield the most expensive hydrogen due to their small size (~10kg/day) and the high cost to refill them.
9. 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 high-temperature fuel cell energy stations have yet been built.
10. Station sited near an industrial demand for hydrogen can share the hydrogen use and thus take advantage of scale-economies and high capacity factors.
11. Pipeline stations have potential for low cost at low flow rates when sited near existing pipelines.

1.0 INTRODUCTION

Industry and government face three key challenges in planning new hydrogen infrastructure: 1) identifying appropriate locations for refueling stations; 2) the lack of accurate data on current station costs; and 3) the need to find cost-effective infrastructure development strategies. These issues are especially important in California since the state is planning to build an intrastate network of fueling stations (i.e., the "California Hydrogen Highway Network"). We particularly address the second of these challenges in this report, but the findings are relevant to addressing the third challenge as well.

The variability in hydrogen station costs makes it is difficult to accurately estimate the cost of building new stations. Actual station costs have in some cases greatly exceeded the budgeted amount. 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 are few public reports of the actual costs of station construction.

Addressing the challenges of hydrogen infrastructure cost assessment requires a transparent modeling tool to explore a variety of hydrogen infrastructure deployment scenarios. Most of the tools available today do not provide the ability to explore different station mixes, operating assumptions, and siting conditions.

In this analysis we use the Compendium of Hydrogen Refueling Equipment Costs (CHREC) to compile and analyze hydrogen station component costs. It collects and organizes data from equipment suppliers, existing stations, and literature on hydrogen station costs.

We then use the Hydrogen Station Cost Model (HSCM), an engineering/economic spreadsheet 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.

1.1 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 be produced from a variety of feedstocks, such as water and electricity, natural gas, or biomass (e.g. agricultural waste, wood clippings, etc.).

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

1. Hydrogen production equipment (e.g. electrolyzer, steam reformer) (if hydrogen is produced on-site)

2. Purification system: 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)

Station construction also require the following primary siting, permitting, and installation tasks:

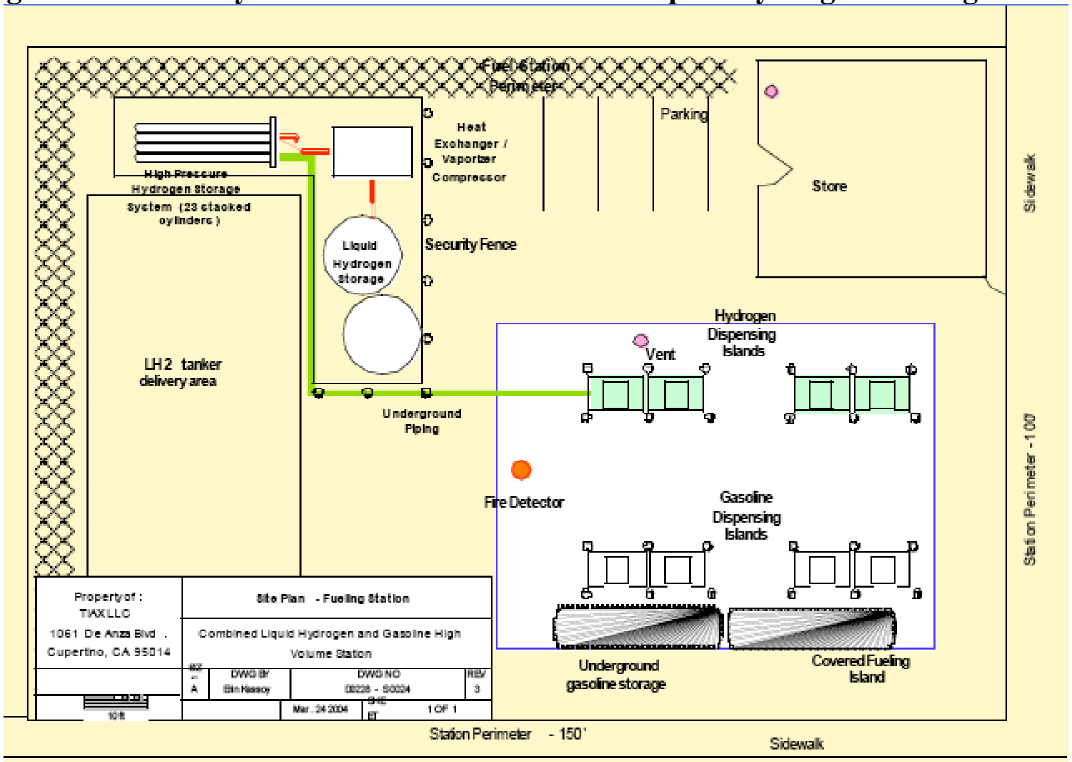
1. Engineering and design
2. Site preparation
3. Permitting
4. Installation
5. Commissioning (i.e. ensuring the station works properly)

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 production costs and sales prices. 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 1-1: Site Layout for Combined Gasoline/Liquid Hydrogen Fueling Station[3]



1.2 Scope

The HSCM was originally created to calculate the cost of the California Hydrogen Highway (H2Hwy) Network. As such, the analysis uses 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?

1.3 Research Tools and Methodology

The following research and analysis tools are used to answer the aforementioned questions. These tools were created by Jonathan Weinert as part of his Master's Thesis (see Weinert, 2005).

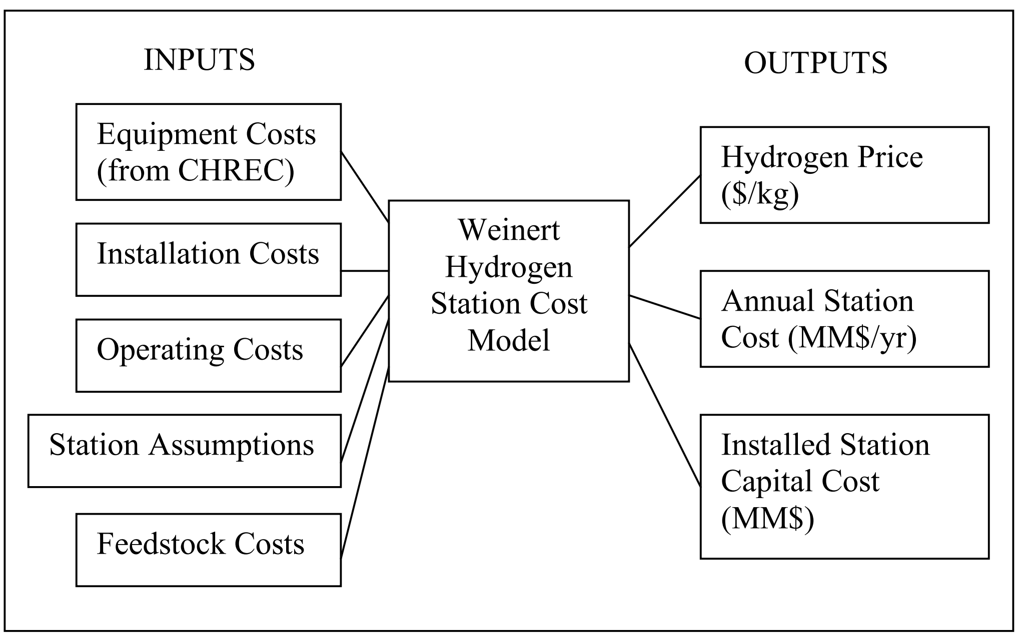
[3] Diagram provided by Erin Kassoy of Tiax, LLC

Compendium of Hydrogen Refueling Equipment Costs (CHREC):
The CHREC database stores data 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 from the literature, and to compare these estimates to "real world" 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 year 2004 dollars.

The Hydrogen Station Cost Model (HSCM):
The HSCM analyzes the economics of different types and sizes of hydrogen stations. Technological learning is 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 more detail throughout the report.

Figure 1-2: HSCM Structure



1.4 Report Outline

The second section of the report summarizes the existing body of knowledge on hydrogen station costs. In the third section, we 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 fourth section presents the Hydrogen Station Cost Model (HSCM), an engineering/economic model also created as part of this thesis, to analyze the cost of stations. Finally, section five presents key conclusions.

2.0 LITERATURE REVIEW OF HYDROGEN FUELING STATION COSTS AND CONFIGURATIONS

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.

2.1 Literature Review Summary

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 our evaluation of the reviewed reports into two main categories: Hydrogen Station and Equipment Costs and Model Features. The matrix ranks the degree to which they adequately address the given factors, using the following scale:

> **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 2-1: Literature Review Summary for Station and 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 Cogeneration	Kreutz, Ogden	I	N	A	A	I	I	I
99	Analysis of Utility Hydrogen Systems & Hydrogen Airport Ground Support Equipment	Thomas	I	N	I	A	A	A	A
02	Economic Analysis of Hydrogen Energy Station Concepts	Lipman	I	I	I	N	A	I	I

Table 2-2: Literature Review Summary for Model Features

Year	Source	Primary Author	Model Features: 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 Appliances	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			

2.2 Previous Studies of Hydrogen Station and Equipment Costs

The following section provides brief summary of literature containing information on the costs of hydrogen stations and hydrogen equipment. These studies include those by Simbeck and Chang (2002), Meyers et al. (2002), Thomas et al. (2001), Sepideh (2004), Amos (1998), and Padro and Pusche (1999). The general scope and overall findings of these studies are presented here. For a more detailed review of the assumptions and approaches used in these studies, see Weinert (2005).

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) analyze 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 current equipment costs and/or contain state-of-the art forecasts?
2. For what aspects of hydrogen stations costs are there limited amounts of information?
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 are neglected?

The conclusion after reviewing these papers is that most of the cost models presented in these reports focus on relatively 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 for this 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 circa 2004. Very few reports from literature look at non-capital costs of building stations. Also, there are limited amounts of recent data from equipment manufacturers in the literature. While some assumptions in these reports are valid, many use production volume and utilization estimates that are unrealistically high for near-term scenarios.

2.3 Conclusions

There are several studies that evaluate the cost of both hydrogen stations and equipment. An important area 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, and so on. Simbeck and Chang's (2002) spreadsheets make rough estimates of these costs based on estimates from other industries.

The next section of the report 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 section.

3.0 SURVEY OF HYDROGEN EQUIPMENT COSTS FROM LITERATURE AND INDUSTRY

The following section presents data from the Compendium of Hydrogen Refueling Equipment Costs (CHREC), a database used 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 draws 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 previous section). Industry data were gathered from equipment makers/vendors.

3.1 Data Sources

Data presented in CHREC are drawn from various sources in the technical literature and from quotes supplied by industry. The primary literature sources are shown in Table 3-1 below.

Table 3-1: Literature Source Summary

Primary Author	Source	Year
Amos, Wade	Costs of Storing and Transporting Hydrogen	1998
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 industry data for the CHREC is provided in the acknowledgements section at the beginning of this report. To protect the confidentiality of the company supplying cost data, equipment costs do not have a “source” associated with them.

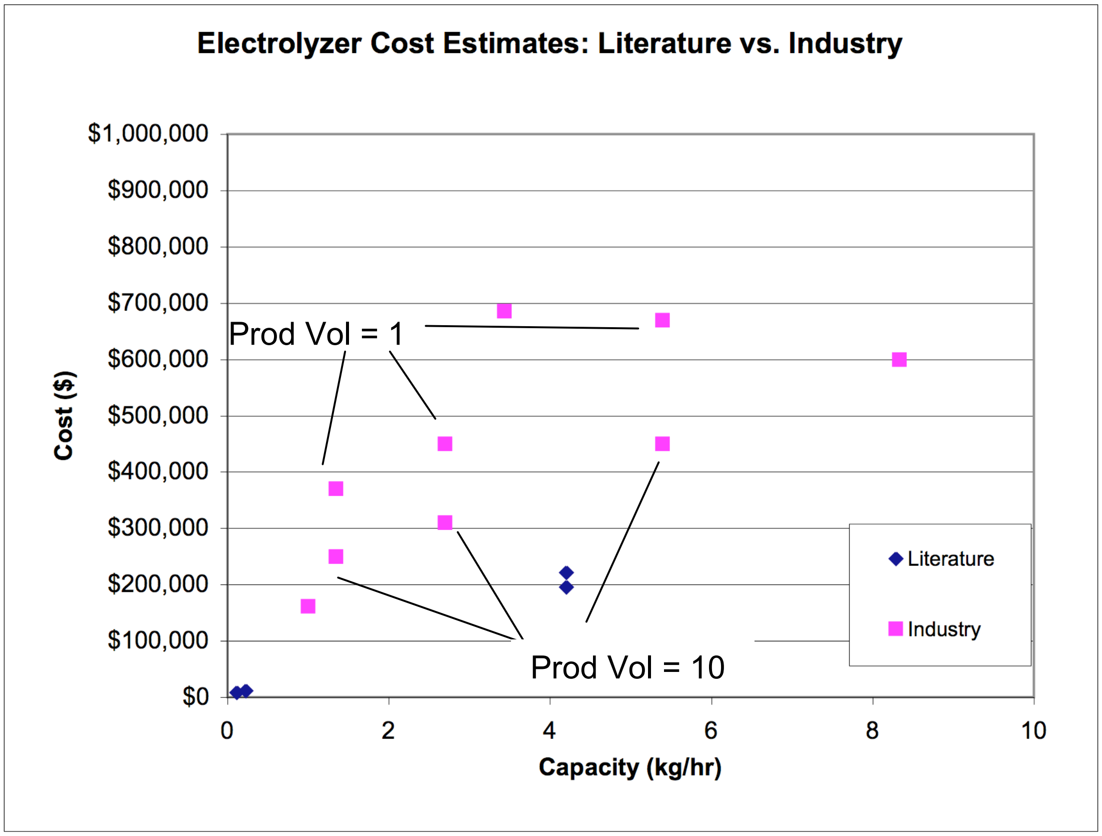
3.2 Hydrogen Production

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.

