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Hydrogen refueling station costs in Shanghai

Jonathan X. Weinert[a,b,*], Liu Shaojun[b], Joan M. Ogden[a], Ma Jianxin[b]

[a]*Hydrogen Pathways Program, Institute of Transportation Studies, University of California - Davis, 1 Shields Ave, Davis, CA, 95616, USA*
[b]*Institute of Hydrogen Technologies, College of Automotive Studies, Tongji University, 4800 Cao An Lu, Jia Ding, P.C. 201804, People's Republic of China*

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Abstract

Interest in hydrogen as a transportation fuel is growing in Shanghai. Shell Hydrogen, Tongji University, and the City of Shanghai plan to construct a network of refueling stations throughout the city to stimulate fuel cell vehicle and bus deployment. The purpose of this paper is to (1) examine the near-term costs of building hydrogen stations of various types and sizes in Shanghai and (2) present a flexible cost analysis methodology that can be applied to other metropolitan regions.

The costs for four different station types are analyzed with respect to size and hydrogen production method. These costs are compared with cost estimates of similar stations built in California. Based on the hydrogen station cost analysis conducted here, we have found that hydrogen costs ($/kg) vary considerably based on station type and size. On-site hydrogen production from methane or methanol results in the lowest cost per kg. The higher cost of truck-delivered hydrogen from industrial sites in Shanghai vs. California is mainly due to feedstock costs differences. Electrolyzer stations yield the highest hydrogen cost.
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1. Introduction

Interest in hydrogen as a transportation fuel is growing in Shanghai. Shell Hydrogen, Tongji University, and the City of Shanghai plan to construct a small network of hydrogen refueling stations throughout the city, the "Shanghai Hydrogen Lighthouse Project" (SHLP).

Industry and government face two key challenges in planning a new hydrogen infrastructure: (1) the lack of accurate data on current station costs; and (2) the need to find cost-effective infrastructure development strategies. In this paper, we focus on the first of these challenges, but the findings are relevant to the second challenge as well.

There are few publicly available reports of the actual costs of hydrogen stations and these vary widely. This variability makes it difficult to accurately predict the cost of building new stations. While there are many estimates in the literature [1–4] of the anticipated costs of future fueling stations, most analyses till date project costs below the costs experienced today. In some cases, actual station costs have greatly exceeded the budgeted amount [5].

In this paper, we estimate the near-term costs for hydrogen stations in a specific region (Shanghai), using engineering/economic spreadsheet models for hydrogen station costs and delivery. Data for these models come from the compendium of hydrogen refueling equipment costs or CHREC [6] and from industrial sources in Shanghai. These models are used to determine the costs of several types of hydrogen stations under various conditions and assumptions. Both the hydrogen station cost model (HSCM) and CHREC were developed for use in calculating the cost of stations in California for the Hydrogen Highway Initiative (2005).[1] The delivery model was created at Tongji University for calculating the costs of hydrogen

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* Corresponding author. Hydrogen Pathways Program, Institute of Transportation Studies, University of California - Davis, 1 Shields Ave, Davis, CA, 95616, USA.
E-mail address: jxweinert@ucdavis.edu (J.X. Weinert).

[1] The goal of the California Hydrogen Highway Initiative is to develop the infrastructure for a hydrogen transportation economy, reducing California's dependence on foreign oil and improving air quality. http://hydrogenhighway.ca.gov/.

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delivery in Shanghai. Although our focus in this paper is Shanghai, the methods used in this report can be adapted for hydrogen station cost analysis in other regions.

1.1. Background

1.1.1. Hydrogen stations

Hydrogen fueling stations are key building blocks of a hydrogen transportation infrastructure. They can provide hydrogen fuel for vehicles in many different ways. For instance, stations can be designed to produce hydrogen on-site, or to have hydrogen 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 purity for use in hydrogen vehicles.
3. Compressor: compresses hydrogen gas to achieve high-pressure 5000–10,000 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).

Capital costs for this equipment must be included in an analysis of station costs. Total station construction costs also include the following: engineering and design, site preparation, permitting, installation, and commissioning (i.e. ensuring the station works properly).

Stations typically have the following recurring operating expenses: equipment maintenance, labor (station operator), feedstock costs (e.g. natural gas, methanol, electricity, delivered hydrogen), insurance, and rent.

It is important for station economic analyses to include all of these capital and operating costs when evaluating hydrogen production costs. Many analyses in the existing body of literature omit some of these; particularly costs associated with permitting and site preparation.

1.1.2. Shanghai

Shanghai was chosen as the region of analysis because it has been identified by both the Chinese central government and foreign industry as a particularly attractive location for building hydrogen stations. A city of international status, Shanghai is home to the two biggest automakers in China, and one fuel cell manufacturing company, which is currently developing its own hydrogen vehicles.[2] Recently, Shanghai was chosen as a site for one of Shell hydrogen's hydrogen lighthouse projects (SHLP). The goal of the Shanghai hydrogen lighthouse project (SHLP) is to operate 90 fuel cell taxis and 10 fuel cell buses, serviced by multiple hydrogen refueling sites in the city by 2010. This rapid development is motivated in part by the 2010 Shanghai Expo, which will provide excellent international exposure for hydrogen and fuel cell vehicle technologies.

Table 1
Proposed hydrogen refueling stations

Station	Size (kg/day)	Feedstock
1, 2. On-site steam methane reformation	100, 300	Natural gas, Shanghai
3. On-site methanol reformation	100	MeOH, Shanghai coking Co.
4. Electrolysis	30	Shanghai utility
5, 6. Truck delivered gaseous H_2	150, 300	H_2 from industrial sources[a]

[a] Industrial sources in Shanghai include Baoshan Steel and Shanghai Coking Carbonization Company.

