Title
Implementing a Hydrogen Energy Infrastructure: Storage Options and System Design

Authors
Ogden, Joan M
Yang, Christopher

Publication Date
2005-11-01

Year 2005

UCD—ITS—RR—05—28

Implementing a Hydrogen Energy Infrastructure: Storage Options and System Design

Joan M. Ogden

Christopher Yang

Institute of Transportation Studies ⋄ University of California, Davis
One Shields Avenue ⋄ Davis, California 95616
PHONE: (530) 752-6548 ⋄ FAX: (530) 752-6572
WEB: http://its.ucdavis.edu/

Implementing a Hydrogen Energy Infrastructure: Storage Options and System Design

Joan M. Ogden [a,b] and Christopher Yang [b]
[a] Department of Environmental Science and Policy
[b] Institute of Transportation Studies
One Shields Avenue
University of California
Davis, CA 95616, U.S.A.

ABSTRACT

The development of a hydrogen infrastructure has been identified as a key barrier to implementing hydrogen as for a future transportation fuel. Several recent studies of hydrogen infrastructure have assessed near-term and long-term alternatives for hydrogen supply [1-2]. In this paper, we discuss how advances in material science related to hydrogen storage could change how a future hydrogen infrastructure is designed. Using a simplified engineering/economic model for hydrogen infrastructure design and cost, we explore some potential impacts of advances in storage materials, in terms of system design, cost, energy use, and greenhouse gas emissions.

INTRODUCTION

Hydrogen is receiving increased attention as a future transportation fuel. Fuel cell vehicles fueled by hydrogen offer the potential for a significant increase in vehicle efficiency, reductions in emissions of greenhouse gases and air pollutants to near zero and the possibility of using diverse primary energy sources for fuel production. Fuel cell vehicles might also enable new energy services, such as mobile electricity and the ability to plug in the electrical grid, and innovative automotive designs built around electric drive trains [3].

There are also many challenges to overcome before hydrogen can be widely used for energy applications. Hydrogen production, storage and distribution are mature technologies that efficiently delivery large quantities of hydrogen to chemical users. However, many existing hydrogen technologies need further development, in order to reduce costs and improve performance, before they can be commercialized for consumer energy markets.

Fuel cells for light duty vehicles are still an order of magnitude more costly than internal combustion engines, and durability needs to be increased by roughly a factor of three [4].

To fully realize hydrogen's environmental benefits, low carbon emitting, low polluting, low cost hydrogen production systems are needed. Hydrogen is produced at large scale today for industrial applications such as oil refining and ammonia production (about 2% of world primary energy is used to produce industrial hydrogen). Hydrogen production via reforming or gasification of fossil fuels and water electrolysis are well-established commercial technologies. However, further work is needed on renewable hydrogen production methods such as biomass gasification, wind electrolysis and technologies for carbon capture and sequestration.

Hydrogen storage onboard vehicles has been identified as a key challenge. Hydrogen energy storage density has been steadily increasing, but the range of today's experimental hydrogen cars (about 150-300 miles) is still substantially lower than cars using liquid fuels such as gasoline and diesel. New storage materials might also reduce energy requirements and emissions in the fuel chain.

Many of these challenges facing the development of a hydrogen economy relate to advances in materials. For example, fuel cell vehicle development would benefit greatly from more durable, high performance and low cost fuel cell materials, such as polymer membranes and electro-catalysts. Hydrogen production could benefit from new technologies for renewable hydrogen production such as photo-electrolytic, thermolytic and biological processes and hydrogen separation and purification technologies such as membranes and adsorbants that could also enable lower cost CO_2 capture. Finally, there is a need for new methods of compact, low cost hydrogen storage [5].

In this paper, we pose a system-level question that relates to fundamental materials science. If new hydrogen storage materials are successfully developed, what are implications for hydrogen infrastructure design and economics? Storage is an important and pervasive part of hydrogen energy systems, both for the end-use (vehicle) and supply infrastructure. Several studies have explored the impact of different onboard hydrogen storage methods for hydrogen vehicle design [6]. The effect of alternative hydrogen storage options on infrastructure has been less studied and is the focus of this paper. In particular, we seek to understand how improvements in existing storage technologies might reduce costs and affect the system design. We find that the characteristics of hydrogen storage play a major role in the design, cost, energy use, and CO_2 emissions of hydrogen supply infrastructure.

DESIGN OF HYDROGEN TRANSPORTATION FUEL INFRASTRUCTURE

A hydrogen supply infrastructure for consumer light-duty vehicles consists of a hydrogen production system, hydrogen storage (to meet time varying demand and assure reliable supply), a delivery system to bring hydrogen from the production site to refueling sites, and a network of refueling stations to dispense hydrogen to vehicles. Hydrogen can be made at a large production facility (i.e. central plants) and distributed to refueling stations or produced onsite (e.g. at the refueling station) from other energy carriers such as natural gas or electricity. Centralized and onsite production systems are shown in Figure 1.