Electrolysis

The following figure summarizes 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. The following figure plots electrolyzer costs from both literature and industry, as a function of capacity in kilograms per hour.

Figure 3-1: Summary of Alkaline Electrolyzer Costs from Literature and Industry

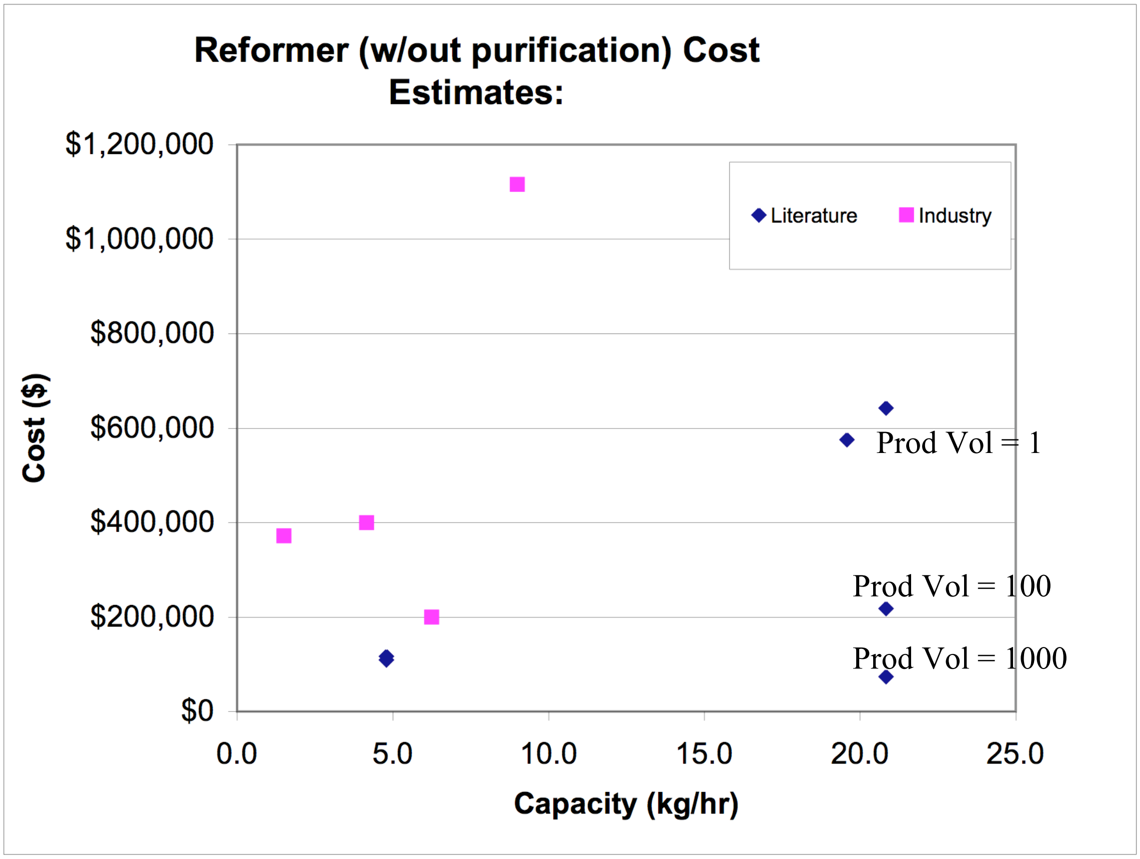


In general, electrolyzer costs reported in literature are much lower than the electrolyzers quoted by industry. The economies of scale associated with higher production volumes partially accounts for the large differences between the literature and station costs.

Reformation

The following tables summarize steam methane reformer (SMR) cost data from both literature and industry. Reformers convert methane (or 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. The following figure plots reformer cost against capacity for both industry and literature, again showing that industry estimates tend to exceed those reported in the literature.

Figure 3-2: Steam Methane Reformer Costs[4]



3.3 Hydrogen Storage

Hydrogen Storage data collected in CHREC are presented in the following figures. 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.

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.

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

Figure 3-3: Gaseous Hydrogen Storage System Costs

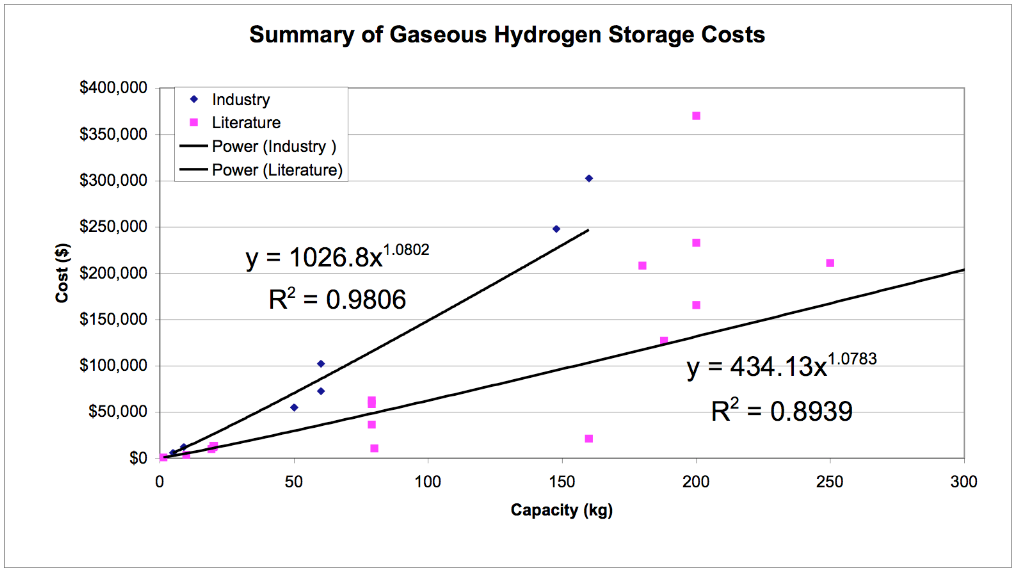
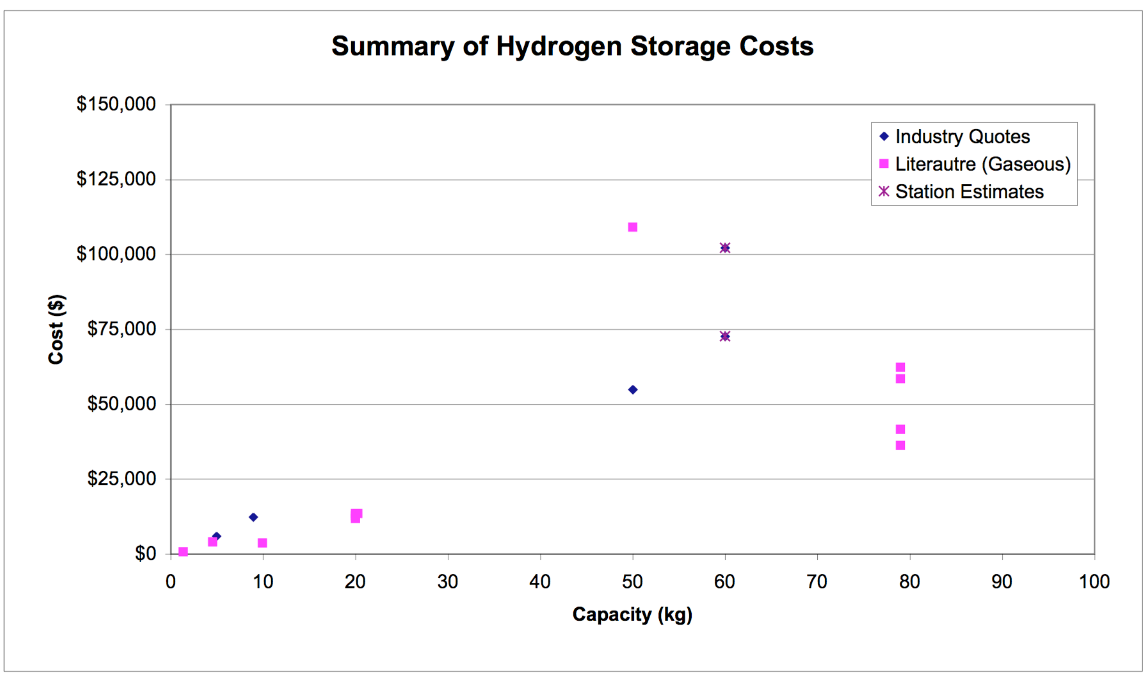


Figure 3-4 below shows just the cost of only the small-scale systems.

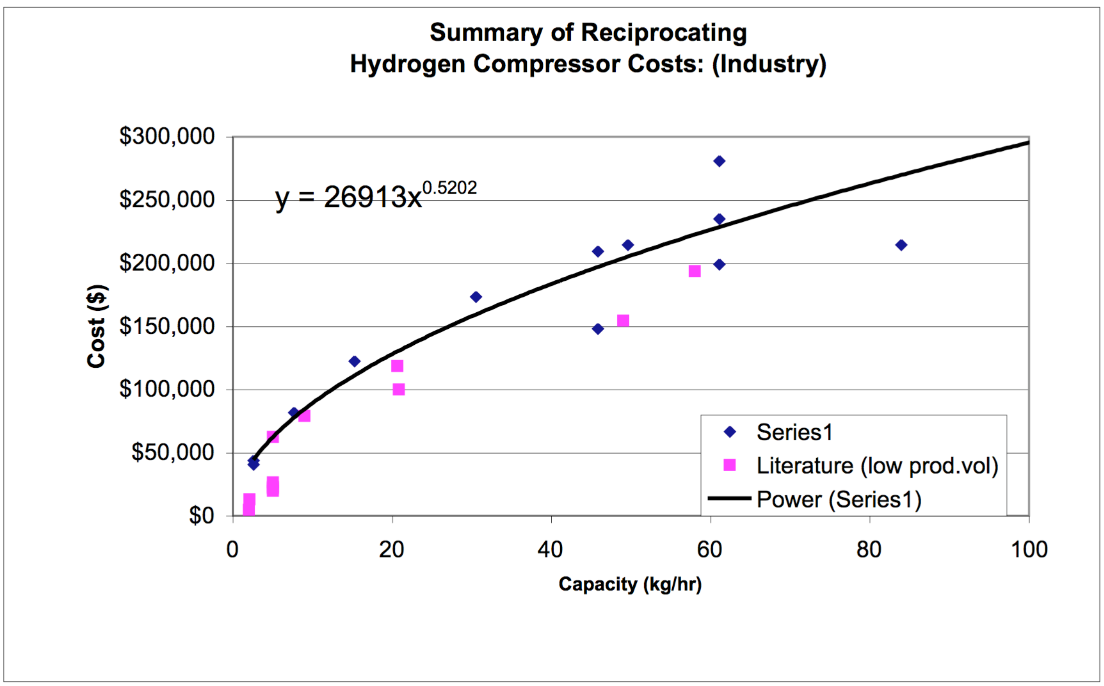
Figure 3-4: Small-Scale Gaseous Hydrogen Storage System Costs (0-100 kg)



3.4 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 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.[5] 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 "booster" compressors.