Shanghai is well positioned to meet this hydrogen demand in several ways. Both electricity and natural gas (which is widely used in the city) could be used for onsite production. Excess in the existing industrial hydrogen production capacity might also be used. There is an estimated 48,000 tons/yr of existing hydrogen production and 3600 tons/yr of excess hydrogen production capacity from industry in Shanghai.[3] The majority of this hydrogen comes from two companies: Baoshan Steel and the Shanghai Coking Carbonization company.

1.2. Scope

We estimate the costs of four different station types in Shanghai. The specifications for each station design are presented in Table 1. Station sizes and types are based on anticipated vehicle demand for hydrogen and feedstock availability in Shanghai.

To put these station sizes in perspective, 1 kg of hydrogen has about the same energy content as 1 gal of gasoline. A hydrogen fuelling station that delivers 100 kg of hydrogen per day delivers enough energy in a gasoline equivalency to fuel about 5 gasoline SUV's, 10 gasoline hybrids or 20 hydrogen fuel cell vehicles (each carrying 5 kg of hydrogen) per day. Today's typical gasoline stations serve several hundred cars per day.

Station 1,2. On-site steam methane reformation production, 100 and 300 kg/day: This station converts natural gas feedstock into hydrogen using a steam methane reformer (SMR). The SMR is integrated with a natural gas compressor, blower, and water pump and pressure-swing adsorption (PSA) hydrogen purification system. A compressor is used to compress the low-pressure hydrogen output of the reformer into high-pressure stationary hydrogen storage tanks. The storage tanks are arranged in cascade design that allows the user to refill from a bank of high-pressure tanks without additional compression.

Station 3. On-site methanol production, 100 kg/day: In this type of station, methanol is delivered by truck to the station from the central production plant, stored on-site in an underground

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[2] Shanghai Fuel Cell Powertrain Co. plans to manufacture 100 fuel cell taxis by the end of 2010 (Ma Jianxin, 2005).

[3] Tongji University (2005) Lighthouse Feasibility Report to Shell Hydrogen, p. 28.

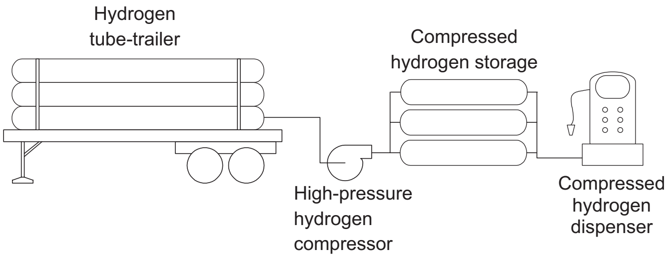

Fig. 1. Diagram of delivered hydrogen station utilizing by-product hydrogen.

storage tank, and converted into hydrogen using a methanol reformer. Aside from the methanol reformer and storage tank, the station is identical to the natural gas reformer station.

Station 4. On-site electrolysis production, 30 kg/day: This station uses an alkaline electrolyzer powered by grid electricity to split water into hydrogen and oxygen. Aside from the electrolyzer, this station uses much of the same equipment as the on-site reformer station. A PSA unit is not required since we assume a purifier is included in the electrolyzer system.

Station 5,6. Delivered hydrogen from industrial hydrogen production, 150 and 300 kg/day: This station receives its hydrogen from either Shanghai Coking Co or Baoshan Steel. The hydrogen is delivered to the station by truck using a tube trailer, carrying high-pressure hydrogen gas. This type of station consists of two 300 kg, 200-bar hydrogen tube trailers, a diaphragm compressor, high-pressure gaseous hydrogen storage containers, and a dispenser. The main difference between the 150 and 300 kg/day station is the frequency of hydrogen delivery, the size of storage capacity and number of dispensers. The large station receives deliveries daily while the small station receives them every two days. The truck leaves a full hydrogen trailer, and picks up an empty trailer for refueling. This station is shown in Fig. 1.

1.3. Literature review

This section provides a brief summary of the literature on the costs of hydrogen stations. For a more detailed review of the assumptions and approaches used in these studies, see [6].

1.3.1. Previous studies of hydrogen station and equipment costs

We reviewed several reports that contain information on equipment used in hydrogen stations, and on station design and cost. These studies are listed in Tables 2 and 3 .

Our goal is to identify particularly useful cost data and cost models that serve as input to our models. Several questions guide our assessment of these reports:

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 station costs are there limited amounts of information? Which station costs items are neglected?
3. Are the assumptions in these studies, most of which were conducted in the United States, valid in Shanghai?

Simbeck [4] analyzes the total station costs for several different types of stations through the use of a comprehensive spreadsheet model. Sepideh [7] is useful in evaluating data from several reports on hydrogen equipment costs. Meyers [2] provides an in depth analyses of reformer, compressor, and storage equipment costs. Amos [8] reviews delivery and storage costs. Padro [9] reviews over 100 publications containing hydrogen cost data for production, storage, transport, stationary power, and transportation applications. Recently, the USDOE released a new database on station costs as part of its H2A project [1], which contains extensively reviewed estimates for hydrogen production, delivery and refueling stations.

1.3.2. Summary of literature review

Tables 2 and 3 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.