There are many options (or pathways) for supplying hydrogen to vehicles. A pathway consists of all of the feedstock inputs and processes involved with producing and delivering hydrogen to the refueling station. The role of storage depends on the hydrogen supply pathway chosen. We have developed simplified engineering/economic models [7, 8] to study the following alternative hydrogen supply pathways:

Production Options	***Storage and Delivery Options***
• **Large Central production plants** - Steam methane reforming (with or without carbon sequestration) - Coal gasification (with or without carbon sequestration) - Biomass gasification - Electrolysis • **Small scale onsite production** - Reforming - Electrolysis	• **Storage** (at central plants, refueling stations, vehicles) - Compressed Gas - Liquid Hydrogen • **Delivery** (for central production pathways) - Truck (compressed gas or liquid hydrogen) - Pipeline

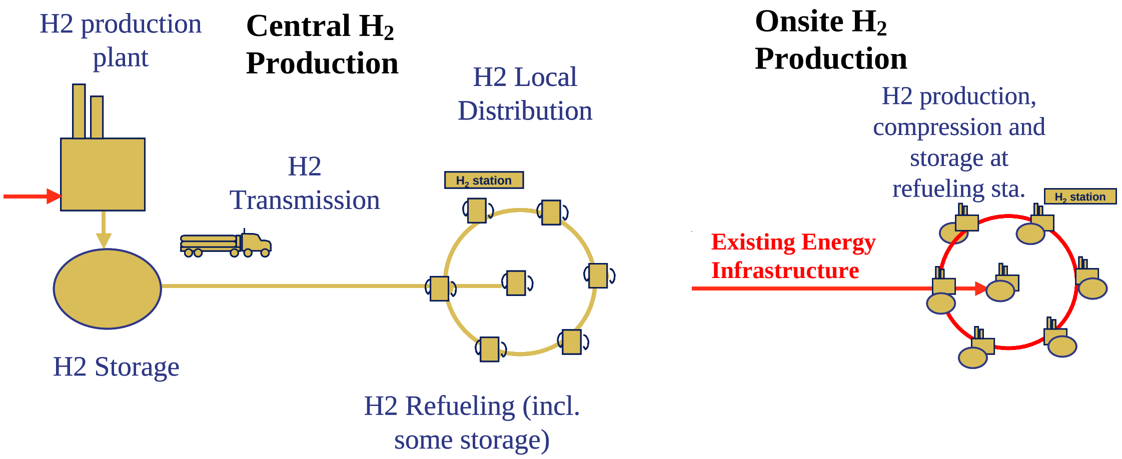


Figure 1. Hydrogen infrastructure using centralized and onsite hydrogen production

Given user-specified input assumptions for the level of hydrogen demand, parameters describing geographic and market factors, and technical and cost parameters, our model finds an idealized layout for the hydrogen infrastructure, sizes the equipment needed for storage, delivery and refueling, and estimates costs, energy use and emissions for the entire system.

Using this model, we identified several important factors that influence hydrogen infrastructure design and cost. These include the level of hydrogen demand, geography (urban versus rural demand, city population, population density, city size, and delivery distance), market factors (vehicle miles traveled, number of stations needed for consumer convenience, market fraction of hydrogen cars, and station size), and technology assumptions (fuel cell vehicle efficiency, the cost and performance of infrastructure components, including hydrogen storage). The operational strategy, to meet a time varying demand for hydrogen and provide reliable and cost-effective supply, is also important and can impact the amount of storage needed.

In Figure 2, we show how the hydrogen transmission (point-to-point) cost depends on two important parameters: the hydrogen flow rate (size of the hydrogen demand), and the delivery distance. Three different storage and delivery modes are compared: compressed gas storage with truck delivery (G), compressed gas storage with pipeline delivery (P) and liquefaction of hydrogen and liquid hydrogen storage with truck delivery (L).

The lowest cost mode is plotted for each delivery distance and flow rate. Compressed gas trucks are least costly at very low hydrogen flow rates and short distances. Because a compressed gas truck carries small quantities of hydrogen (~300 kg), many trucks are required to move significant amounts of hydrogen and costs rise strongly with transport distance. At small to medium hydrogen flows and medium to long distances, liquid hydrogen truck delivery is preferred. Liquid hydrogen costs are dominated by the large (and scale sensitive) capital costs associated with the liquefaction plant. However, costs for liquid transport are relatively independent of transport distance because a liquid truck can carry larger quantities of hydrogen (3000 kg) and truck fuel costs are a small component of total delivery costs. For large hydrogen flows, pipelines offer the lowest transmission costs. Pipeline transmission costs increase with distance, and have strong scale economies with flow rate. For details of the model, we refer the reader to [7, 8].

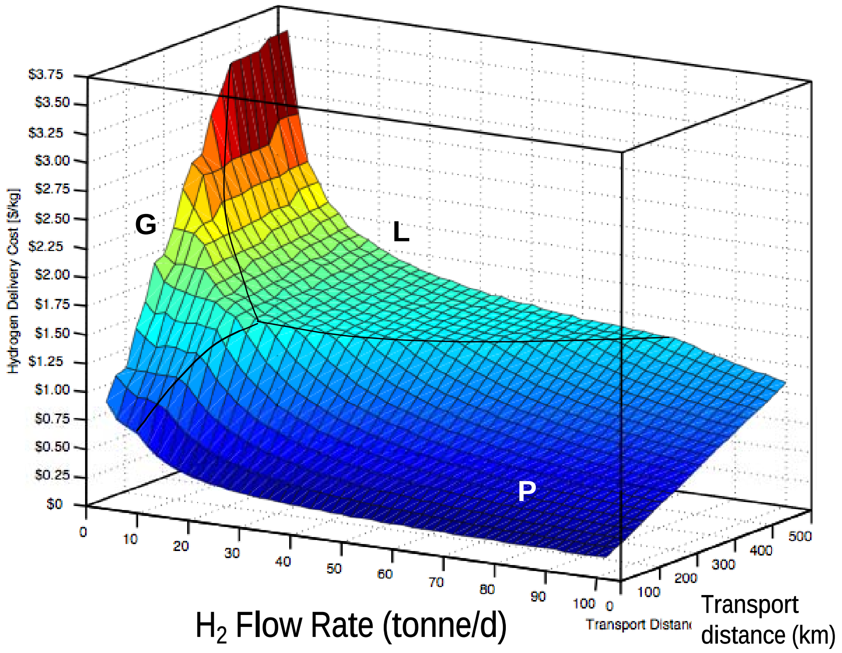


Figure 2. Levelized hydrogen transmission costs ($/kg) as a function of hydrogen flow rate (tonne/day) and transport distance (km), for three delivery methods: compressed gas truck delivery (G), liquid hydrogen truck delivery (L), and compressed gas pipeline delivery (P). Transmission includes compression or liquefaction and storage at the central production site, but not refueling stations.