Figure 3-5: Reciprocating Compressor Costs



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

Figure 3-6: Diaphragm Compressor Costs

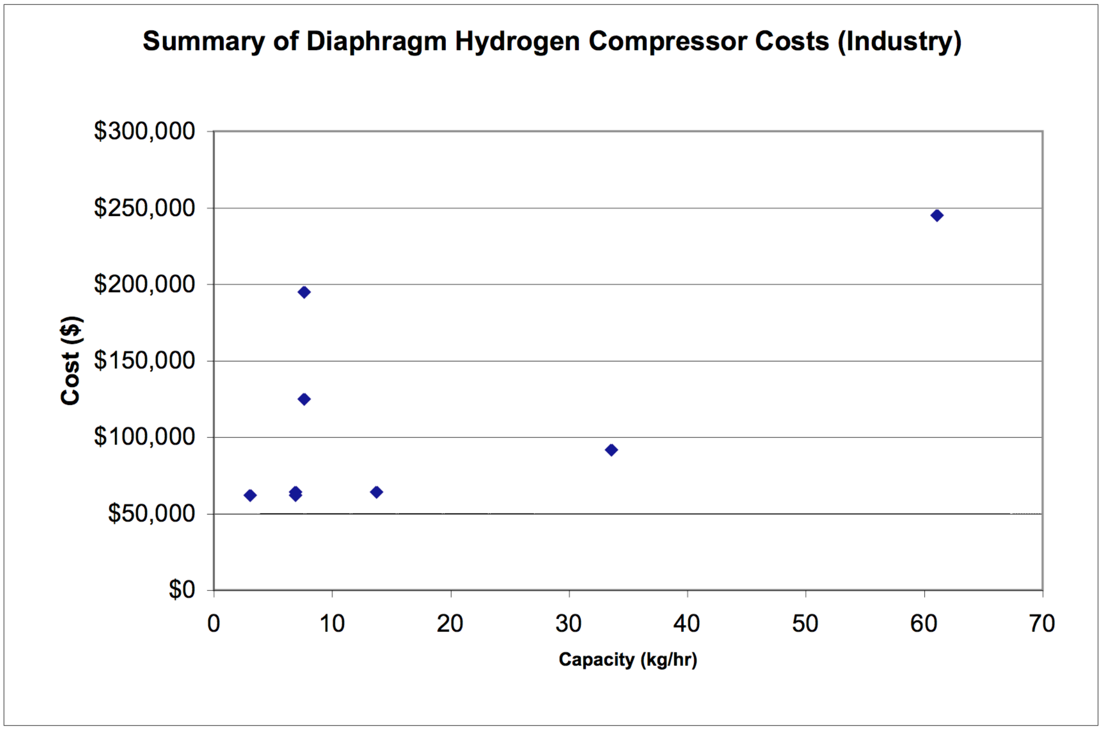
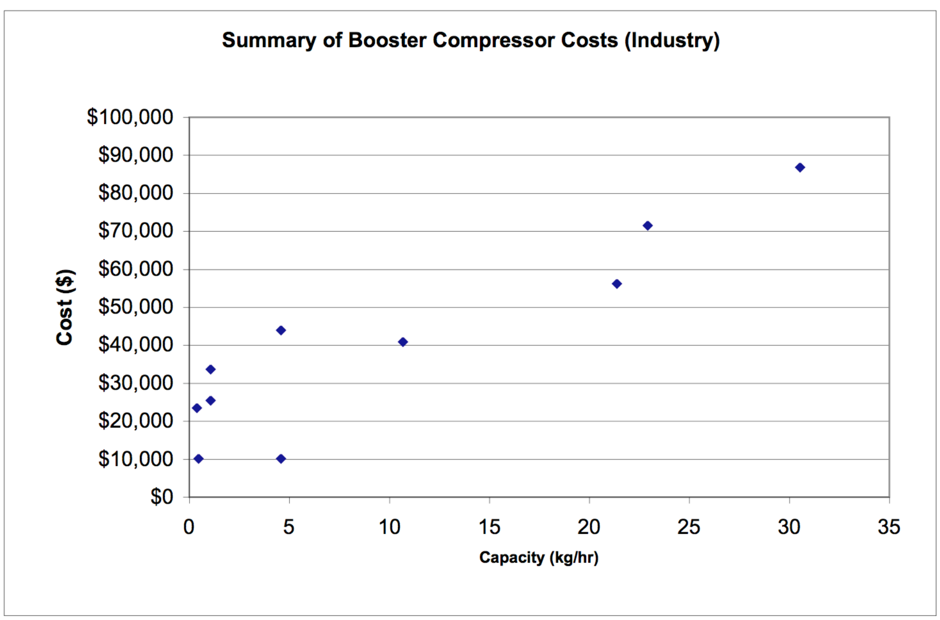


Figure 3-7: Booster Compressor Costs



3.5 Hydrogen Purification

Table 3-2 summarizes cost data from literature on different hydrogen purification technologies. Most of these estimates are for pressure-swing adsorption (PSA) systems. Table 3-3 shows data collected from industry on these same types of technologies.

Table 3-2: 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 3-3: 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	$100,000	$33,333	2004
PSA	9		99.999	$200,000	$22,222	2004

There is nearly an order of magnitude difference between literature and industry costs for purifiers. One possible reason for this is technological immaturity and hence lack of industry data on PSA purification technology.

3.6 Dispensers

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

Table 3-4: Hydrogen Dispenser Cost Summary from Literature

Capacity (kg/hr)	Pressure (psi)	Production Volume (units/yr)	Dispensers (#)	Total Cost ($2004)	Cost ($/disp)	Primary Author
2		10,000	1	$5,111	$5,111	Thomas, Sandy
		10,000	1	$5,424	$5,424	Padro, C.E.G.
20.83		10,000	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
48	4,997	None reported	2	$15,592	$7,796	Simbeck, Dale
76.33		250	1	$21,517	$21,517	Myers, Duane B.
300		None reported	1	$31,184	$31,184	Simbeck, Dale
5,000	Liquid	None reported	2	$103,946	$51,973	Simbeck, Dale
4,000	Liquid	None reported	2	$155,919	$77,960	Simbeck, Dale

Table 3-5: Hydrogen Dispenser Cost Summary from Industry

Pressure (psi)	Capacity (kg/hr)	Production Volume (units/yr)	Dispensers (#)	Total Cost ($2004)	Cost ($/disp)
5,000	1197.6	None reported	1	$45,000	$45,000
5,000	0.16	None reported	1	$20,789	$20,789
5,000	0.16	None reported	1	$72,762	$72,762
5,076		None reported	1	$81,741	$81,741

3.7 Electricity Production/Controls Equipment

Electricity production equipment is used to generate electricity on-site. These systems can be of interest to hydrogen stations that co-produce electricity using some of the hydrogen at the station (also known as "hydrogen energy stations").

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

Table 3-6: Electricity Production/Control Cost Summary from Literature

Equipment Type	Power (kW)	Prod. Volume (units/yr)	Total Cost ($2004)	Cost ($/kW)	Primary Author	Year
Fuel Cell_MCFC	25	10,000	$37,912	$1,516	Padro, C.E.G.	1999
Fuel Cell_MCFC	250	10,000	$486,839	$1,947	Padro, C.E.G.	1999
Fuel Cell_MCFC	3,250	10,000	$4,837,617	$1,488	Padro, C.E.G.	1999
Fuel Cell_MCFC	100,000	10,000	$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	10,000	$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	10,000	$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	10,000	$18,352		Thomas, Sandy	2001

Table 3-7: Electricity Production/Control Cost Summary from Stations and Industry

Equipment Type	Power (kW)	Prod. Volume (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

3.8 Station Installation Costs

This section contains data on the costs of installing hydrogen 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). 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. When one cost estimate includes two expense categories, the information is put in two expense categories columns.

Table 3-8: 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	Commissioning		$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	Commissioning		$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
			Total Capital Cost		$428,500	98%	
4	On Site Electrolysis	3	Labor		$11,674	1%	2003
4	On Site Electrolysis	3	Commissioning		$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
			Total Capital Cost		$1,026,000	29%	
5	Delivered LH2		Engineering/Design	Installation	$82,354	26%	2003
			Total Capital Cost		$312,760		
6	Renewable Electrolysis		Site Preparation	Permitting	$200,000		

Table 3-9: 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
				Average	$712	
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).[6] 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.

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

Table 3-10: Estimates Used in NAS/NRC Study for Installation Costs of Hydrogen Stations

Installation Cost Category	**% of Capital Cost**	**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, and 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 and 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 3-11: Station Installation Cost Comparison

Source	**Installation Cost as percentage of Station Capital Cost**	**Station Type**
Simbeck and Chang	45%	Reformer
Chevron Texaco	117%	Reformer
SCAQMD Station 3	98%	Electrolyzer
SCAQMD Station 4	29%	Electrolyzer
SCAQMD 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 SCAQMD stations 4 and 5 are most likely artificially low since the data on installation costs for these stations is incomplete.

3.9 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 are limited data on the non-capital costs of hydrogen station installation. Only Simbeck and Chang (2002) quantify the non-capital installation costs, which in that case are given as a certain percentage of equipment capital costs. 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 section, the industry data are normalized and scaled for size and production volume for use with the HSCM spreadsheet model.

4.0 HYDROGEN STATION COST ESTIMATES

This section introduces and describes the Hydrogen Station Cost Model (HSCM) and presents model results for various types and sizes of hydrogen stations in the near term.

The HSCM is intended to be a general tool for analyzing hydrogen refueling station economics. It was created to achieve the following two goals:

1. Obtain realistic near term hydrogen station costs
2. Identify important factors that affect station costs and quantify their impacts on overall station costs.

This provides insight into the difficult questions surrounding the hydrogen infrastructure expansion, including trade-offs between how many stations, how large they are, what kind of stations they are (e.g. electrolysis vs. reformation), and what specific policies will help drive the costs of delivered hydrogen.

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 the levelized hydrogen cost ($/kg).

The following station types are considered in this model:

Table 4-1: Station Types and Sizes

Station Type	**Capacity Range (kg/day)**
1. Steam methane reformer	100-1,000
2. Electrolyzer, using grid or intermittent electricity	30-100
3. Mobile refueler	10
4. Delivered liquid hydrogen	1,000
5. PEM/Reformer energy station	1,000
6. High temp. fuel cell energy station	91[7]
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

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

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.

4.1 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:

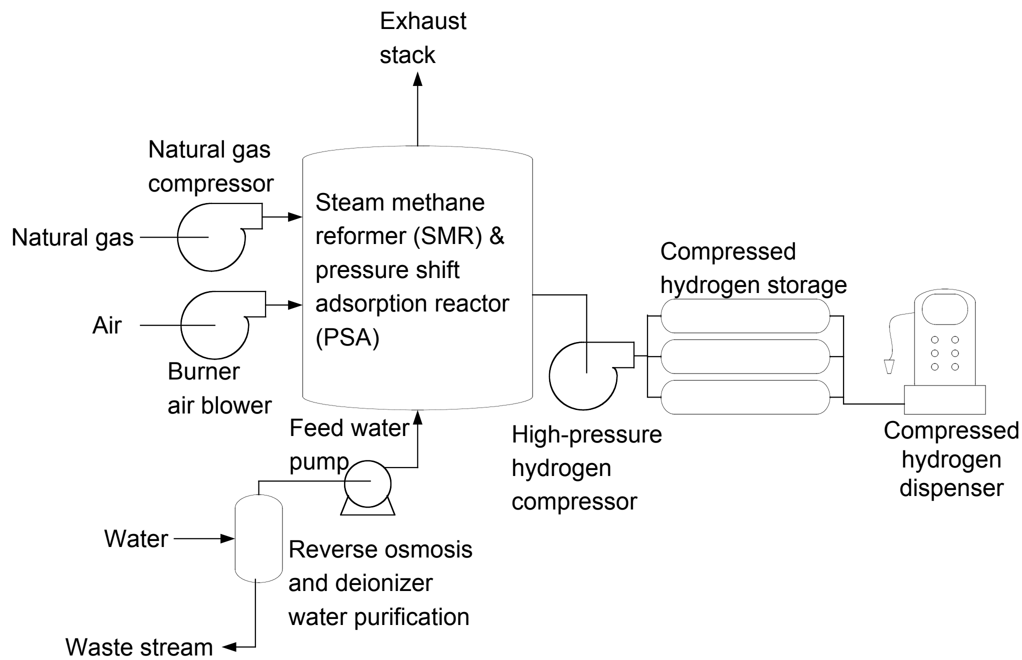
The stations store hydrogen at 6,250 psi to serve fuel vehicles with 5,000 psi on-board vehicle storage. The model assumes the stations will use the following equipment:

Table 4-2: Station Equipment

Station Type	**Key Technology**	**Additional components**
Natural gas reformer	Steam methane reformer, purifier	Reciprocating-piston compressor (6,250 psi), cascade storage/dispensing
Electrolyzer	Alkaline electrolyzer	
Pipeline delivery of hydrogen	Purifier	
Energy station (ES)	Fuel cell, reformer, shift reactor (for high temp ES), purifier	
Delivered liquid hydrogen tanker truck	Cryogenic storage tank, 6,250 psi cryo-pump, evaporator	Gaseous cascade storage/dispensing
Mobile refueler	Integrated refueler trailer	Cascade storage/dispensing (no compressor)

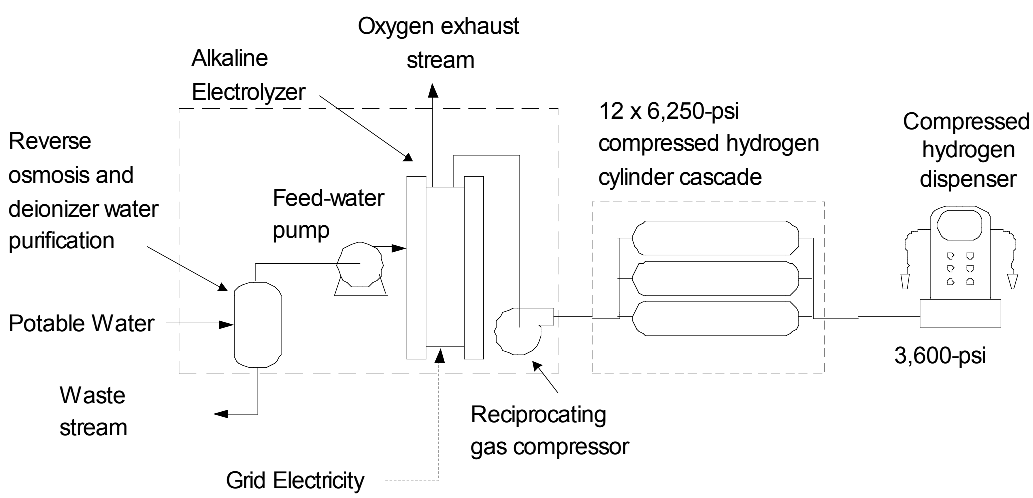
The following figures show how these components are connected together to create a hydrogen station.

Figure 4-1: Reformer Station



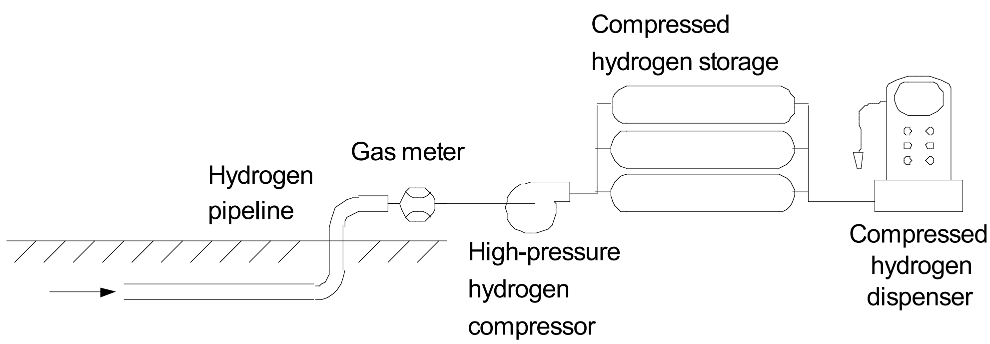
Reformer Station: For this type of station, shown in Figure 4-1, the natural gas compressor, blower, and water pump are integrated with the SMR and PSA as one unit.