We find that most of the cost models presented in the literature focus on relatively large stations (> 100 kg/day) at high production volume levels (> 100 units/yr). In general, they lack information on near-term, actual equipment and station costs. (Some of the older reports were written before any hydrogen stations were built. Some of the equipment cost data from older reports under-estimate current costs, even when adjusted for inflation.). While the reports include equipment costs at different sizes and production volumes, most overlook non-capital costs such as installation, permitting and siting.[4] Moreover, many reports assume high capacity factors that are unrealistically high for near-term scenarios. Clearly, the existing models reported in the literature are not adequate for estimating near term hydrogen stations costs in Shanghai.

To address the shortcomings of existing data and models, one of the authors (Weinert [6]) developed an EXCEL database of current hydrogen station equipment costs (see CHREC below), and a station cost model (see HSCM). These are further adapted for use in the Shanghai case study.

1.3.3. Studies of hydrogen infrastructure in China

There have been very few reports on hydrogen systems in China, particularly for the cost of hydrogen refueling stations. These reports do not provide data on equipment costs, nor do they provide specific cost estimates of hydrogen stations. Zheng

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[4] Simbeck and Chang's (2002) spreadsheets make rough estimates of these costs based on estimates from other industries.

Table 2
Literature review summary for station and equipment costs

Year	Source	Primary author	Hydrogen station and equipment costs						
			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
04	Hydrogen Analysis Group (H2A)	H2A [1]	A	I	A	A	A	A	A
04	National Academy of Science Report A critical review and analysis of publications on the costs of hydrogen	NAS [3]	A	I	A		A	N	A
03	Infrastructure for transport hydrogen supply: cost estimate for hydrogen	Sepideh [7]	I	N	N	N	N	I	A
02	Pathways-scoping analysis	Simbeck [4]	A	I	A	I	A	I	A
02	Cost and performance comparison of stationary hydrogen fueling applications	Myers [2]	A	N	I	N	I	A	A
01	Distributed hydrogen fueling systems analysis	Thomas [14]	I	N	I	A	I	A	I
99	Survey of the economics of hydrogen technologies	Padro [9]	I	N	N	N	I	A	A
98	Costs of storing and transporting hydrogen	Amos [8]	A	N	A	N	I	N	A
05	A comprehensive comparison of fuel options for fuel cell vehicles in China	Wang [12]	N	N	I	N	N	N	N

Table 3
Literature review summary for model features

	Source	Primary author	Model features			
			Performs sensitivity analyses on key variables	Includes technical Info on equipment	Includes rational for design choices	Explores regional effects of station siting
2004	Hydrogen Analysis Group	H2A [1]	A	A	I	I
2004	National Academy of Science Report	NAS [3]	A			
2002	Hydrogen supply: cost estimate for hydrogen pathways-scoping analysis	Simbeck [4]	N	N	A	I
2002	Cost and performance comparison of stationary hydrogen fueling appliances	Myers [2]	N	A	A	N
2001	Distributed hydrogen fueling systems analysis	Thomas [14]	A	A	A	I
1998	Costs of storing and transporting hydrogen	Amos [8]	N	A	A	N
2005	A comprehensive comparison of fuel options for fuel cell vehicles in China	Wang [12]	N	N	A	I

[10] reviewed the hydrogen storage and the delivery cost for fuel cell vehicles, however, it does not reflect any data specific to China. Feng [11] employed Life Cycle Assessment to study the environmental, economic and energy efficiency a whole hydrogen system for fuel cell vehicles. The result indicates the total hydrogen cost varies from \$1.8/kg to \$5.2/kg H_2 for

different options; however, it does not present the main assumptions except the economic assumptions, which makes it difficult to assess the result.

A report by Wang [12] analyzes several hydrogen generation pathways, both on-board and off-board the vehicles using a life-cycle-assessment (LCA) model. It analyzes the energy, environmental, and economic impacts of FCVs from well-to-wheels (i.e. from when the energy is first extracted from the ground to when it is used as a fuel in the vehicle). The study looks at 10 vehicle/fuel systems and concludes that methanol is the ideal fuel for the long-term. The report is evaluated in Tables 2 and 3.

Huang [13] analyzes hydrogen infrastructure in Shanghai, however this report does not include economic analysis. It simulates 10 different hydrogen pathways and performs a well-to-wheels analysis on their energy use, pollutants, and greenhouse gas (GHG) emissions using the GREET model.[5] The feedstocks used in the 10 pathways include petroleum, natural gas, petroleum-based naphtha, coal, and electricity. The only part of this analysis however that is unique to Shanghai is that it used Shanghai's grid mix.

2. Research tools and methodology

We use three Excel-based spreadsheet models to estimate station costs. The CHREC and HSCM were originally created by one of the authors (Weinert [6]) for general analysis of hydrogen station costs. These models were used for analysis of the California Hydrogen Highway Network [6]. The Tongji hydrogen delivery cost model (THDCM) is used to determine hydrogen delivery costs from industrial sources. In this paper we adapted these models to analyze the economic feasibility of the SHLP.

2.1. 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. engineering, design, permitting), operating costs, 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 (see Tables 2 and 3) 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 and Chemicals, Inc., Stuart Energy, H2Gen). All cost data are normalized to year 2004 dollars.

2.2. The hydrogen station cost model (HSCM)

Station costs are calculated using the HSCM. For each station type, the HSCM sizes the required equipment according to assumed design constraints.[6] The model then computes the total installed station capital cost ($), operation and maintenance costs ($/year) and levelized hydrogen cost ($/kg). It uses cost data from hydrogen equipment suppliers, energy suppliers, and previous hydrogen station installations. This cost model was used by the California Hydrogen Highway Network Blueprint Panel to calculate the costs of a network of stations in California. While some of the costs and assumptions have since been modified for Shanghai, the original costs and assumptions were reviewed by several companies in the hydrogen industry including Chevron and Air Products and Chemicals, Inc., as well as the members of the DOE's Hydrogen Analysis Group (H2A [1]). When cost data were available from Chinese manufacturers, we adjusted the model to reflect these costs. The structure of the model is presented in Fig. 2.