HYDROGEN INFRASTRUCTURE DESIGN AND COST FOR VARIOUS STORAGE OPTIONS

We use this model to explore several infrastructure questions related to storage:

- What are the infrastructure costs, energy use and emissions associated with storage for current hydrogen technologies and pathways?
- How might advances in hydrogen storage affect hydrogen infrastructure costs, energy use and emissions?
- How would advances in hydrogen storage onboard vehicles (that enabled a longer range or a faster refueling time) effect the infrastructure requirements, especially for refueling stations?

In our study, “storage” includes not only compressed gas cylinders or cryogenic liquid hydrogen storage vessels, but also compressors or liquefaction equipment. We trace the entire hydrogen supply pathway from hydrogen production through dispensing to a vehicle.

Base case assumptions

Two methods are commonly used today for large-scale storage of hydrogen: compressed gas systems and liquid hydrogen systems**.** Compressed gas systems are used to increase the hydrogen energy density, which depends upon the storage pressure. Large industrial compressed hydrogen storage tanks use storage pressures from 1000-5000 psi, while tube trailers are typically pressurized to 2500 psi. In applications where volumetric energy density is critical (such as light duty vehicles), pressures of 5000-10,000 psi (340-680 atm) are currently used. Liquid hydrogen is formed when hydrogen is cooled to 20K. Due to the extremely low temperatures, a great deal of electricity is required in the Linde process to form liquid H_2.

Table I shows the current cost and performance and projected (2010 and 2015 goals) for compressed gas and liquid hydrogen storage [4]. (For reference, gasoline has an energy density of about 30 MJ/liter. Liquid H_2 has an energy density of around 9 MJ/liter while compressed H_2 has an energy density of 3 MJ/liter at 5000 psi and 5 MJ/liter at 10000 psi.) Table II shows our base case assumptions for hydrogen storage and delivery system costs and energy requirements [10].

Table I. Current Values and DOE Targets for On-board H_2 Storge Systems

Parameter	**Units**	2005	2010	2015
Specific Energy	MJ/kg	5.4	7.2	10.8
Energy Density	MJ/L	4.3	5.4	9.7
Storage Cost	$/MJ	1.7	1.1	0.6

Table II. Delivery and Storage Assumptions for Infrastructure Model.

Delivery Component	**Quantity**	**Cost**
Liquid H_2 truck		
Liquid H_2 Station Storage	200% of daily flow	$20-40/kg
Liquefier	Electricity use 11 kWh/kg	$\$40M\left(\frac{H_2 DailyFlow}{30t/day}\right)^{0.57}$
Refueling Station Pump (Truck to Storage)	Electricity use 0.8 kWh/kg	$\$41000\left(\frac{\mathrm{H_2\ Flow}}{\mathrm{114\ kg/hr}}\right)^{0.7}$
Compressed Gas Truck		
Central Plant Compressor (Plant to Truck)	Electricity Use 2.0 kWh/kg	$\$15{,}000\left(\frac{CompPower}{10kW}\right)^{0.9}$
Compressed H_2 Truck Station Storage	50% of daily flow	$400/kg
Refueling Station Compressor (Truck to Storage)	Electricity Use 1.1 kWh/kg*	$\$15{,}000\left(\frac{CompPower}{10kW}\right)^{0.9}$
Pipeline		
Central Plant Compressor (Plant to Pipeline)	Electricity Use 0.7-1.0 kWh/kg	$\$15{,}000\left(\frac{CompPower}{10kW}\right)^{0.9}$
Pipeline compressed H_2 Station Storage	50% of daily flow	$400/kg
Refueling Station Compressor (Pipeline to Storage)	Electricity Use 1.6 kWh/kg	$\$15{,}000\left(\frac{CompPower}{10kW}\right)^{0.9}$

Not all H_2 needs to be compressed at station due to use of tube trailer as part of cascade system.
In calculating compressor electricity use, we assume H2 comes from the production system at 120 psi.

Research is ongoing to reduce the cost of compressed gas storage cylinders, and to increase the allowed pressure, particularly for vehicles. In addition, a variety of innovative materials are being considered for advanced hydrogen storage, including metal hydrides and carbon nanostructures [4, 5]. In future work, we plan to examine the implications of these materials for system design.

Results

We first estimate the infrastructure costs, energy use and emissions associated with storage for *current* hydrogen technologies and pathways. This provides a baseline of comparison, to explore how *changes* in current storage technologies might impact hydrogen infrastructure design and cost. In Figures 3-5, we estimate the fraction of the levelized hydrogen delivery cost ($/kg) that is due to hydrogen storage.