Figure 4-2: Electrolyzer Station



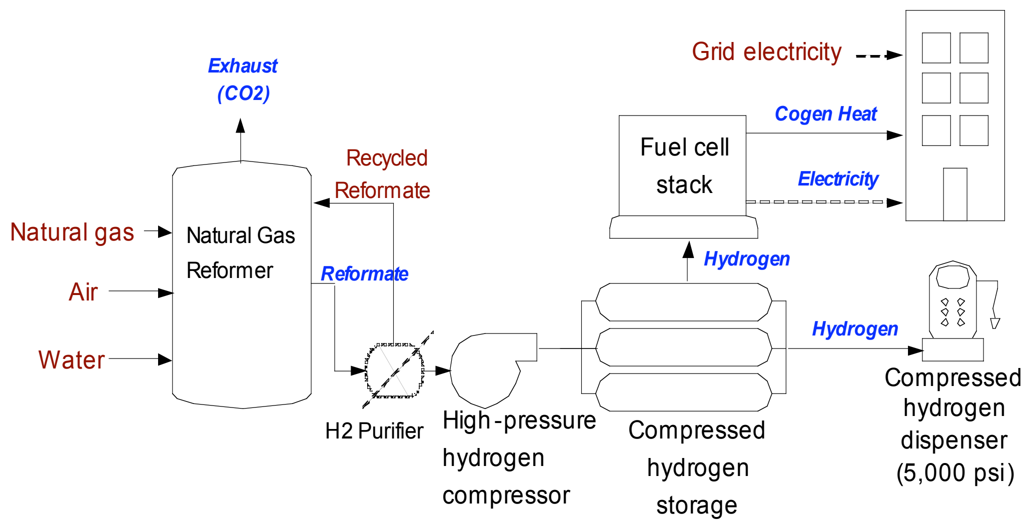
Electrolyzer Station: This station type can use either grid power or a dedicated renewable electricity source (or combination of the two) to produce hydrogen using water as a feedstock. For this station type, we assume that either grid electricity or solar photovoltaic (PV) electricity provides power. We assume the PV system costs $3/W_{peak}$, (based on significant subsidies available in California, and that the PV array is sized to provide ~17% of the total electricity to make hydrogen when the station operates at 50% capacity.[8]

Figure 4-3: Pipeline Hydrogen Station



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 in Southern California, with the opportunity to site several stations along the pipeline.

Figure 4-4: Energy Station



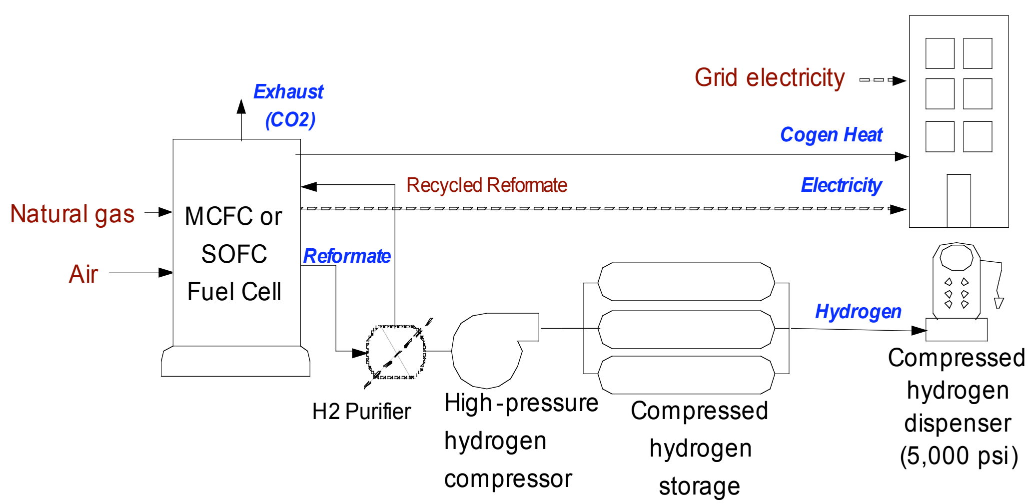
[8] These assumptions are from TIAX, LLC and are based on an assumed an average insolation of 1 kW/m^2 and $3,000/kW capital cost for the photovoltaics system.

Energy Station: This type of station combines on-site hydrogen fuel production with electricity production using either a fuel cell or hydrogen combustion engine "gen-set." By doing so, the station co-produces hydrogen fuel, electricity, and heating/cooling, yielding three value streams. 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 requirements for hydrogen for production processes.

Evaluating the economics of an energy station is a complex due to the many possible ways to design and 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. $0.10/kWh) since it will be used for demand reduction and emergency backup. 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 $1,500/kW from the California Public Utilities Commission (CPUC).

Figure 4-5: High-temperature Fuel Cell Energy Station

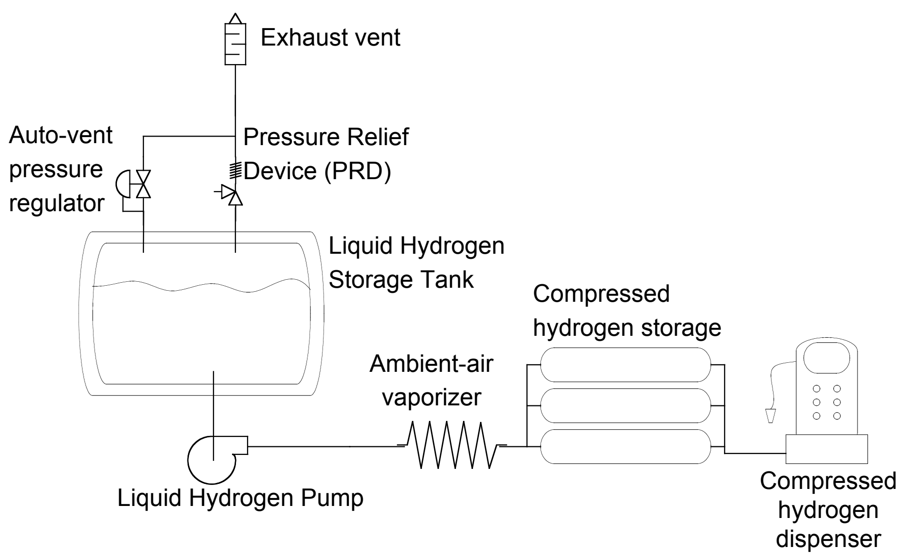


The figure above shows a different energy station configuration considered in the analysis, a high-temperature fuel cell (HTFC) energy station. The main difference between the two is that this energy station uses a HTFC instead of a low temperature PEM fuel cell system. This eliminates the need for a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

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. Note that this assumption artificially deflates hydrogen price for this station option under low vehicle capacity factors.

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. As one industry representative notes, "since the costs of producing hydrogen using this technology (~$5.60/kg) is lower than the bottled hydrogen costs (~$6.00-7.00/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."[9] 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.[10] Thus, the costs presented in the report are expected costs and not field-tested costs.

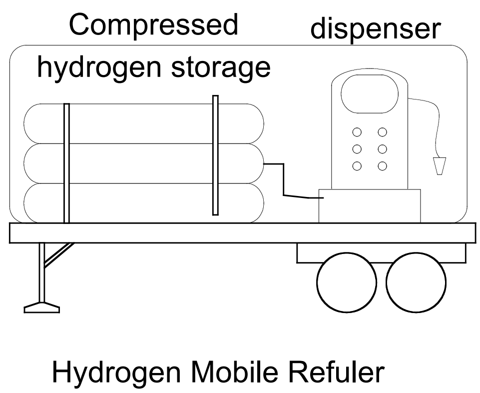
Figure 4-6: Liquid Hydrogen Station



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

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

Figure 4-7: Mobile Refueler Station



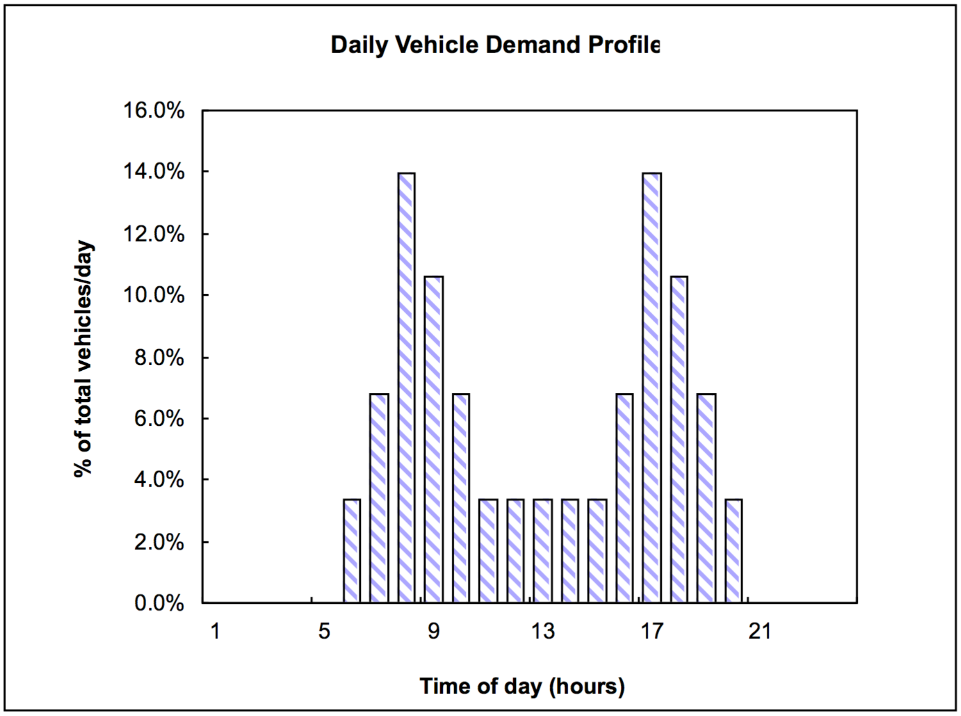
Mobile Refueler Station: This is the simplest type of station. It consists only of high-pressure gaseous hydrogen storage and dispenser, mounted into a mobile trailer. The refuelers are towed to and from hydrogen production facilities so that the hydrogen tank can be refilled when needed. If equipped with a solar PV system 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, we assume 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)[11]. Refueling takes place during the day, with peaks in the morning and late afternoon/early evening.

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

Figure 4-8: Vehicle Demand Profile



<u>Equipment Sizing</u>
Based on the demand profile above, the compressor and storage equipment are sized to be able to: 1) fuel 40% of the daily-expected vehicle load in 3 hours[12] and 2) 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 primarily on studies by TIAX LLC.[13]

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 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.

[12] Lasher, S. (2004) "Forecourt Hydrogen Station Review", DOE Hydrogen Analysis Team (H2A), presentation at the National Hydrogen Association Annual Conference
[13] Unnasch, S. (2004) TIAX LLC proprietary spreadsheet model and personal communications.

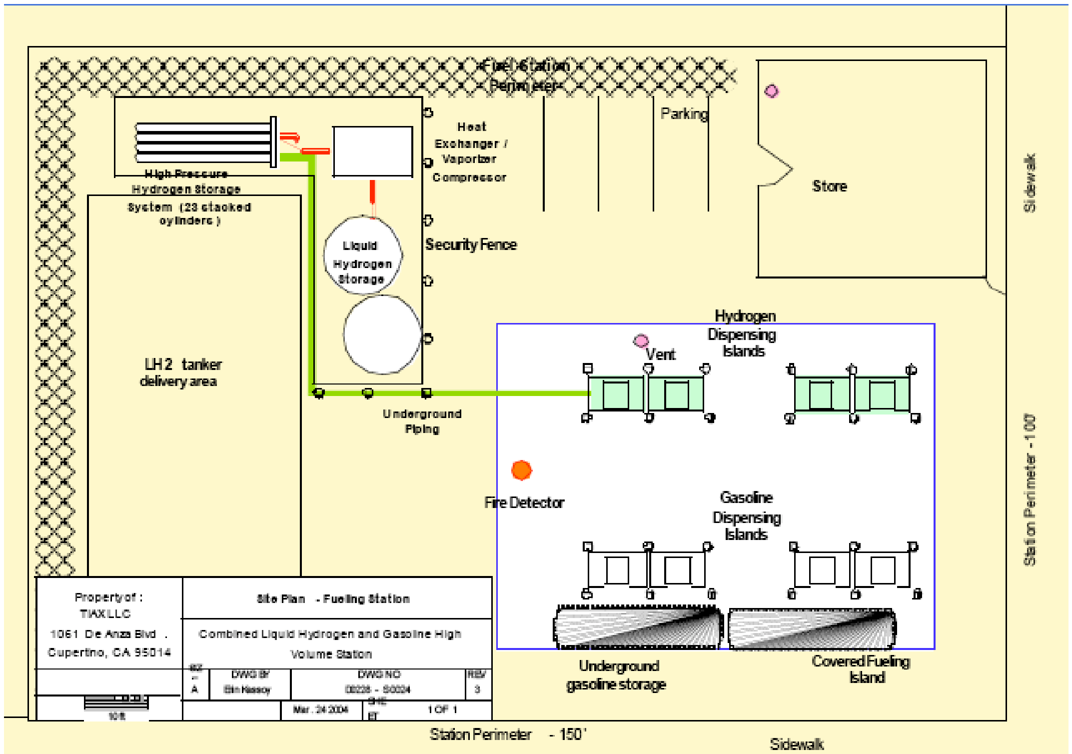
Table 4-3: Storage and Compressors Sizes By Station Type

Station Type	Capacity Range (kg/day)	Storage (kg)	Compressor Size (kg/hr)
1. Steam methane reformer	100-1,000	135-1,354	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	1,000	667	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 HSCM 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 this analysis, we assume that H_2 stations are integrated into existing gasoline stations with 8 dispensers total. Small stations (≤100 kg/d) use one H_2 dispenser and large stations (1,000 kg/d) use three H_2 dispensers. The following diagram provides an example of a liquid H_2 and gasoline station layout.