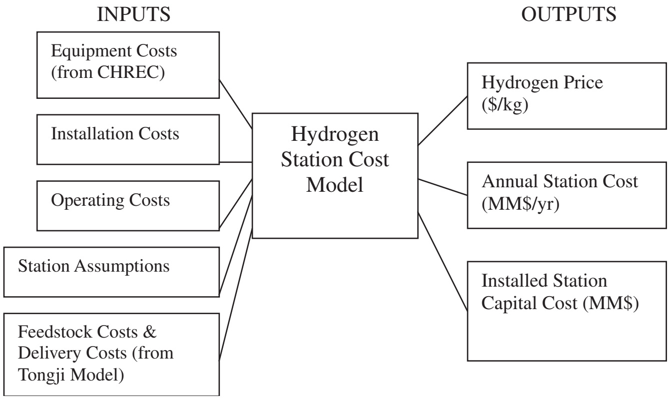

Fig. 2. Hydrogen station cost model (HSCM) structure.

The HSCM analyzes the economics of different types and sizes of hydrogen stations. The following figure shows the key inputs and outputs of this model.

2.3. Tongji hydrogen delivery cost model (THDCM)

The THDCM uses data from Shell Hydrogen and the US Department of Energy H2A Hydrogen Analysis Model[7] to determine hydrogen delivery costs, for cases 5 and 6, between the industrial hydrogen source and station location.

The THDCM was then integrated into the HSCM model described above. Some data were derived from the H2A analysis, while other data were based on actual costs in Shanghai. The number of the trucks and tube trailers was calculated to determine the capital cost. The total cost includes the capital depreciation cost, labor cost, fuel cost and other fixed cost, e.g. insurance, license and permit, maintenance, and overhead.

2.4. Assumptions

The model makes the following assumptions regarding equipment, site layout, station design, operation and cost.

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[5] http://www.transportation.anl.gov/software/GREET/.

[6] The sizing method and constraints were developed by Stefan Unnasch of TIAX LLC., Cupertino, CA, USA.

[7] http://www.hydrogen.energy.gov/h2a_delivery.html.

2.4.1. Equipment assumptions

The stations store hydrogen at 432 bar to serve fuel vehicles with 350 bar on-board vehicle storage. The model assumes the stations use the diaphragm compressors, cascade storage (432 bar), and a two-hose dispenser (350 bar). We assume 2.1 kWh/kg of electricity is required to compress the hydrogen at these stations based on the compression of hydrogen from 200 psi to 6250 psi at 65% isentropic efficiency for the motor/compressor system.

2.4.2. Equipment sizing assumptions

Stations are designed to provide 40% of the daily vehicle demand in 3 h. This assumption determines the amount of storage required for on-site production stations since the compressor size is fixed by the hydrogen production rate. For stations with delivered hydrogen, there is some flexibility in choosing compressor size, however there is a trade-off between compressor and storage size. Using a larger compressor allows for smaller storage capacity and vice versa, though the former is the more inexpensive option. Table 4 shows the compressor and storage size for each station type.

2.4.3. Economic assumptions

Table 5 presents the key economic assumptions used in the model. These assumptions can be modified when conducting sensitivity analyses. Some assumptions are based on economic analyses by the US Department of Energy Hydrogen Analysis Group (H2A [1]) while others are specific to Shanghai.

Capacity factor is defined as the ratio between the average hydrogen dispensed at a station per day compared to its peak output. Of all the assumptions above, capacity factor has the greatest effect on hydrogen cost ($/kg). We have assumed 80% capacity factor to account for the variable demand for hydrogen, since the hydrogen generator must be designed to accommodate the peak daily load while daily demand will be much less than the peak on most days during the year. A small fraction of this 80% capacity factor also accounts for scheduled and unscheduled maintenance.

In the US, alternative fuel stations such as natural gas experience much lower capacity factors due to the lack of vehicles. Capacity factor and thus hydrogen cost therefore depend on the fleet of fuel cell vehicles available.

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 are used to calculate the capital recovery factor (or "fixed charge rate"). The formula for calculating this is

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

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 the land occupied by the station. Real estate costs in Shanghai are among the highest in China and \$5.4/m^2/month corresponds to average commercial real estate price in the US.

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.[8]

Station labor cost includes the cost of hiring one employee per station to refuel vehicles, report equipment problems, and handle emergencies. A truck driver in Shanghai earns $5000/yr[9] ; we assume a station manager will make $7500/year.

Import tariff of 27% is applied to goods manufactured internationally, which applies to hydrogen storage vessels and compressors.

2.4.4. Feedstock cost assumptions

Feedstock costs include the costs of purchasing the fuel required to produce or dispense hydrogen. For the four station types included in the analysis, the assumed feedstock costs are shown in Table 6.

2.4.5. Cost of supplies

This section provides cost data on the most expensive hardware of hydrogen fueling stations, namely, the equipment used for production (or delivery), storage, compression, and dispensing. The cost of equipment for these stations was collected from the following companies (see Table 7). We have used cost quotes specific to Shanghai when available.