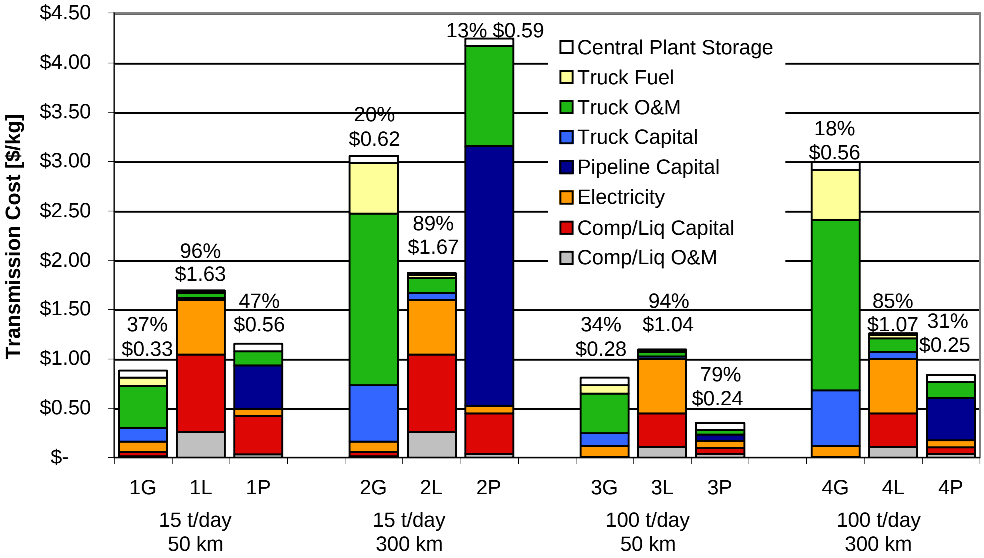


Figure 3. Levelized cost of hydrogen transmission ($/kg) for four cases. The components of the cost are shown, and the fraction and levelized cost due to storage are indicated at the top of each bar.

In Figure 3, we estimate storage costs for the *transmission* section of the infrastructure (no refueling stations are included). This figure shows a more detailed view of the same data as Figure 2. The levelized transmission cost is compared for three delivery modes (compressed gas truck = G, liquid hydrogen truck = L, and gas pipeline = P). Transmission is defined everything between, but not including, the production plant and the refueling station. Costs include compression or liquefaction and storage at the production plant. Four cases (labeled 1-4) correspond to low (15 tonnes/day) and high (100 t/d) flow rates and short (50 km) and long (300 km) delivery distances. For the liquid hydrogen cases, liquefaction and liquid hydrogen storage costs are 85-96% of the transmission cost. (Liquefaction of hydrogen is an energy and capital-intensive process that accounts for most of this, whereas the energy and capital associated with moving and storing the cryogenic liquid is relatively low.) For compressed gas trucks, storage is about 18-37% of the total. Hydrogen compression and storage account for 13-79% of the pipeline transmission cost. Absolute storage-related transmission costs ($/kg) are lower for gas storage routes than for liquid storage routes, for all cases.

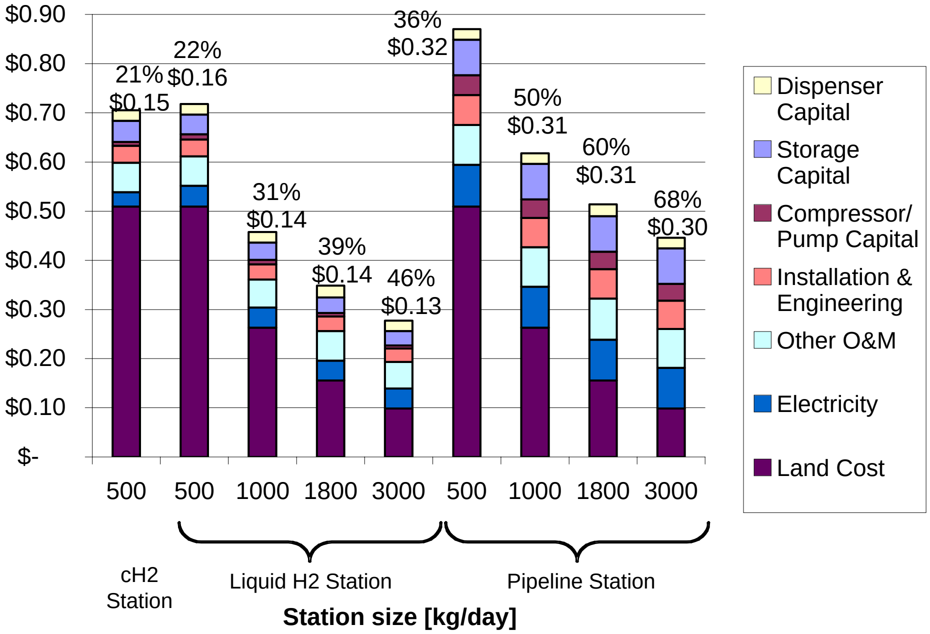


Figure 4. Levelized cost of hydrogen refueling stations ($/kg) of various types. The station size is shown along the x-axis in kg per day of hydrogen dispensed. Compressed gas trailer delivery (cH2) is shown for a 500 kg/d station. Liquid hydrogen truck delivery and pipeline delivery stations are shown in sizes ranging from 500 to 3000 kg/d. The components of the cost are shown, and the fraction due to storage is indicated at the top of each bar.