Figure 4-9: Integrated Hydrogen/Gasoline Station Layout[14]



4.2 Additional 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 4-4: Model Economic Variables

Parameter	Value
Natural Gas Price ($/MMBtu)	$7.00
Electricity Price ($/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)	10%

[14] Diagram provided by Erin Kassoy of Tiax, LLC.

The *Natural Gas Price* is based on the Energy Information Administration's projected price of $7.09/MCF for California industrial users in 2010.[15] The electricity price is based on a California Energy Commission projection of $0.0948/kWh for California industrial users in 2010.[16] The 50% of labor allocated to fuel sales is based on a Tiax estimate.[17]

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 70 kg/day, yielding a 70% capacity factor. A 70% capacity factor is based on a similar assumption for hydrogen stations by the DOE Hydrogen Analysis Group (H2A)[18] and is similar to average gasoline station capacity factors today.

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:

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

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 $0.50/ft2/mo.[19] These costs include the rental cost of the land and retail outlet, landscaping, and upkeep of 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.

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.[20]

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[15] www.eia.doe.gov/oiaf/aeo/index.html
[16] www.energy.ca.gov/electricity/rates_iou_vs_muni_nominal/industrial.html
[17] Personal communication with Stefan Unnasch, Tiax LLC, August 2004.
[18] Lasher, S. (2004)
[19] 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).
[20] This assumption was "vetted" with representatives from ChevronTexaco in October 2004.

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

We calculated station costs under the following three scenarios to determine how hydrogen cost is affected when several key assumptions change at once: 1) *Base case 2010 Retail Station*: this scenario describes the average station 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 capacity factors since the location ensure a more reliable demand. It may also be able to achieve a lower utility rate through incentives and industrial classification. 3) *Champion Application*: this scenario leverages state-owned land and public-private partnerships between gov't and industry to reduce costs further.

Table 4-5: Siting Scenario Assumptions

Station Assumptions	Scenario		
	Basecase	**Public Fleet Location**	**Champion Applications**
Natural gas ($/MMBtu)	$7.00	$6.00	$5.00
Electricity ($/kWh)	$0.10	$0.06	$0.05
Demand charge ($/kW/mo.)	$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/mo.)	$0.50	$0.50	$0.00
Contingency	20%	15%	10%
Property Tax	1%	1%	1%

4.3 Methodology to Calculate Station Costs

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. These data are compiled in the CHREC database presented in Section 3. 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 Section 3.

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 1,000 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 4-6: Scaling Factors

Equipment	**Scaling Factors**[21]	**Size over which scaling factor valid (kg/hr)**
Reformer	0.6	~11
Electrolyzer	0.46	0.05-0.12
Purifier	0.5	~11

Scaling factors for storage and compressors are derived by curve-fitting the data. See Weinert (2005) for more details.

Production Volume Adjustment
To calculate cost reduction from production volume increase, progress ratios are estimated for the equipment. The technologies are clustered into 3 categories to reflect its maturity (as of 2005) and potential for cost reduction. Each cluster has an associated progress ratio. Table 4-7 below shows the clusters categories and their assumed progress ratios.

[21] 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.

Table 4-7: Progress Ratios for Equipment

Technological Maturity	Equipment	Progress ratio[22]
1. Nascent technology, low production volume levels	Reformers, electrolyzers, purifiers, fuel cells	0.85
2. Reasonably mature technology, predominantly used for H2 stations	Compressor, dispenser, mobile refueler, non-capital station construction costs	0.90
3. Mature technology, relatively high production volume levels	Storage	0.95

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

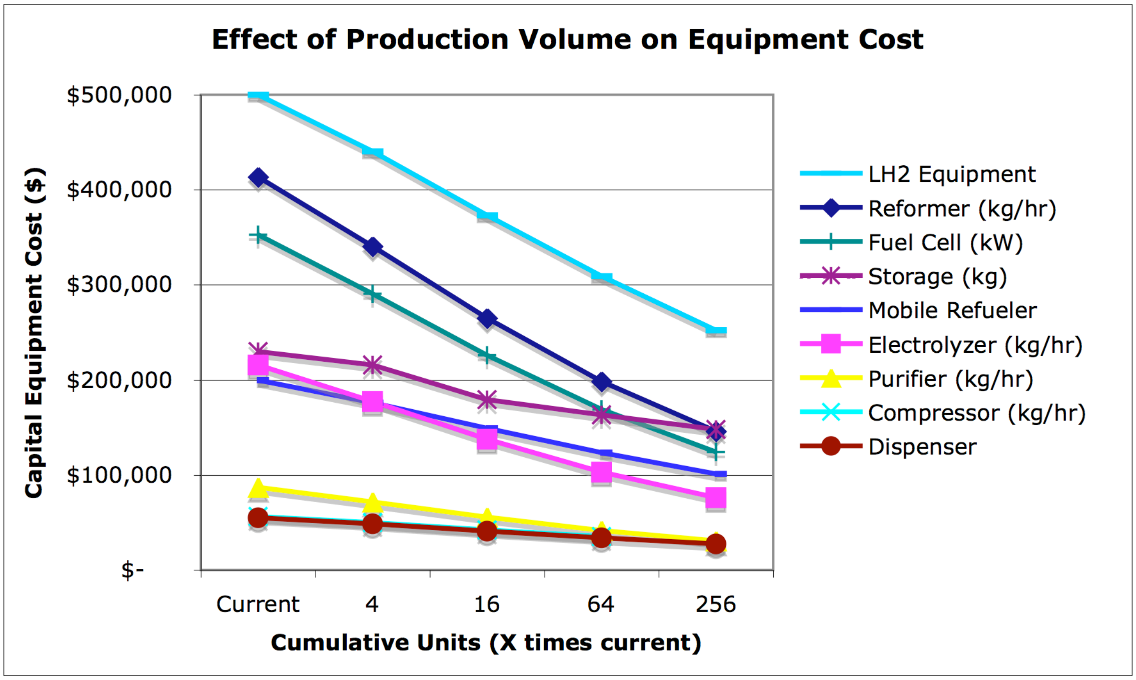
Table 4-7: Production Volume Assumptions

Equipment	Type	Current Cumul. Prod Vol. (units)	Future Cumul. Prod Vol. (units)	Progress Ratio	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
Liquid Hydrogen Equipment	Includes Dewar and Vaporizer	5	12	0.90	0.93
Station Construction (non-capital Costs)		15	265	0.9	0.74

[22] The manufacturing progress ratio is a measure of the decline in product manufacturing costs with increased cumulative production over time. A 0.85 or 85% progress ratio means that the costs of manufacturing fall 15% with each doubling of cumulative production (so higher progress ratios reflect *slower* progress in lowering costs). Progress ratios are typically in the 0.75 to 0.95 range (Dutton and Thomas, 1984; Ghemawat, 1985).. We conservatively assume relatively high progress ratio values and higher values for more mature technologies, based on evidence that progress ratios can increase over time for particular products. See Lipman and Sperling (2000) for more on applying manufacturing progress ratios or "experience curves" to transportation technologies.

The figure below shows how the costs of various pieces of equipment change for different scenarios.

Figure 4-10: Effect of Production Volume on Equipment Cost



Note: Liquid hydrogen (LH2) equipment includes the storage tank and vaporizer.

The following graphs show the relationship between cost ($/kg/hr) and size for fueling station equipment under three cumulative levels of production.