A given piece of equipment can be manufactured in China or imported from foreign suppliers. For imported equipment, shipping costs and import taxes must be added to the total. We have some data to suggest that Chinese-manufactured equipment might be lower cost than imported equipment. For example, the capital cost for the Chinese-manufactured electrolyzer is less than half the cost of electrolyzer quotes from Canadian companies. We were not able to obtain comparable quotes for all types of equipment from both Chinese and foreign manufacturers. For methanol reformers we have an estimate from a Chinese manufacturer, but not from other sources. The quotes for the tube trailer, storage equipment, and compressor are from US and Korean companies, for equipment delivered to Shanghai. Thus, we cannot speculate on the general difference in cost between Chinese and Western manufacturers.

We use data from Weinert [6] for the remainder of equipment costs. Since these cost data are for equipment of various sizes (from various companies, mostly in the US), it has been

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[8] This assumption was reviewed by representatives from Chevron Texaco, October 2004.

[9] Shell Delivery Cost Model, 2005.

Table 4
Storage and compressors sizes by station type

Station type	Capacity (kg/day)	Peak fuel demand (kg)	Duration of peak (hours)	Storage (kg)	Compressor size (kg/h)
1. SMR	100	40	3	135	4.2
2. SMR	300	120	3	406	13
3. Methanol	100	40	3	135	4.2
4. Electrolysis	30	12	3	39	1.3
5. Delivered H_2	150	60	3	71	13
6. Delivered H_2	300	120	3	142	26

Table 5
General station assumptions

Assumption	Value	Unit	Source
Capacity factor	80%		
After-tax rate of return	10.0% $=d$		H2A
Equipment life (i.e. recovery period)	15	Years (n)	H2A
Capital recovery factor	13.1% =CRF		H2A
Annual salary of station employee[a]	$7398		50% higher than annual salary of truck driver (Shell delivery model, 2005)
Real estate cost (\$/ft^2/month)	$5.4	/m^2/month	Based on US commercial real estate cost of \$0.50/ft^2/month[b]
Contingency	10%	Of total installed capital cost (TIC)	Vetted with reps from energy industry
Property tax	1%	Of TIC	Vetted with reps from energy industry
Shanghai installation cost reduction factor	25%	Estimate of reduced station installation cost in Shanghai compared to US	Avg Shanghai laborer wage: \$88–125/month[c] vs. \$1936/month for US construction worker
Currency conversion	8.10	RMB/$	August 17, 2005, www.finance.yahoo.com/currency
Import tariff on foreign equipment	27%		Based on taxes paid previously for H_2 storage tanks

[a] We assume each station will require one full-time employee.

[b] Real-estate rent cost accounts for only 1–2% of total station costs for Shanghai stations.

[c] China Business Review (2004) http://www.chinabusinessreview.com/public/0401/shanghai_letter.html.

Table 6
Feedstock prices

Feedstock	RMB	USD	Source
Natural gas (Shanghai)	1.3/N m^3	$4.4/MMBtu	China People's Daily Newspaper[a], 2003
Methanol	2700/ton	$0.27/L	Shanghai Coking Co., 2005
Hydrogen	2/N m^3	\$0.25/N m^3(\$2.7/kg)	Coking Carbonization Co., 2005
Hydrogen	4/N m^3	\$0.49/N m^3 (\$5.5/kg)	Baoshan Steel, 2005
Average electricity price	0.66/kW h	$0.08/kW h	Shanghai Jiading Foreign Economic Commission, 2005

[a] http://www.people.com.cn/GB/paper40/10381/946662.html.

Table 7
Specific cost data used in the analysis (pre-import tax)[a]

Source	Equipment	Size/specs		Cost (USD)	Subject to 27% import tax
Suzhou Electrolyzer (Chinese)	Electrolyzer	20 N m^3/h	1.7 kg/h	$99,000	
Various manufacturers (US)	Steam methane reformer	100 kg/day	4.2 kg/h	$420,000	
Shanghai Ally Gas Company Limited (Chinese)	Methanol reformer	100 kg/day	4.2 kg/h	$86,000	
Various manufacturers (US)	Reciprocating compressor	Varies based on flow \$27,000 $*$ (kg/h)$^{0.52}$	4.2 kg/h	$53,000	Yes
Various manufacturers (North America)	Storage vessels	Varies based on storage capacity \$1000 $*$ (kg)$^{1.08}$	135 kg	$200,000	Yes
CPI (US)	Tube trailer	3575 N m^3 at 200 bar, 300 kg	300 kg	$170,000	Yes

[a] Steam methane reformer cost, compressor cost, and storage cost are calculated using data from several manufacturers (see [6]).

Table 8
Key results and assumptions for hydrogen delivery

Item	Value	Unit	Annualized cost ($/yr)
Hydrogen feedstock cost	4.1	$/kg	
Hydrogen delivery cost (300 kg/d station: daily delivery)	1.2	$/kg	$108,000
Hydrogen delivery cost (150 kg/d station: every two days)	2.3	$/kg	$99,000
Assumptions			
Tube trailer capacity[a]	300	kg	
Tube trailer cost (after tax)	$220,000	/trailer	
Truck cost[b]	$85,000		
Driver salary	3	$/hr	
Delivery distance (1-way)	25	km	
Diesel[c]	0.45	$/liter	
Truck fuel efficiency[b]	34	liter/100 km	
Maintenance cost	8%	% of capital cost	
Tube trailer lifetime	10[d]	yrs	
Discount rate	10%		

[a] Quotation from CPI.

[b] Quotation from Volvo.

[c] Market price as of August 17, 2005.

[d] Equipment life for tube trailers differs from the assumed equipment life for the other station components (15 yrs).