In Figure 4, the storage contributions to *refueling station* costs are shown for different station types and sizes. For large stations (≥1800 kg/day), which would be preferred because of their lower cost, storage makes up 39-68% of the refueling station cost. For each delivery type (G,L, and P), absolute storage costs (in $/kg) are relatively constant for different station sizes. However, the storage-related *percentage* changes to reflect the cost reductions associated with larger stations. Refueling stations with pipeline delivery have the highest absolute storage costs (approximately double the costs of the other station types), because they have a relatively large amount (equal to half a day's hydrogen throughput) of very expensive ($400/kg) compressed gas storage at the station. With compressed gas truck delivery, the truck tube trailers are parked at the station and form the bulk of the hydrogen storage at the station, which reduces station costs.

Figure 5 shows the levelized cost ($/kg) of *hydrogen delivery through a network of refueling* stations (counting everything between the production plant and the car) as well as the hydrogen costs for an onsite H_2 production via a natural gas SMR station. In the left part of the graph, we show delivery costs for small (16%) and large (100%) market penetrations of hydrogen vehicles, in a densely populated city (San Jose, California) and a less dense city (Cincinnati, Ohio). Both urban areas have populations of about 1.5 million people. At 16% market penetration, compressed gas trucks are the least cost delivery mode, for both cities. Storage accounts for approximately 35% of the total cost of delivery and refueling. Other large costs are refueling station land costs (which are high because we assume that we have many small 500 kg/d stations) and truck O&M (i.e. labor) and fuel costs. At 100% market penetration, pipelines offer the lowest costs for the denser city, and liquid delivery is lowest cost for the less dense city. (These results are illustrative. The lowest cost mode varies depending on the assumptions about city size, city density and station size.) The storage costs associated with liquid delivery are the highest of the three modes. However, in all cases storage is a large part of the overall delivery system cost (>33%) and thus, we expect that each delivery technology and the associated infrastructure will be sensitive to cost and efficiency changes associated with advanced storage technologies.

If we add central hydrogen production costs ($1.00 -1.50/kg for large steam reformer or coal gasification systems or $1.5-2.5/kg for biomass gasification [1]) to delivery costs in cases 1-4, we can estimate the total delivered cost of hydrogen, accounting for *all* infrastructure costs from production through refueling. The storage fractions of the total delivered hydrogen cost would be lowered by 20-60% compared to the fractions of delivery shown in Figure 5. For example, if we assume that hydrogen is centrally produced for $1.5/kg, the storage *fraction* for case 3P (large scale pipeline delivery) drops from 33% (when only delivery costs are considered) to about 15% (when both production and delivery are considered). For comparison, we also show the consumer's cost of hydrogen from a station with onsite production via small scale steam methane reforming (SMR) (two right-most bars). Storage accounts 27-31% of the total.

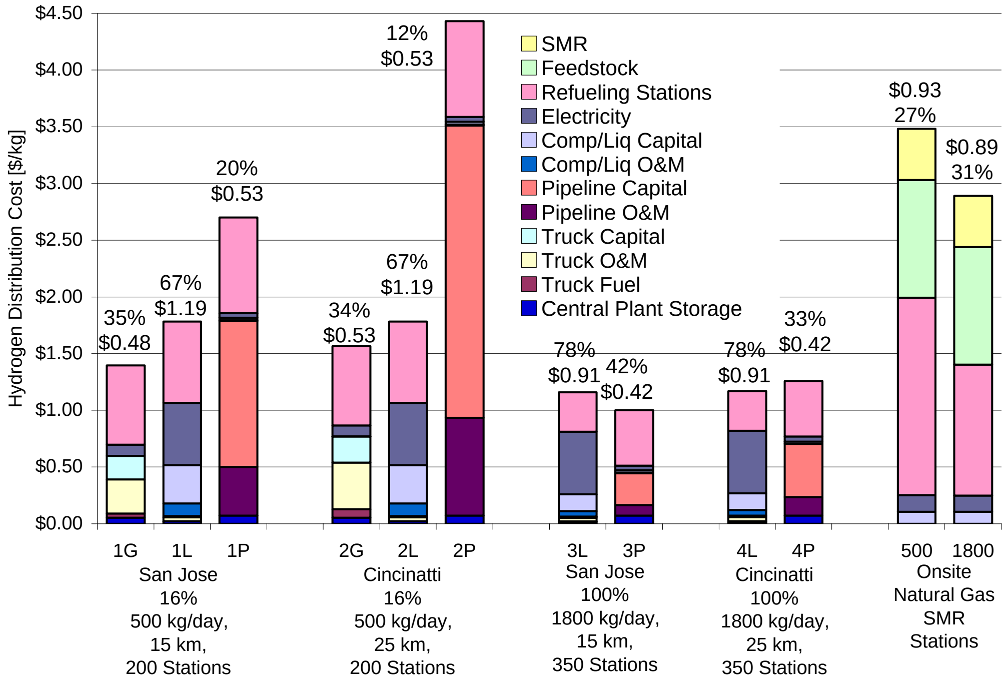
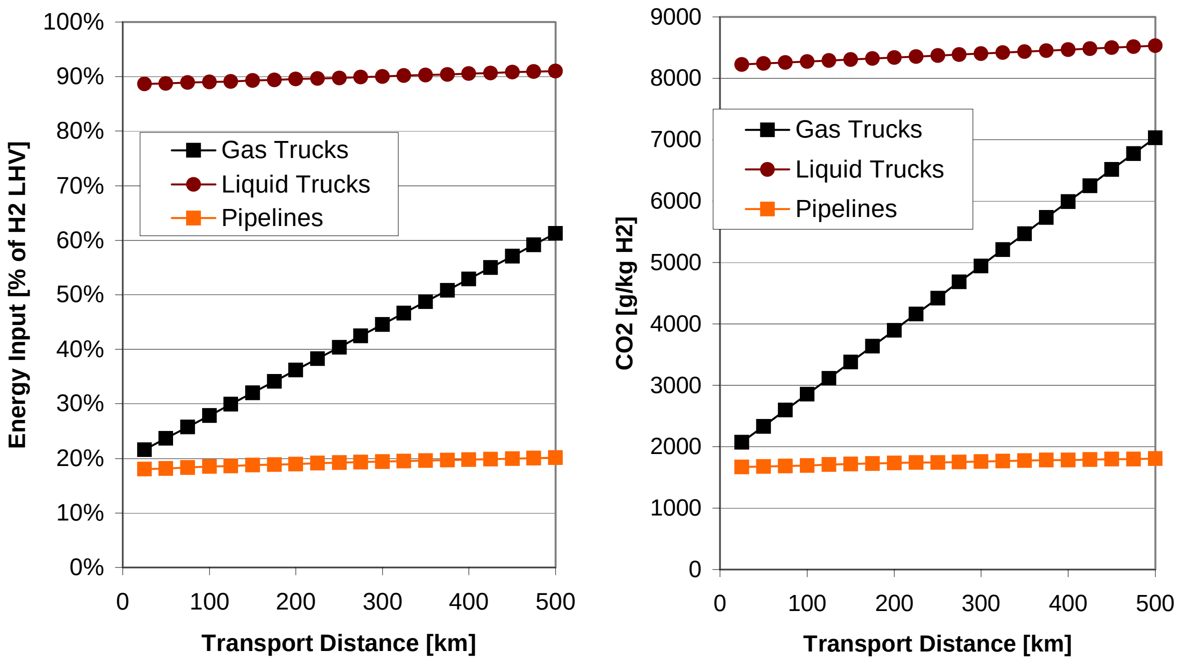