Figure 4-11: Reformer Cost vs. Size

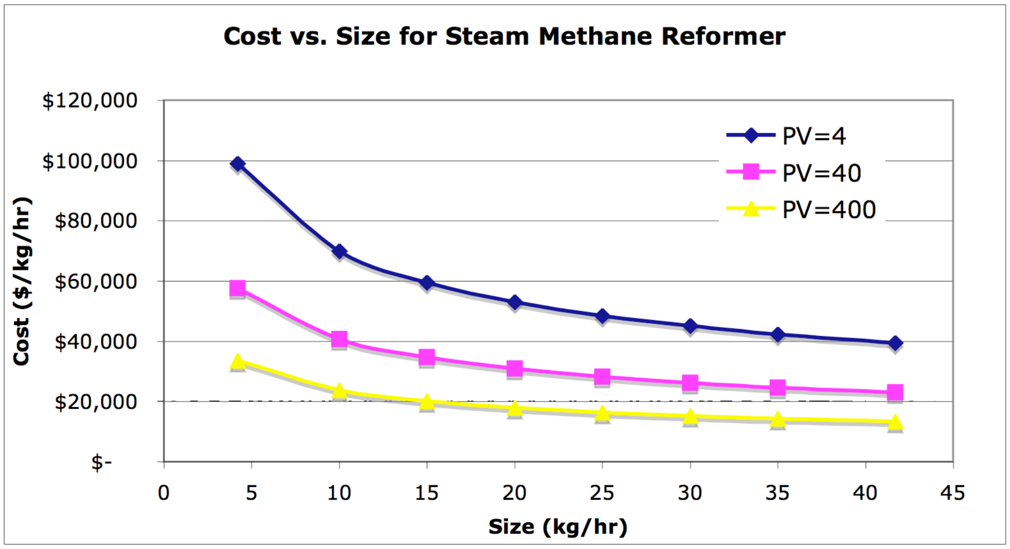


Figure 4-12: Electrolyzer Cost vs. Size

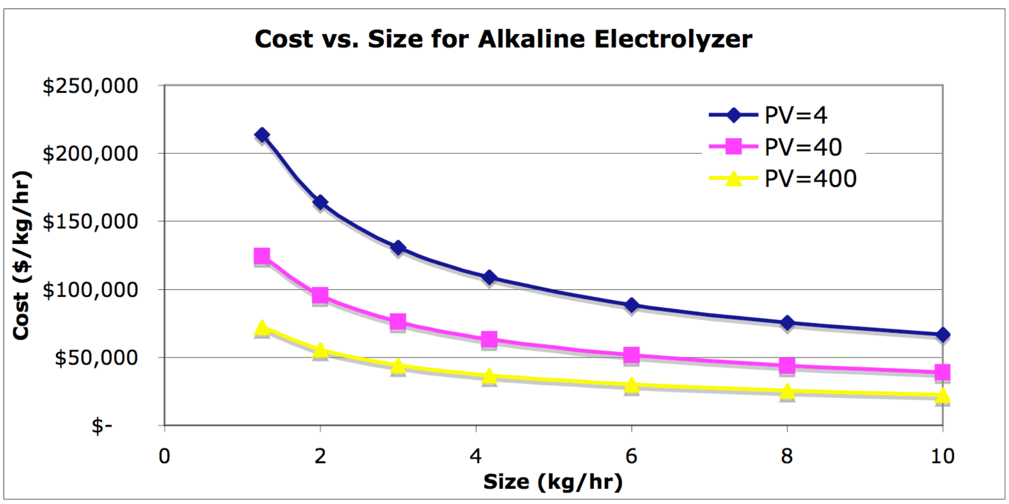


Figure 4-13: Purifier Cost vs. Size

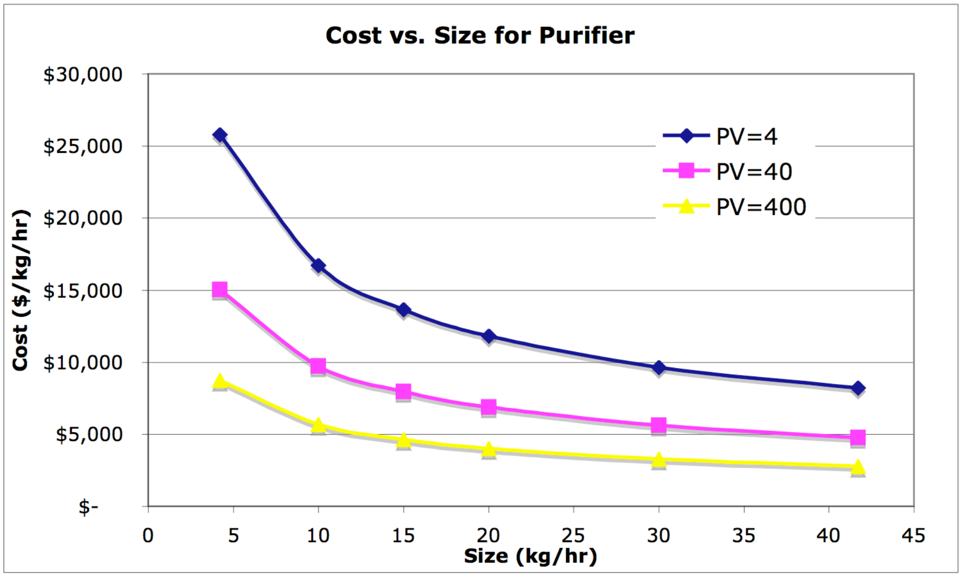


Figure 4-14: Compressor Cost vs. Size

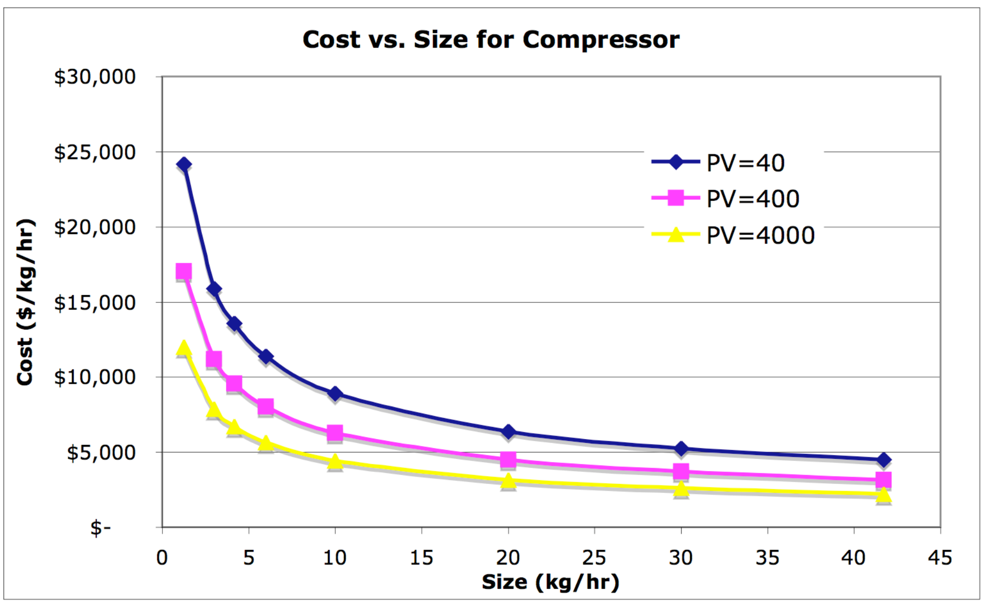


Figure 4-15: Storage Cost vs. Size

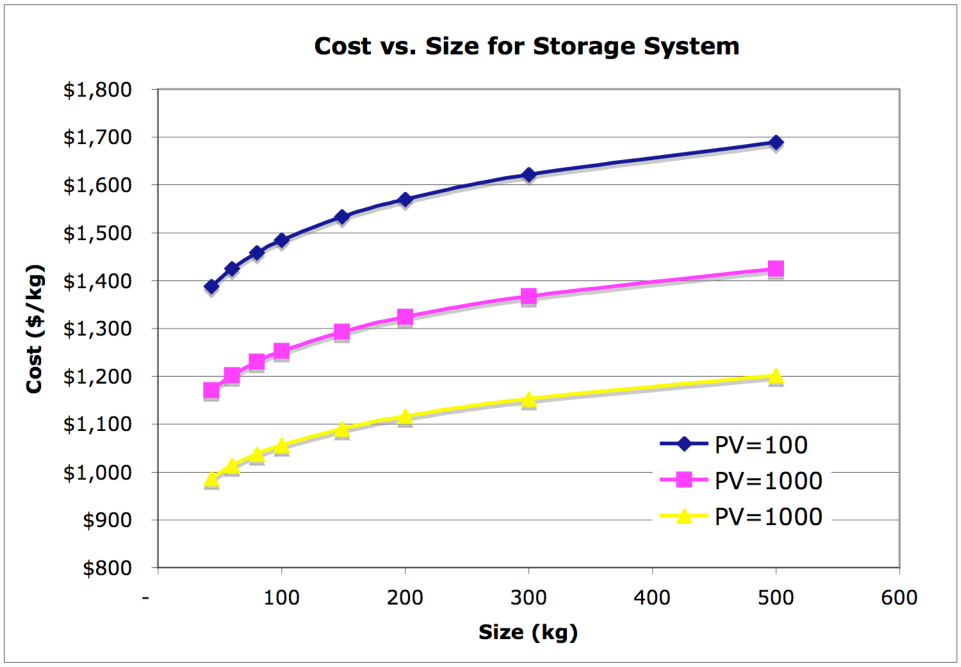


Figure 4-15 indicates that storage appears to get more expensive on a per kilogram basis as capacity increases. The cost curve based on original manufacturer data has a positive exponent (Cost in $/kg = 1,026 x Size$^{1.08}$). One possible explanation for this is that the cost quotes for small systems 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.

<u>3. Application of Adjusted Costs in Model</u>

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.

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

Equipment Costs:

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)

Installation Costs:

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

Operating Costs:

1. Feedstock Costs (natural gas, electricity)
2. Equipment Maintenance
3. Labor (station operator)
4. Real Estate
5. Insurance

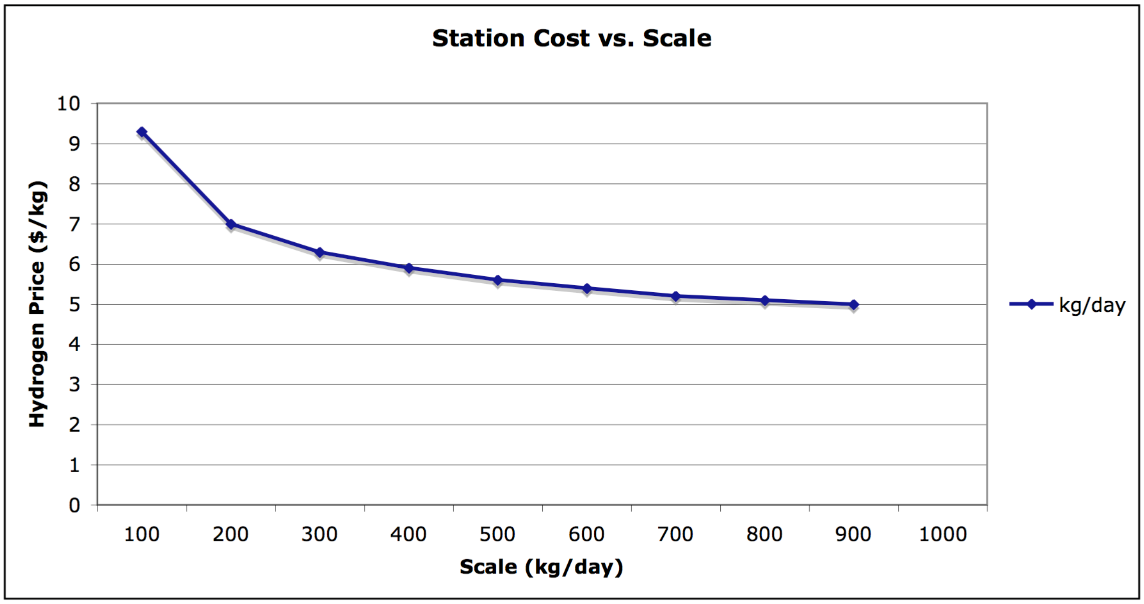
The operating cost for the PEM Fuel Cell/Reformer energy station is determined by subtracting the electricity revenue from the feedstock costs.

4.4 Example Station and Levelized Hydrogen Cost Results

The model can be used to determine total station costs and levelized hydrogen costs over a range of capacities. Figure 4-16 shows the cost of hydrogen at a reformer-type station between 100 and 900 kg/day. We assume that 10 stations have been built for this example.[23]

[23] Figures 4-16 and 4-17 demonstrate the functional capabilities of the model. The results ($/kg) should be referenced with caution because they are dependent on assumptions that are not mentioned. See the station cost estimates in Appendix A for more details.

Figure 4-16: Hydrogen Cost vs. Station Size for Reformer Station



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 4-17: Cost vs. Production Volume for the Reformer Station

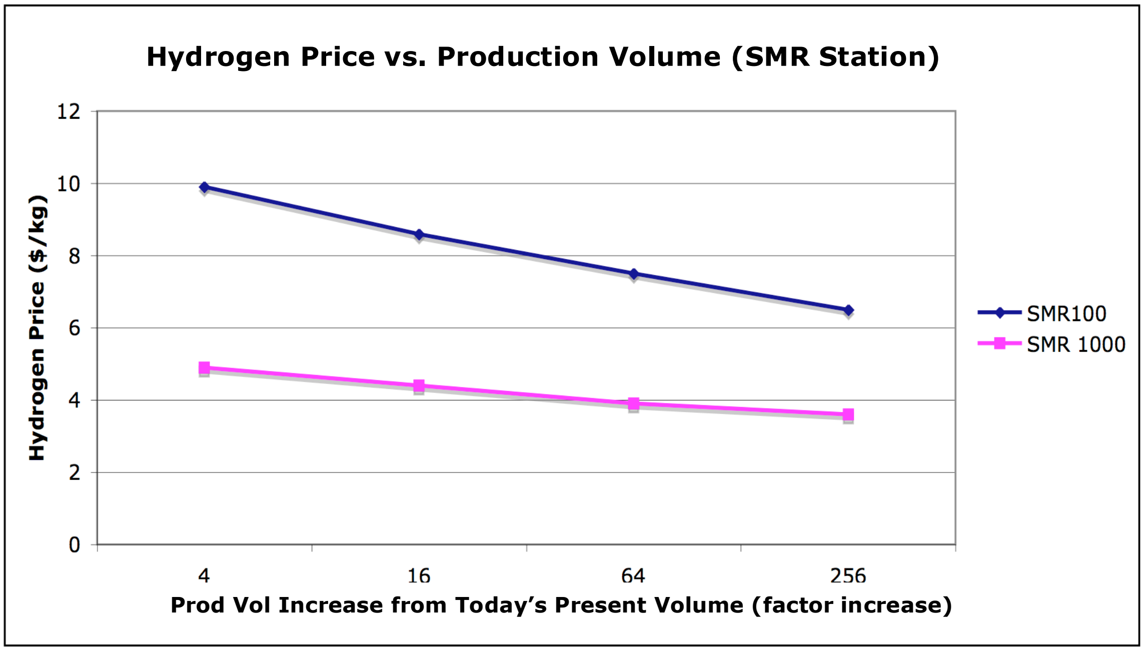


Table 4-8 below presents near-term cost results for ten example station types, as calculated by the HSCM. Appendix A presents a more detailed table of these results.

Table 4-8: Sample Cost Estimates for Ten Hydrogen Refueling Station Types (in thousands of $)

All units in $1,000 except $/kg	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	$318	$1,266	$147	$147	$250	$163	$510	$318	$365	$100
Purifier	$64	$201	$0		$0			$64		$20
Storage System	$197	$2,372	$51	$51	$189		$1,103	$41	$136	$46
Compressor	$52	$171	$28	$28	$52		$219	$52	$49	$76
Dispenser	$42	$127	$42	$42	$42		$127	$42	$42	$42
Additional Equipment	$72	$77	$67	$67	$72	$10	$87	$107	$123	$72
Installation Costs	$193	$300	$165	$128	$229	$44	$330	$193	$197	$175
Contingency	$110	$621	$49	$63	$89	$25	$302	$131	$147	$52
Fuel Cell / Photovoltaics				$90				$268	$285	
Total Capital Investment	$1,048	$5,137	$550	$616	$923	$243	$2,677	$1,216	$1,345	$583
Hydrogen + Delivery $/yr						$5	$714			$35
Natural gas $/yr	$20	$197	$0					$37	$107	
Electricity $/yr	$6	$63	$43	$27	$143		$19	($38)	($201)	$6
Maint., Labor, Overhead $/yr	$67	$196	$34	$39	$60	$17	$168	$76	$79	$39
Total Operating Cost $/yr	$93	$456	$77	$66	$203	$22	$901	$76	($16)	$79
Annualized Cost $/yr	$230	$1,130	$149	$147	$324	$54	$1,250	$236	$161	$156
Annualized Cost $/kg	$13	$6.5	$29	$28	$19	$31	$7.2	$14	$4.9	$9.0
Capacity kg/day	100	1000	30	30	100	10	1000	100	91	100
Hydrogen Sales 1000kg/yr	17.3	173	5.2	5.2	17.3	1.7	173	17.3	33.2	17,324

Key Assumptions: 13% Capital recovery factor Capacity Factor 47% for all except HTFC 100 (100% CF)

Installation Costs includes engineering and design, permitting, site development and safety & haz-ops analysis, installation, delivery, start-up & commissioning
Additional equipment includes mechanical, electrical, and safety equipment

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

Figures 4-18 through 4-21 show sample results for various station types and sizes, including the effects of varying assumptions for the "Basecase" case, the "Public Fleet Location" case, and the Champion applications" case. These results are based on capacity factors of 24% (basecase), 34% (public fleet location), and 44% (champion application), along with additional assumptions discussed above and shown in Table X.