Table 9
Summary of cost estimates for six station types

	SMR 100[a]	SMR 300[a]	MeOH 100[b]	EL-30[c]	Del 150[d]	Del 300[d]
Equipment capital costs (1000$)						
Hydrogen production equipment	417	810	127	99	(Included in delivery cost)	(Included in delivery cost)
Purifier	77	130	77	–	100	130
Storage system	250	820	250	65	130	260
Compressor	68	120	68	36	120	180
Dispenser	60	120	60	43	60	120
Additional equipment	49	49	49	67	70	70
Installation costs	94	94	62	45	64	64
Contingency	87	190	59	29	45	72
Total investment (1000$)	1100	2300	750	380	590	900
Operating costs (1000 $/yr)						
Hydrogen	–	–	–	–	180	360
Methanol	–	–	87	–	–	–
Natural gas	21	63	–	–	–	–
Delivery cost	–	–	–	–	99	110
Electricity	5	15	5	43	4	8
Maint., Labor, Overhead	58	115	44	25	45	63
Total operating cost	84	190	140	68	330	540
Annualized costs						
Annualized investment cost, 1000$/yr	150	310	99	50	77	120
Total annualized cost, 1000$/yr	$230	$500	$230	$120	410	660
Total levelized cost, $/kg	$7.8	$5.7	$8.0	$13.5	9.3	7.5
Actual production/capacity, kg/day	80/100	240/300	80/100	24/30	120/150	240/300
Annual hydrogen production, kg/yr	29,200	87,600	29,200	8760	43,800	87,600

[a] SMR 100 (case 1), SMR 300 (case 2) = Steam methane reforming of natural gas at the station.

[b] MeOH 100 (case 3) = reforming of methanol delivered to station.

[c] El-30 (case 4) = water electrolysis using electricity at the station.

[d] Del 150 (case 5), Del 300 (case 6) = H_2 truck delivered from industrial plant.

adjusted to the sizes used in the analysis based on equipment scaling factors. Costs are also adjusted using progress ratios to account for the cost reduction due to learning (i.e. from increased equipment and station production volumes).

Equipment delivery from North America to China is negligible. Shipping costs are roughly $\$85/\text{m}^3$ from California to Shanghai by ship plus an additional \$125 for unpacking the container once in Shanghai.[10] For example, a station compressor delivery (estimated at $6\,\text{m}^3$ package size) would add roughly

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[10] Estimate from Zhu Zheng, Maximator Fluid Engineering Co. Ltd. (2006).

$635 to costs. However, import taxes can be significant, adding about 27% to the capital cost for equipment imported to China.

2.4.6. Hydrogen delivery assumptions

The delivery of hydrogen in the Shell model contains the levelized capital cost of the trailer and truck, fuel cost, and labor cost. Table 8 shows the key results and assumptions of the calculation.

Hydrogen Feedstock Cost is an average of the feedstock quotes from Baoshan Steel and the Shanghai Coking Carbonization Co. (see Table 6), the two largest potential suppliers of hydrogen for fuel. This cost includes purification of the gas to 99.9% purity. The station also has an additional PSA system to purify the hydrogen to 99.99%, suitable for fuel cell vehicles.

Hydrogen Delivery Cost is calculated by calculating the fuel and labor cost of driving the trailer to and from a station and adding the levelized capital cost of the truck and trailer. The levelized delivery cost ($/kg) is almost twice as high for the 150 kg/day station (delivery every other day) than the 300 kg/day station (daily delivery) because the capital cost of the tube trailer and truck outweighs the operating cost of the trailer. We assume delivery stations use two tube trailers and one truck each. The difference in annual delivery cost between the two station sizes is only ~$9000 ($108,000/yr vs. $99,000/yr). This $9000 represents the additional annual cost of diesel and labor for daily deliveries.

3. Results

The results of our analysis of Shanghai hydrogen fueling station costs are summarized in Table 9.

Table 10 provides the levelized cost of hydrogen delivery for both small and large stations calculated using the THDCM. The capital cost of the truck and trailer dominate the total levelized delivery cost.

Figs. 3 and 4 show the different cost components of each station. We have presented these data in two different metrics: the levelized cost of hydrogen (in $/kg) and the annualized station cost (in $/yr). The $/yr figure shows the relative magnitude of the annualized investment for each station. The $/kg shows the levelized cost of hydrogen produced at the station. The second figure is more useful for comparing stations of varying size.

4. Discussion

As seen in Figs. 3 and 4, costs vary considerably depending on the station type and size. For stations with onsite production, station capital and operating costs are dominant factors in hydrogen cost ($/kg). For truck delivery the cost of industrial hydrogen "feedstock" is the single largest factor.

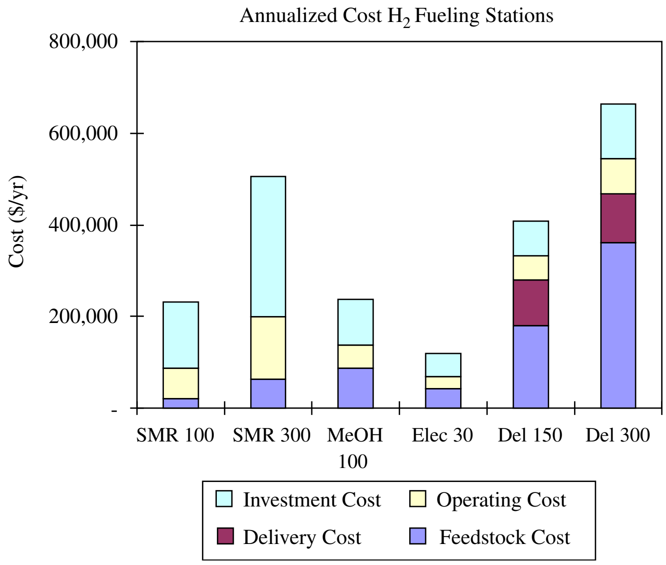

Fig. 3. Annualized cost of H_2 fueling stations.