Figure 5. Levelized cost of hydrogen delivery and refueling stations ($/kg) for two cities San Jose and Cincinnati, for market fractions of 16% and 100% . The delivered cost of hydrogen is shown for onsite SMR stations producing 500 and 1800 kg/day. The components of the cost are shown, and the fraction due to storage is indicated at the top of each bar.

Delivery and refueling energy use and CO_2 emissions are shown in Figures 6 and 7 for each mode. The energy use is calculated as a function of the energy content (LHV) of the delivered hydrogen and includes the primary energy inputs for electricity generation assuming the average US grid mix. The CO_2 emissions calculation also assumes a US grid mix for electricity inputs. Energy use and greenhouse gas emissions are highest for pathways that use liquid hydrogen. Compressed gas trucks are the most sensitive to transport distance of the significant use of truck fuel. Clearly, compressed gas pipelines are much preferred in terms of both energy efficiency and greenhouse gas emissions.



Figures 6 and 7. Energy Use and CO_2 Emissions for various hydrogen delivery modes, as a function of transport distance.

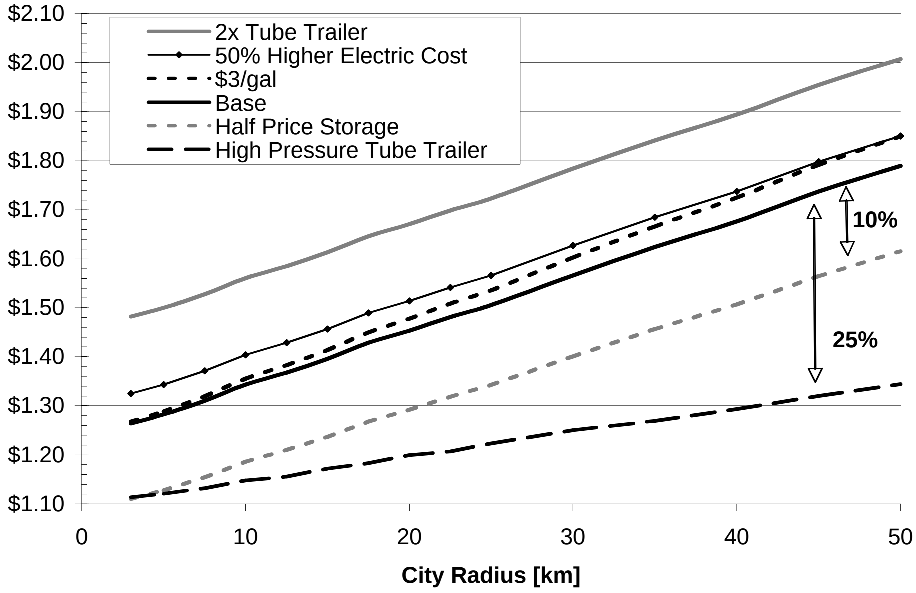


Figure 8. Sensitivity of the levelized cost of compressed gas truck delivery ($/kg) to changes in storage capital cost, storage pressure, electricity cost (for compression) and distance traveled (which is proportional to the city radius).

Sensitivity studies

The preceding analysis used our base case or "most likely" estimates of the current costs of hydrogen infrastructure equipment (Table II). We now perform a sensitivity analysis to see how the results would change if advanced storage systems could be introduced that could reduce the capital cost of storage systems or operate at higher pressure.

Compressed gas truck delivery costs ($/kg) are sensitive to the capital cost for compressed gas cylinders, and to the operating pressure (Figure 8), as well as the delivery distance (which is related to the city size). Halving the gas storage capital cost would result in only a 10% reduction in the delivery cost. Increasing the tube trailer pressure from 2500 to 5000 psi would accomplish a 25% reduction in compressed gas delivery costs.