Figure 4-18: Cost Estimates for 100 kg/day Reformer Station

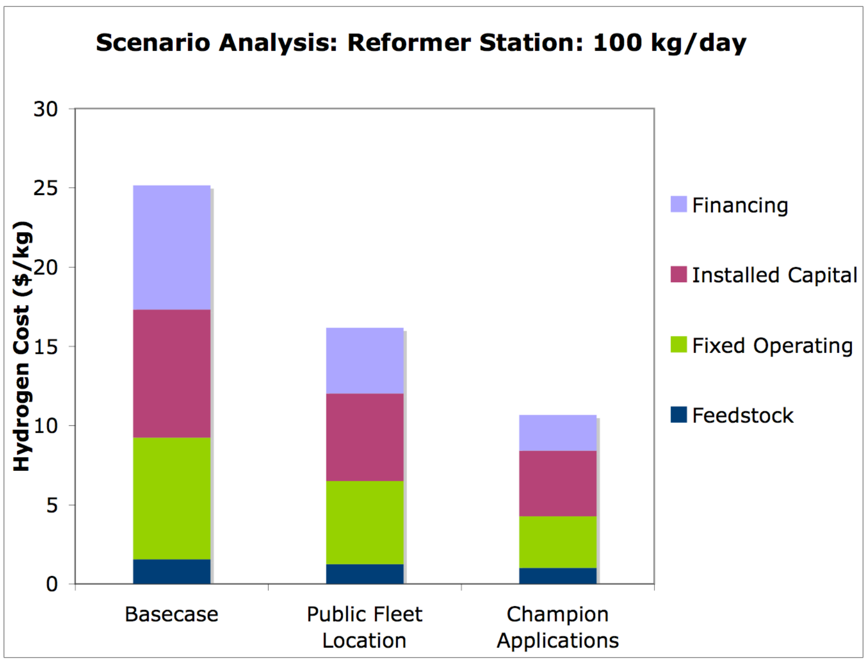


Figure 4-19: Cost Estimates for 30 kg/day Electrolysis Station

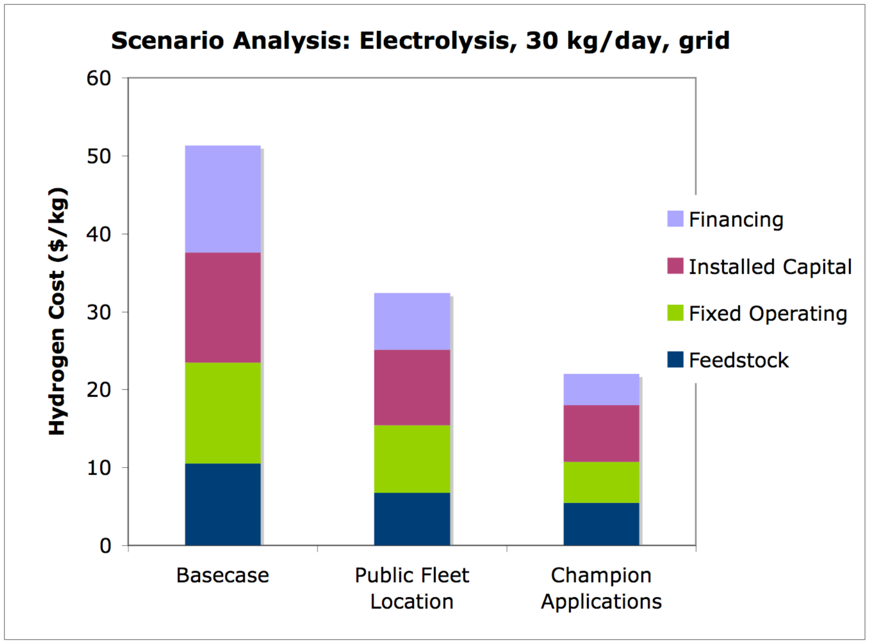


Figure 4-20: Cost Estimates for 10 kg/day Mobile Refueler

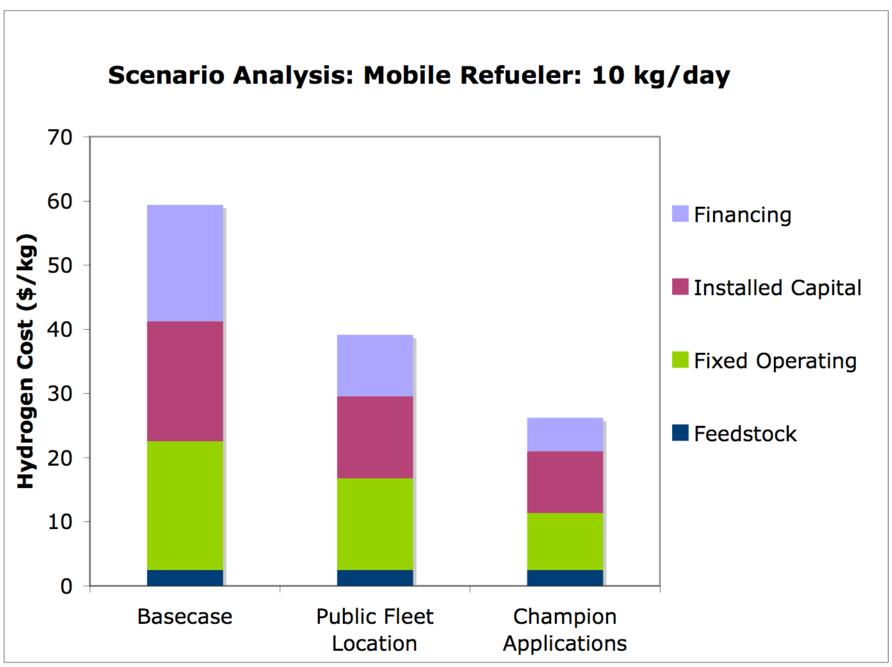
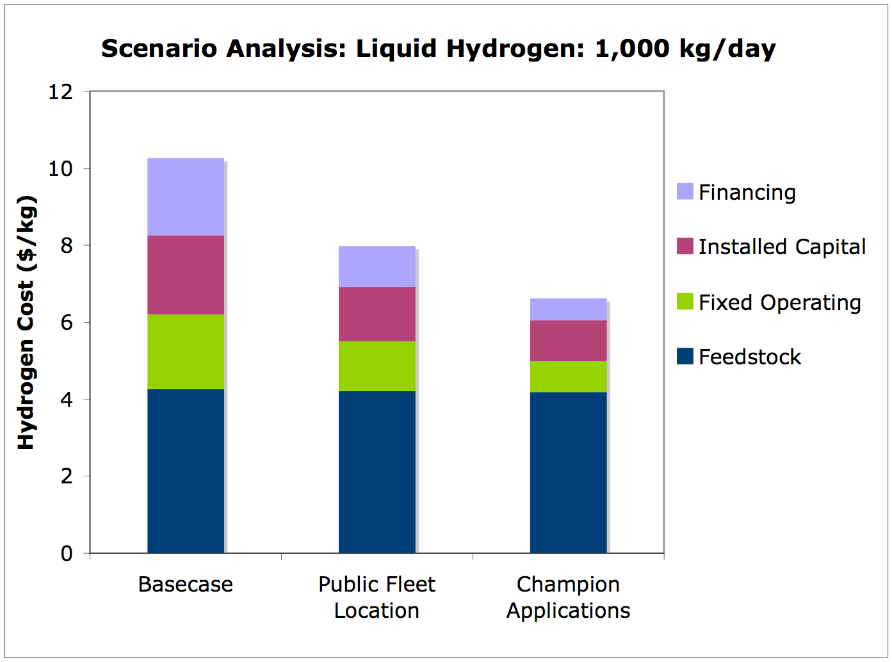


Figure 4-21: Cost Estimates for 1,000 kg/day Liquid Hydrogen Station



4.5 Comparison of Model Results

To assess and compare the results of the HSCM, the authors 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 those by NAS/NRC,[24] Tiax[25], the H2A gropup,[26] and General Motors.[27] An example of this comparison is provided in Table 4-9 below.

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[24] National Academy of Sciences/National Research Council (2004).
[25] Unnasch, S. and Powars, C., (2004) "Requirements for Combining Natural Gas and Hydrogen Fueling", Tiax LLC, Consultant Report for the California Energy Commission.
[26] Lasher, S. (2004), "H2A Forecourt Hydrogen Station Cost Analysis", Presentation at the National Hydrogen Asociation Conference, Los Angeles CA.
[27] 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.

Table 4-9: Comparison of Assumptions

Parameter	Study	On-site NG Reformation	Electrolysis
Total Electric Consumption (kWh/kg)	***This study***	***3.0***	***60.0***
	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	-

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[28] and the National Academy of Sciences[29] for an on-site reformer station. In general, costs estimated by the HSCM are higher than those in other studies since the other studies typically assumed mass production of components and low installation costs, while we assume lower production volumes and higher installation costs. In this comparison, we modified our assumptions (where possible) to match the assumptions used in the other two studies. Tables 4-10 and 4-11 and Figures 4-22 and 4-23 show the assumptions and results for this comparison. Since NAS presents both current and future costs, we present results using two different production volume levels (40 and 4,000 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.

[28] Thomas, C.E. (2004) The numbers in the study were emailed to Weinert by Sandy Thomas directly.
[29] National Academy of Sciences/National Research Council (2004).

Figure 4-22: Hydrogen Cost Comparison for Reformer Station, H2Gen Data

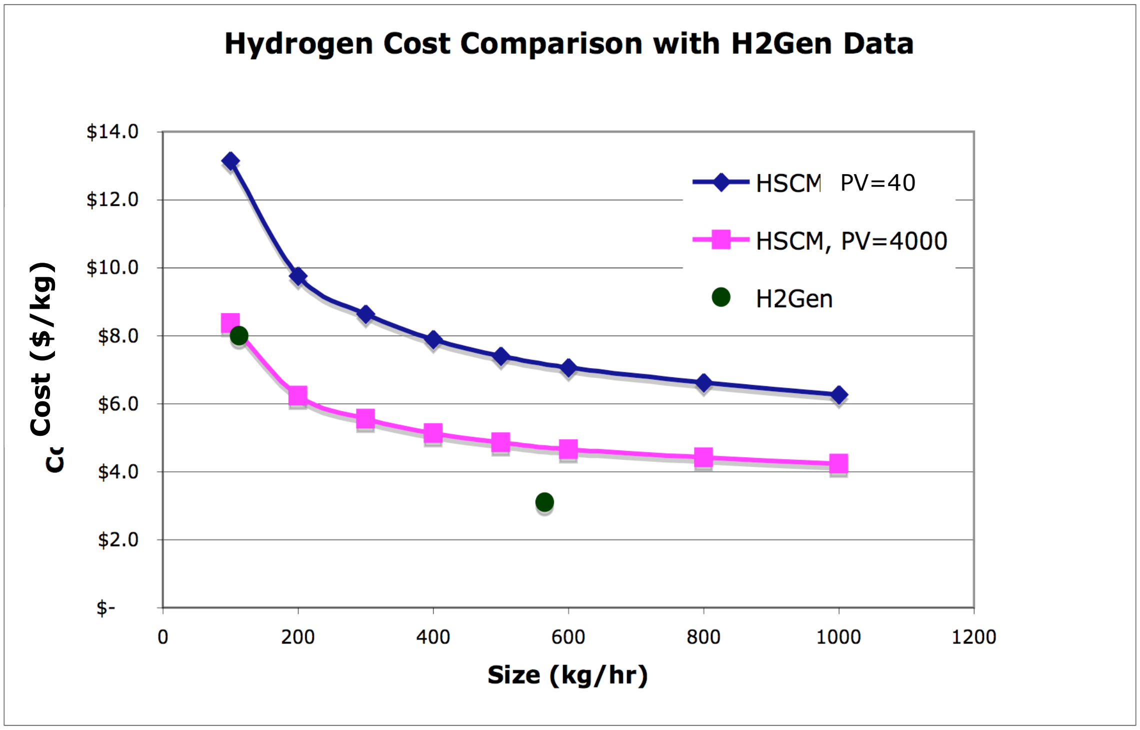


Figure 4-22 shows that the results are comparable only when the HSCM is adjusted for a cumulative production volume of 4,000 units. The large H2Gen unit has lower estimated costs than even the HSCM "4,000th unit" cost for a similar size reformer station. The table below provides a more detailed look at this comparison.

Table 4-10: Cost Comparison for Reformer Station With H2Gen Estimates

	HSCM (2010)		H2Gen	
			HGM-2000	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 (cumulative units)	40	40	not reported	not reported
Storage Capacity (kg)	153	765	50	250
Production Efficiency (reformer, %)	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 Hydrogen Cost (\$/kg)	**\$12.3**	**\$7.0**	**\$8.0**	**\$3.1**

The biggest discrepancy between the HSCM and H2Gen estimates 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. We collected data on D&I costs from several recently built stations and thus believe they are more indicative of true near-term 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.[30] 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 authors assume 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 authors assume 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.

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

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 4-23 shows where NAS costs fall in relation to HSCM costs for two production volume scenarios. Table 4-11 compares the HSCM to NAS results for reformer station costs.