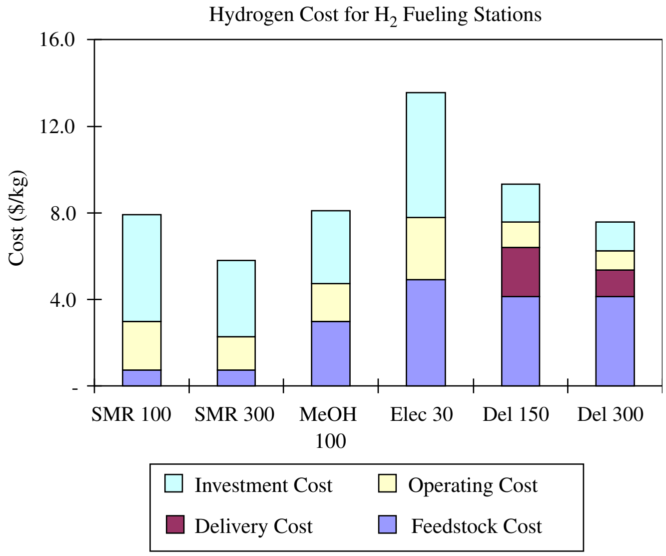

Fig. 4. Hydrogen cost for H_2 fueling stations.

Table 10
Levelized hydrogen delivery cost ($/kg)

	Large (300 kg/day) station	Small (150 kg/day) station
Labor	$0.05	$0.04
Fuel	$0.06	$0.03
Maintenance & misc.	$0.15	$0.26
Capital (truck and trailer)	$0.97	$1.93
Total	$1.23	$2.26

For a particular station type, hydrogen costs are lower for larger stations because of scale economies in both capital and operating costs.

The contribution of the feedstock cost varies depending on the station type.[11] For onsite SMRs where low-cost natural gas is used, the feedstock cost is relatively low (only about $\frac{1}{6}$ of the total hydrogen cost). For methanol reformers, the feedstock cost becomes more important, because methanol costs more

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[11] The following feedstocks are used at each station. Cases 1 and 2 (SMR 100, SMR 300) use natural gas at the station; Case 3 (MeOH 100) uses methanol delivered to station; Case 4 (El-30) uses electricity at the station, and Cases 5 and 6 (Del 150, 300) use hydrogen truck delivered from an industrial plant.

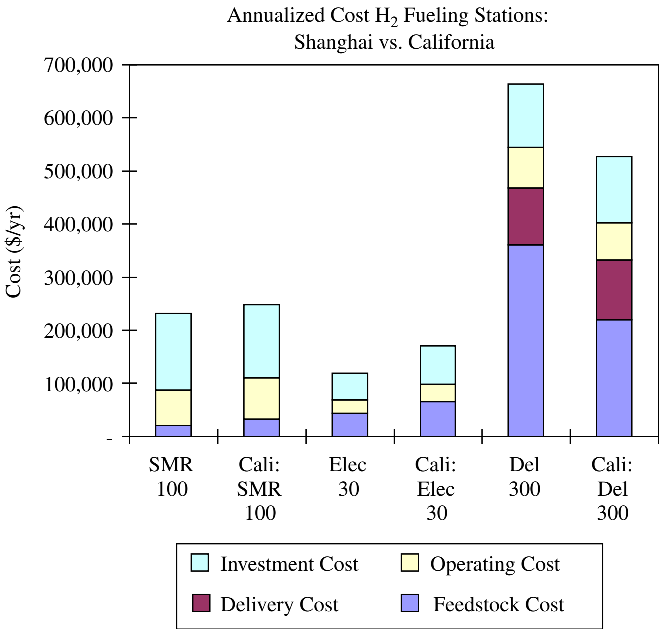

Fig. 5. Hydrogen station cost ($/yr) in Shanghai vs. California.

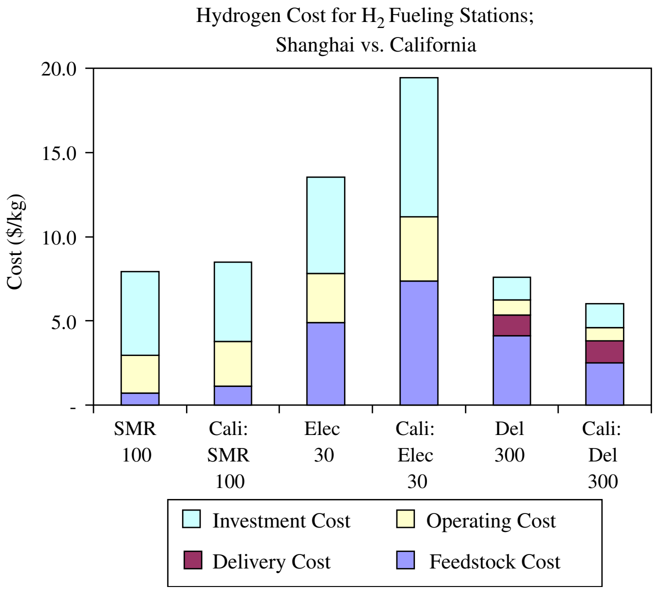

Fig. 6. Hydrogen station cost ($/kg) in Shanghai vs. California.

than natural gas. For electrolyzers and truck delivery, feedstock costs are dominant factors.