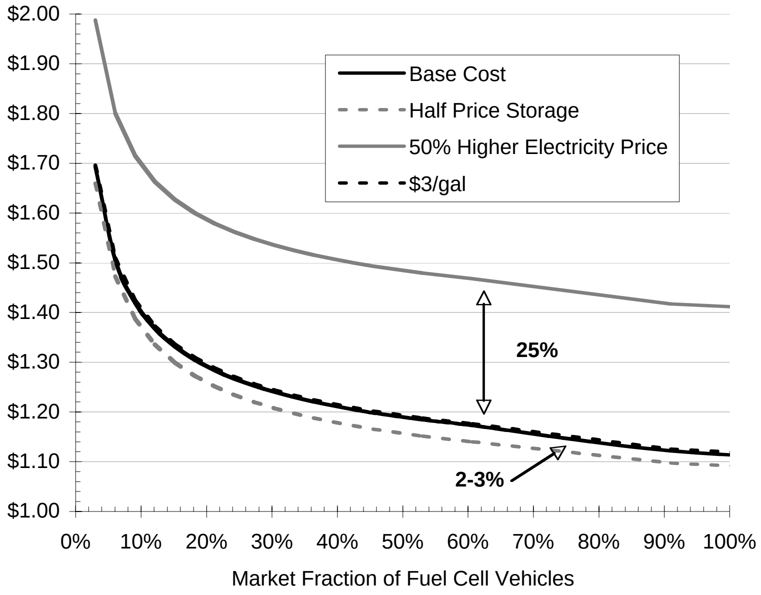


Figure 9 Sensitivity of the levelized cost of liquid truck delivery ($/kg) to changes in storage capital cost, electricity cost (for liquefaction), gasoline price and hydrogen demand.

Liquid hydrogen delivery cost is sensitive to electricity price and to the scale of the hydrogen demand (because of liquefier scale economies). Reducing the liquid hydrogen storage dewar cost has only a small impact (2-3%) on the system economics (Figure 9). Because of the importance of electricity for liquefaction, electricity price can significantly change the infrastructure economics. If it were possible to improve the efficiency of liquefaction, this could reduce costs as well.

For pipeline delivery, scale (expressed as market penetration) is the most important factor determining delivery costs (Figure 10). Halving the gas storage capital cost has only a small effect on delivery cost (9%), while increasing the station size from 1800 kg/d to 3000 kg/d reduces delivery costs by about 16%. (If production costs are added to delivery costs, the total *delivered hydrogen cost* experiences smaller fractional changes.)

Improved hydrogen storage might enable hydrogen vehicles with a longer range. This would mean fewer refueling stops per car per year (less consumer time spent on refueling), fewer refueling bays at the station and less refueling labor per car per year. The relationship between refueling cost and vehicle range is shown in Figure 11. We take as our base case, a vehicle with a 350-mile range, and estimate the extra costs involved for a shorter-range vehicle. Current fuel cell vehicles have ranges of 150-300 miles. Increasing the vehicle's range from 200 to 350 miles, would have a small direct impact on the refueling station cost for refueling bays and labor. It might be a key factor in consumer purchasing decisions, however. Vehicle ranges of less than 150 miles entail substantial extra costs because of the value placed on the consumer's time.

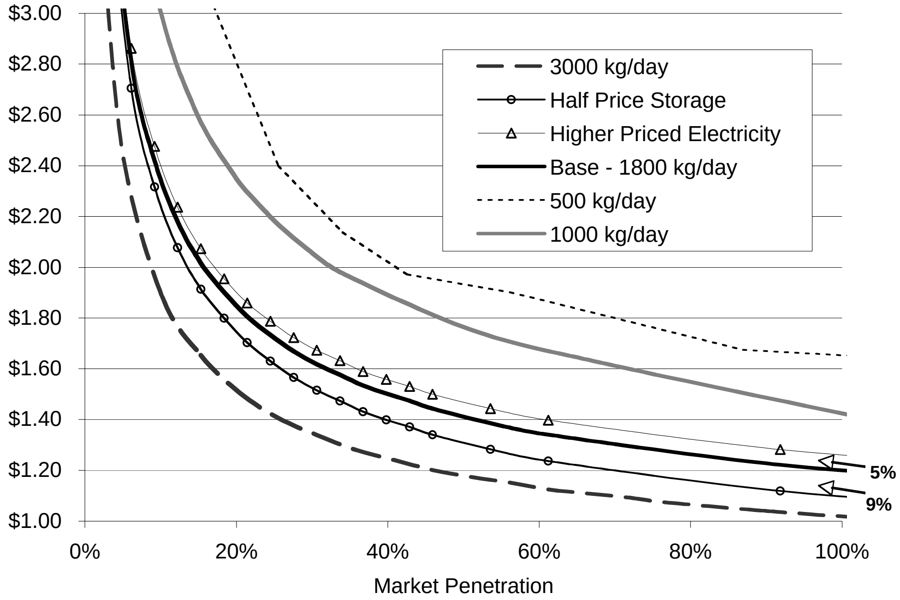


Figure 10 Sensitivity of the levelized cost of pipeline delivery ($/kg) to changes in storage capital cost, compression electricity cost station size, and hydrogen demand.