Figure 4-23: Hydrogen Cost Comparison for Reformer Station, NAS

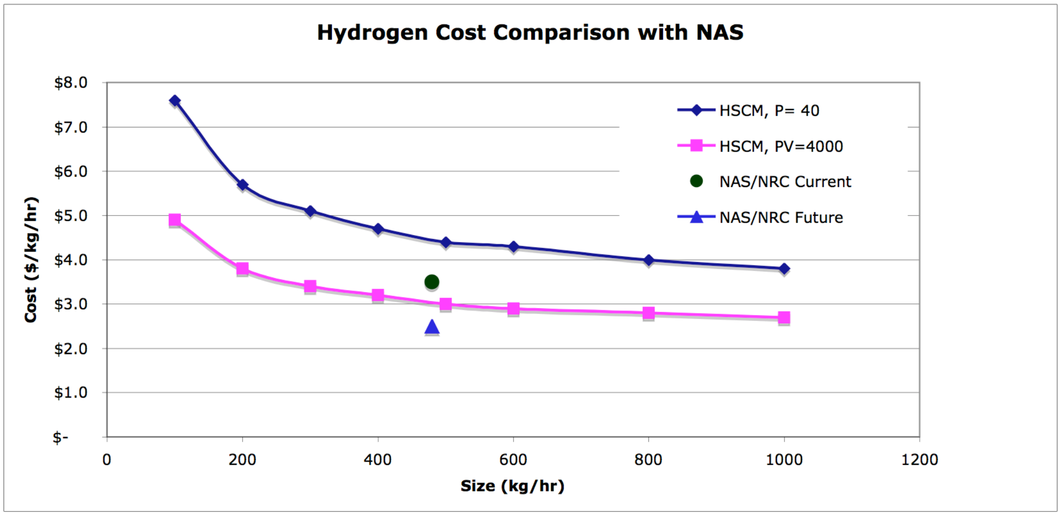


Table 4-11: Cost Comparison for Reformer Station With NAS Results

	HSCM Current	HSCM Future	NAS-current[31]	NAS-future[32]
	SMR 480	SMR 480	Onsite SMR	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)	$6.50	$6.50	$6.50	$6.50
Electricity Cost ($/kWh)	$0.07	$0.07	$0.07	$0.07
Production Volume	40	4,000		
Storage Capacity	650	650	108	108
Production Efficiency (%)	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	$0.26
Total Hydrogen Cost ($/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 we assume that a much larger hydrogen storage capacity is required (650 kg vs. 108 kg for a 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.

The NAS model does not account for "lulls" in the vehicle at the station during nighttime, and therefore assumes that vehicles are theoretically drawing fuel from the station 24 hrs/day. Our model assumes that there are two peak fueling periods each day, and essentially zero fueling occurring at night. This pattern of fueling requires extra storage capacity to store the output of

[31] NAS, p. E-35.
[32] NAS, p. E-36.

the reformer. Because of this high storage capacity estimate, the high cost of storage dominates. The HSCM actually assumes a lower reformer and compressor cost, and thehe D&I costs from both models are 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 4-12: Hydrogen Cost Comparison for Electrolysis Station With NAS Estimates

	HSCM	**HSCM**	**NAS Model v.3**	**NAS Model v.3**
	Current	Future	Current	Future
Electrolyzer Capacity (kg/day)	100	100	480	480
Capacity Factor (%)	90	90	90	90
Annual Capital Recovery Factor (%)	14	14	14	14
Electricity Cost ($/kWh)	$0.07	$0.07	$0.07	$0.07
Production History (cumulative units)	40	4000		
Storage Capacity (kg)	149	149	108	108
Production Efficiency (kWh/kg includes compressor)	54.8	50.2	54.8	50.2
Capital Costs	$593,748	$340,609	$1,760,000	$396,000
Hydrogen Equipment	$256,448	$94,253	$1,287,000	$143,000
Storage System	$176,768	$128,283	$176,000	$33,000
Compressor	$44,799	$23,290	$275,000	$209,000
Dispenser	$43,635	$22,684	$22,000	$11,000
Delivery and Installation Cost	$340,059	$155,932	$774,000	$181,500
Hydrogen Cost				
Natural Gas Cost ($/kg)	$-	$-	$-	$-
Electricity Cost ($/kg)	$4.9	$4.5	$3.8	$3.3
O&M ($/kg)	$1.8	$1.4	$0.5	$0.1
Capital Charge ($/kg)	$2.5	$1.4	$1.6	$0.4
Delivery and Installation Charge ($/kg)	$1.4	$0.7	$0.7	$0.2
Total H2 Cost ($/kg)	**$10.7**	**$8.0**	**$6.6**	**$3.9**

The NAS model analyzes a much bigger electrolyzer (480 versus 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 (estimated at about 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 4,000 units, small-scale reformer-type stations achieve the costs reported from the H2Gen report. This corresponds to a demand of ~250,000 vehicles.[33] 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.

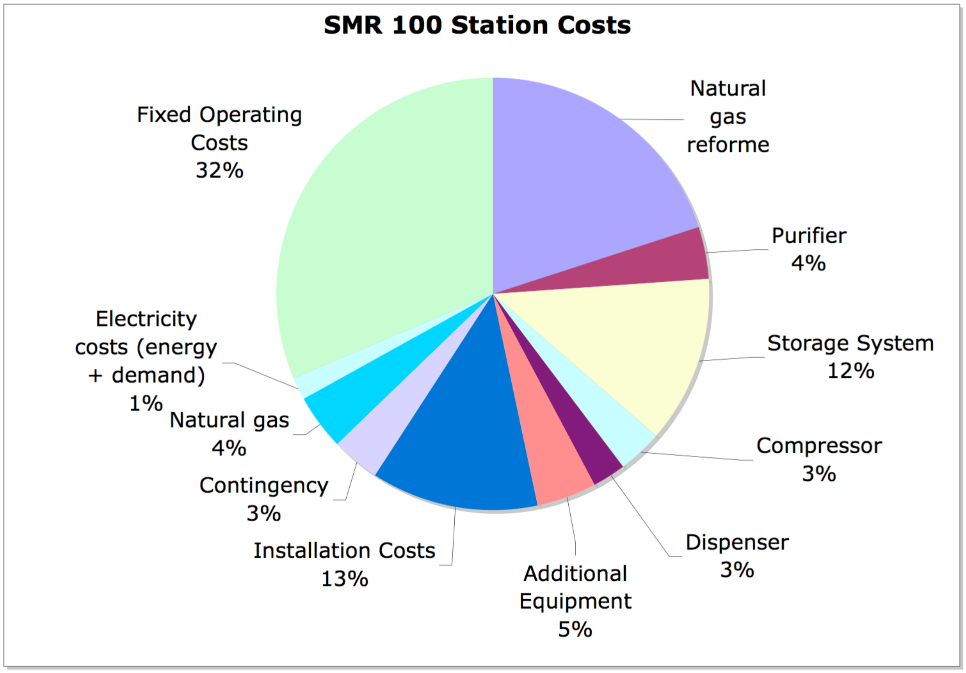
Sensitivity Analysis
A sensitivity analysis was conducted on the six important station assumptions to determine their effect on overall hydrogen cost. The table below shows the high and low values used for each variable in the sensitivity analysis.

Table 4-13: Sensitivity Analysis Parameters

	Basecase	Optimistic	Pessimistic
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%

[33] 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.

Figure 4-24: Reformer Station Costs (100kg/day)



5.0 CONCLUSIONS

In this report we have reviewed the existing body of literature on hydrogen fueling station costs and documented our efforts to develop our own "best guess" estimates of near term costs for hydrogen stations of various types. Based on this analysis, we make the following conclusions:

1. Commercial scale hydrogen station costs vary widely, mostly as a function of station size, and with a range of approximately $500,000 to over $5 million for stations that produce and/or dispense 30 kg/day to 1,000 kg/day of hydrogen. Mobile hydrogen refuelers represent less expensive options for small demand levels, with lower capital costs of about $250,000.
2. 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.
3. In order to achieve hydrogen costs competitive with gasoline prices of around $2.00 per gallon, production volumes for key station components will need to reach levels of 1,000 or more units per year.[34] This is equivalent to about 6% of gasoline stations in California
4. 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.
5. 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.
6. Large stations of 1,000 kg/day or more 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.
7. 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.
8. Mobile refuelers yield the most expensive hydrogen due to their small size (10kg/day) and the high cost to refill them.

[34] For a single manufacturer.

9. 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.
10. Station sited near an industrial demand for hydrogen can share the hydrogen use and thus take advantage of scale-economies and high capacity factors.
11. Pipeline stations have potential for low cost at low flow rates when sited near existing pipelines.
12. 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.

At present, hydrogen station costs are higher than reported in the available literature. Our analysis shows that this is due to equipment costs that are often higher than reported in the literature, as well as additional costs associated with siting, permitting, and commissioning that are often underestimated or ignored. We expect these costs to fall as more stations are constructed over the next several years, but we also expect the pace of cost reduction in station construction to be relatively slow.

REFERENCES

Amos, W. (1998) "Costs of Storing and Transporting Hydrogen," NREL, Golden, CO, November.

J.M. Dutton and A. Thomas (1984) "Treating Progress Functions as a Managerial Opportunity," *Academy of Management Review* **9**(2): 235-247.

P. Ghemawat (1985) "Building strategy on the experience curve," *Harvard Business Review* **March-April, 1985**: 143-149.

Ianucci, J.J, J.M. Eyer, S.A. Horgan, and S.M. Schoenung (1998) "Economic and Technical Analysis of Distributed Utility Benefits for Hydrogen Refueling Stations," Distributed Utility Associates, Livermore, CA.

Kreutz, T.G. and J.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.

Lipman, T.E., J.L. Edwards, and D.M. Kammen (2004) "Fuel Cell System Economics: Comparing the Costs of Generating Power with Stationary and Motor Vehicle PEM Fuel Cell Systems," *Energy Policy* **32**(1): 101-125.

Lipman, T.E., J.L. Edwards, and D.M. Kammen (2002) "Economic Analysis of Hydrogen Energy Station Concepts: Are "H2E-Stations" a Key Link to a Hydrogen Fuel Cell Vehicle Infrastructure?" *Energy Development and Technology Working Paper Series*, EDT-003, University of California Energy Institute (UCEI), November.

Lipman, T.E. and D. Sperling (2000) "Forecasting the Costs of Automotive PEM Fuel Cells Using Bounded Manufacturing Progress Functions*," Proceedings of the IEA International Workshop on Experience Curves for Policy Making – The Case of Energy Technologies, Stuttgart, Germany, May 10-11, 1999*, Edited by C-O Wene, A. Voss, and T. Fried, April, pp. 135-150.

Melaina, M. (2003) "Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US," *International Journal of Hydrogen Energy* **28**: 743-755.

Myers, D.B., G.D. Ariff, B.D. James, J.S. Lettow, C.E. Thomas, and R.C. Kuhn (2002) "Cost and Performance Comparison Of Stationary Hydrogen Fueling Appliances" DTI, Arlington, VA, April.

National Academy of Science/National Research Council (2004) "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs", National Academies Press, http://www.nap.edu.

Padró, C.E.G. and V. Putsche, (1999) "Survey of the Economics of Hydrogen Technologies," NREL, Golden, CO, September.

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

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.

Rastler, D. (2000) "Challenges for fuel cells as stationary power resource in the evolving energy enterprise", *Journal of Power Sources* **86**: 34-39.

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

Simbeck, D. and E. Chang (2002) "Hydrogen Supply: Cost Estimate for Hydrogen Pathways - Scoping Analysis" SFA Pacific, Mountain View, CA, July.

Thomas, C.E., J.P. Reardon, F.D. Lomax, J. Pinyan and I.F. Kuhn (2001) "Distributed Hydrogen Fueling Systems Analysis," DTI, Arlington, VA.

Unnasch, S. (2002) "Energy Stations for Federal Buildings," Proceedings of the 2002 U.S. DOE Hydrogen Program Review, NREL/CP-610-32405.

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

Weinert, J. (2005) "A Near-Term Economic Analysis of Hydrogen Fueling Stations," Master's Thesis, UC Davis Institute of Transportation Studies, UCD-ITS-RR-05-06.

Appendix A: Summary of Cost Estimates for 10 Station Types

All units in $1,000 except $/kg	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	$318	$1,266	$147	$147	$250	$163	$510	$318	$365	$100
Purifier	$64	$201	$0		$0			$64		$20
Storage System	$197	$2,372	$51	$51	$189		$1,103	$41	$136	$46
Compressor	$52	$171	$28	$28	$52		$219	$52	$49	$76
Dispenser	$42	$127	$42	$42	$42		$127	$42	$42	$42
Additional Equipment	$72	$77	$67	$67	$72	$10	$87	$107	$123	$72
Installation Costs	$193	$300	$165	$128	$229	$44	$330	$193	$197	$175
Contingency	$110	$621	$49	$63	$89	$25	$302	$131	$147	$52
Fuel Cell / Photovoltaics				$90				$268	$285	
Total Investment	$1,048	$5,137	$550	$616	$923	$243	$2,677	$1,216	$1,345	$583
Hydrogen $/yr						$4	$714			$35
Delivery						$1				
Natural gas $/yr	$20	$197	$0					$37	$107	
Electricity $/yr	$6	$63	$43	$27	$143		$19	($38)	($201)	$6
Maint., Labor, Overhead $/yr	$67	$196	$34	$39	$60	$17	$168	$76	$79	$39
Total Operating Cost	$93	$456	$77	$66	$203	$22	$901	$76	($16)	$79
Annualized Cost	$230	$1,132	$149	$147	$324	$54	$1,253	$236	$161	$156
Annualized Cost/kg	$13	$6.5	$29	$28	$19	$31	$7.2	$14	$4.9	$9.0
Capacity 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	$1.1	$1.1	$-	$-	$-	$-	$-	$2.2	$3.2	$-
Electricity Cost/kg	$0.4	$0.4	$8.3	$5.2	$8.3	$-	$0.1	($2.2)	($6.0)	$0.4
Fixed Operating/kg	$3.8	$1.1	$6.5	$7.5	$3.4	$12.8	$5.1	$4.4	$2.4	$4.2
Capital Charge /kg	$5.7	$3.2	$8.5	$10.8	$4.6	$13.1	$1.6	$6.8	$4.0	$2.7
Delivery and Installation Charge /kg	$2.3	$0.7	$5.4	$4.8	$2.4	$5.3	$0.5	$2.5	$1.4	$1.7

Key Assumptions: 13% Capital recovery factor

Additional equipment includes mechanical, electrical, and safety equipment

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

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

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