The model indicates that on-site methane reformation stations offer lower levelized hydrogen costs than hydrogen stations with truck delivery. This is due to the relatively high cost of “feedstock” industrial hydrogen truck-delivered to hydrogen stations. The cost of natural gas at the station is much lower (roughly $\frac{1}{6}$ of the delivered hydrogen).

The difference in cost between the methane and methanol station is negligible because the much lower cost methanol reformer costs (25% of methane reformer) due to the availability of a Chinese manufacturer is offset by higher feedstock costs and slightly higher maintenance cost.

The model also shows that fuel distribution costs for truck-delivered hydrogen stations are a relatively minor portion of total cost, and therefore, it makes more sense to utilize the full capacity of the tube trailer. In other words, making more use of the capital investment of the tube trailer outweighs the incremental fuel and labor cost of making more deliveries.

The electrolysis station is the most expensive option due to the station’s low capacity (30 kg/day) and the high cost of electricity as feedstock.

4.1. Cost comparison with California

We have compared the costs of Shanghai stations to station costs calculated for California [6], adjusting the capacity factor assumption to match the Shanghai case (80%). Input assumptions for hydrogen fueling stations in California and Shanghai are shown in Table 11.

Figs. 5 and 6 show that the overall hydrogen costs from SMR stations in Shanghai are only slightly less than California stations. While natural gas and labor cost less in Shanghai, this is offset by the higher capital cost for equipment in Shanghai due to the heavy import tax. For the electrolysis station, the Shanghai station is lower cost due mainly to the lower electricity price in Shanghai and lower installation costs. Furthermore, the Shanghai station is able to purchase its electrolyzer locally, further reducing costs.

Truck-delivered hydrogen is less expensive in California, primarily due to the assumed lower feedstock (industrial hydrogen) price in California. This is true even though delivery costs are about 33% lower in Shanghai than in California.

The delivery cost is lower in Shanghai due to the higher driver wages in the US (seven times higher), and assumed lower costs for maintenance. However, the capital cost of delivery (i.e. truck and trailers) makes up the majority of delivery cost and is approximately equal for both locations.

It is a common belief that installing new technologies in developing countries will automatically yield substantially lower fuel costs. We have found that this is not offset by the need to import expensive technology from abroad. Station designers are reluctant to use lower-quality domestic products for hydrogen fueling where safety and hydrogen purity is critical.[12] Thus, equipment for items like storage containers and compressors from foreign manufacturers are imported, which require an additional import tax to the total cost of these items (∼27%). For Shanghai SMR stations, we also assumed use of imported SMR though this is not subject to this tax.[13] The tax increased the total installed cost of the Shanghai SMR station by 5% compared to the California SMR station. The hydrogen cost from the Shanghai SMR was still slightly lower than in California, because of lower labor and feedstock costs in Shanghai.

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[12] Ma Jianxin (2005), personal communications.

[13] Zhou Wei (2005), personal communications. According to hydrogen station designers in Shanghai, only high-pressure equipment is subject to the 27% import tax.

Table 11
California—Shanghai comparison for hydrogen delivery

Item	California 300 kg/day	Shanghai 300 kg/day	Unit
Labor	\$0.27	\$0.05	\$/kg
Fuel	\$0.07	\$0.06	\$/kg
Maintenance & misc.	\$0.42	\$0.15	\$/kg
Capital (truck and trailer)	\$1.09	\$0.97	\$/kg
Hydrogen total delivery cost (daily delivery)	\$1.84	\$1.23	\$/kg
Hydrogen feedstock cost	2.5[a]	\$4.1	\$/kg
Assumptions			
Driver salary	21	3	\$/hr
Distance	25	50	km
Diesel[b]	0.45	\$0.50	\$/liter

[a] Verified with air products representative, February 2006.
[b] Market price as of August 17, 2005.

5. Conclusions

In this report we have presented the costs of hydrogen stations in Shanghai. Using models developed at UC Davis and Tongji University for station cost and delivery cost, we have estimated near term costs for hydrogen stations or various types. The costs of some of these Shanghai stations have been compared with the costs of similar sized stations in California.

- On-site production stations in Shanghai using methane or methanol yield lower cost hydrogen than electrolysis, or truck-delivered hydrogen despite the ability to use relatively low cost excess hydrogen from industrial plants.
- Costs vary considerably depending on the station type and size. For stations with onsite production, station capital and operating costs are dominant factors in delivered hydrogen cost (\$/kg). For truck delivery the cost of industrial hydrogen "feedstock" is the single largest factor. The contribution of the feedstock cost varies depending on the station type.
- The difference in cost between on-site reformation stations in Shanghai versus those in California is minimal. The lower-cost feedstock and labor in Shanghai is offset by higher import taxes on equipment.
- Delivered hydrogen in Shanghai is more expensive than in California despite the lower labor costs there. The higher cost is attributed to the higher-cost hydrogen feedstock from excess industrial production.
- It is a common belief that installing new technologies in developing countries will automatically give lower costs. We have found that this is not necessarily true with hydrogen stations in Shanghai. In the case of hydrogen produced via SMR, the lower cost of labor is partially offset by the need to import expensive technology from abroad due to quality concerns.

It should be noted that while small-scale reformers for hydrogen stations appear to be the most attractive on a cost basis, this is still a relatively new technology and therefore capital cost and maintenance cost may be higher (or lower) than the data indicate. Delivered hydrogen stations benefit from decades of experience in the industrial gas industry. It should also be mentioned that this analysis only compares station costs and does not consider the other advantages and disadvantages of station options. For instance, delivered hydrogen stations benefit from greater mobility should hydrogen demand nodes change location. Small-scale electrolyzer stations have the advantage of being able to use renewable energy for feedstock supply.

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