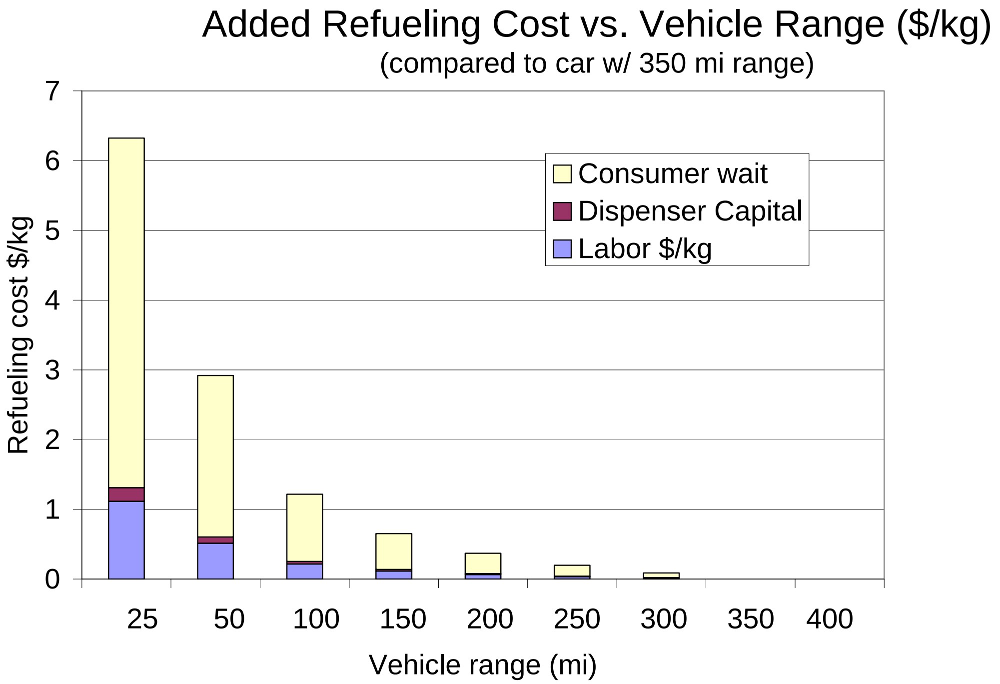


Figure 11. Added refueling costs (compared to a vehicle with a 350 mile range), for shorter-range vehicles. Costs include extra refueling bays, refueling station labor, and consumer time to refuel.

CONCLUSIONS

The design and cost of hydrogen infrastructure depends on type of storage and therefore on the materials used. Hydrogen storage characteristics impact infrastructure in complex ways. The relative importance of storage costs depends on the infrastructure design, which is shaped by the delivery technology, the scale of hydrogen demand, and the geography.

How much do storage-related costs contribute to current hydrogen infrastructure costs? How might improvements in hydrogen storage impact the delivered hydrogen cost? In the early stages of hydrogen infrastructure, when compressed gas trucks serve small stations, storage costs account for approximately 30% of the delivery cost or about 15% of the total hydrogen cost to the vehicle (including central production costs plus delivery costs). Higher-pressure operation appears to be an effective way to reduce compressed gas truck delivery costs. For liquid hydrogen pathways, costs are dominated by storage-related costs, primarily for liquefaction. Storage accounts for 70-80% of the delivery cost or 35-40% of the total delivered cost to the vehicle. This could be reduced by reducing the costs and increasing the efficiency of liquefiers. With onsite production from natural gas, gas storage and compression account for ~ 30% of the hydrogen cost. In the long term, if hydrogen captures a large fraction of the vehicle fleet, pipeline systems will probably give the lowest delivery costs in densely populated cities, and will be preferred in terms of emissions and energy use. As hydrogen use increases, major costs such as pipeline capital and land become less important (because their contributions to the levelized cost $/kg are reduced by scale economies); while gas storage (which is relatively modular and insensitive to scale) becomes proportionally more important. Overall, storage contributes about 15-20% to the cost of hydrogen delivered to the vehicle from a fully developed gas pipeline system. Reducing gas storage capital costs by 50% lowers delivered costs by about 5%. Scale and system layout are the most important factors in reducing pipeline delivery costs. The most important impact of improved hydrogen storage may be through making hydrogen vehicles more attractive to consumers, opening larger markets, which will enable scale economies and lower infrastructure costs.

REFERENCES

1. NRC, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. National Research Council - Board on Energy and Environmental Systems: Washington DC.(2004), p. 394.
2. D.R. Simbeck and E. Chang, *Hydrogen Supply: Cost Estimates for Hydrogen Pathways -Scoping Analysis*. 2002, National Renewable Energy Laboratory (NREL): Golden, CO. p. 32.
3. L.D. Burns, J.B. McCormick, and C.E. Borroni-Bird, *Vehicle of change*, Scientific American, Vol. 287, No. 4, (October 2002), pp 64-73,
4. NRC, *Review of the Research Program of the FreedomCar and Fuel Partnership*, National Research Council - Board on Energy and Environmental Systems and Transportation Research Board: Washington DC (2005), p. 132.
5. United States Department of Energy, Office of Science “Basic Research Needs For A Hydrogen Economy,” May 13-15, 2003, http://www.sc.doe.gov/bes/hydrogen.pdf
6. A. Burke and M. Gardiner, *Hydrogen Storage Options: Technologies and Comparisons for Light-Duty Vehicle Applications*, UC Davis Institute of Transportation Studies Report,. January 2005. UCD-ITS-RR-05-01.
7. C. Yang and J. Ogden, *Analyzing Natural Gas Based Hydrogen Infrastructure – Optimizing Transitions From Distributed To Centralized H_2 Production*, Proceedings of the 2005 National Hydrogen Association Meeting, Washington, DC, (March 2005).
8. C. Yang and J.M. Ogden, *Determining the lowest-cost Hydrogen delivery mode*, Manuscript submitted to International Journal of Hydrogen Energy (November 2005).