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Determining the lowest-cost hydrogen delivery mode

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Abstract

Hydrogen delivery is a critical contributor to the cost, energy use and emissions associated with hydrogen pathways involving central plant production. The choice of the lowest-cost delivery mode (compressed gas trucks, cryogenic liquid trucks or gas pipelines) will depend upon specific geographic and market characteristics (e.g. city population and radius, population density, size and number of refueling stations and market penetration of fuel cell vehicles). We developed models to characterize delivery distances and to estimate costs, emissions and energy use from various parts of the delivery chain (e.g. compression or liquefaction, delivery and refueling stations). Results show that compressed gas truck delivery is ideal for small stations and very low demand, liquid delivery is ideal for long distance delivery and moderate demand and pipeline delivery is ideal for dense areas with large hydrogen demand.

Keywords: Pipeline; Truck; Refueling stations; Infrastructure

1. Introduction

Moving our transportation sector from gasoline and diesel fuels derived from petroleum to hydrogen derived from domestic primary energy resources can provide many societal benefits,[1] including a reduction in well-to-wheels greenhouse gas emissions, zero point-of-use criteria air pollutant emissions, and a reduction in the amount of imported petroleum from politically sensitive areas [1–4]. There are a number of barriers that must be overcome before hydrogen can be widely used as a transportation fuel. One of the most important is the current lack of hydrogen infrastructure. Hydrogen fuel is not widely available to consumers today and the current cost of high-pressure hydrogen at a station is several times that of gasoline [1]. A key component of the hydrogen fuel cost is the hydrogen delivery cost. Widely varying delivery costs have been reported in the literature and these costs can vary greatly depending upon the quantity of hydrogen transported, the transport distance, and for distribution systems, the density of demand.

In this paper, we model the design and cost of alternative systems for delivering hydrogen from a large central production plant to vehicles. We estimate hydrogen delivery costs in terms of a few readily described parameters that can be related to real geographic, technical and market factors. Two types of hydrogen delivery are considered: hydrogen transmission (from a central hydrogen production plant to a single point) and hydrogen distribution (from a central hydrogen plant to a distributed network of refueling stations within a city or region). Three delivery modes are compared: compressed gas trucks, cryogenic liquid trucks and compressed gas pipelines. The least-cost method of transmission depends on two key variables: transport distance and flow rate. Distribution costs within a city are modeled using an idealized spatial layout for a network of hydrogen refueling stations including storage at the central plant. The design and cost of this network can be estimated as a function of the city radius, and the number and size of refueling stations (which can also be linked to population size and market penetration of fuel cell vehicles). Models for estimating the costs for hydrogen delivery were developed based upon previous work of Simbeck and Chang [5], the National Research Council [1], Amos [6], Ogden et al. [7,8], and the United States Department of Energy's H_2A study [9].

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[1] The exact type and amount of benefits will depend upon the primary energy resource employed to produce hydrogen.

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Nomenclature

G	compressed gas H_2 truck
L	liquid H_2 truck
P	H_2 pipeline
M	mass
P_{min}	minimum pressure (atm)
P_{max}	maximum pressure (atm)
d_{pipe}	diameter of pipeline (inches)
CRF	capital recovery factor
O&M	operations and maintenance (fraction of capital cost per year)
CF	capacity factor (availability)
C	cost
S_x	size
β	pipeline cost constant
γ	pipeline scaling constant
N	number of stations
LC	levelized cost
AC	annual cost
$\dot{M}$	mass flow rate (kg/day)
$CO_{2,fuel}$	carbon dioxide emissions from fuel (gCO_2/gal diesel)
$CO_{2,elec}$	carbon dioxide emissions from electricity (gCO_2/kWh)
D	distance traveled (km)
FE	fuel economy (km/gal)
W_{elec}	electricity work used (kWh)
LHV	lower heating value
$\dot{W}$	power output (kW)

Our base case employs cost and performance estimates appropriate for near term (c. 2010) technologies. Sensitivity studies are conducted to show the potential impact of technical improvements on cost. We identify the lowest-cost delivery mode for different hydrogen flow rates, distances, and city characteristics. Our models are applied to a range of cases corresponding to typical values for US cities. The goal of our study is to understand which factors are most important in determining hydrogen transmission and distribution costs.

2. Models of hydrogen delivery modes

Hydrogen is a gas with very low volumetric energy density at standard temperatures and pressures (over three orders of magnitude less than gasoline). As a result, the practical use and transport of hydrogen as an energy carrier require that it be stored with higher volumetric energy density. This packaging requirement imposes significant costs and energy requirements when hydrogen is used as an energy carrier. Typically, improving hydrogen's volumetric energy density is accomplished by transport as a compressed gas, a cryogenic liquid, or as a chemical compound, such as a metal hydride. This analysis focuses only on the three modes of hydrogen delivery in commercial use today: trucks with hydrogen stored in compressed gas tanks (often referred to as tube trailers), trucks with hydrogen stored as a cryogenic liquid (below 20 K), and pipelines that transport compressed hydrogen gas.

The delivery system is defined to include all the equipment required to transport hydrogen from a central production plant to the vehicle (which is assumed to have 5000 psi, high-pressure onboard storage). Table 1 shows the system components for each distribution mode that were included in this analysis. For hydrogen transmission, only the first two components are included (i.e. refueling stations costs are not included), while for hydrogen distribution, all three components are included.

2.1. Central plant hydrogen compression, liquefaction and storage

Storage is provided at the central production plant (and also at refueling stations) to help meet time variations in hydrogen demand, and to assure a reliable hydrogen supply. For compressed gas delivery by truck or pipeline, compression and gas storage are used at the central plant. For liquid hydrogen delivery, liquefaction and liquid hydrogen storage tanks are needed.

Costs for central plant compressors and liquefiers are shown in Table 2. Liquefaction units at the central plant exhibit very strong scale economies compared to compressors (scaling factor 0.57 vs 0.9). Larger liquefiers have a significantly lower cost per unit of hydrogen than smaller units.

Both compression and liquefaction require electrical energy input. Electricity use for compression (from production pressure to storage pressure) is estimated to be in the range of 0.7–1.0 kWh/kg. This is equivalent to about 2–3% of the lower heating value of the hydrogen. Hydrogen gas can be liquefied in an energy intensive process by a process of compression, cooling and expansion, requiring significant electricity use. For this analysis, the energy usage for liquefaction (11 kWh/kg) is based on literature values [6]. The electrical energy input amounts to approximately 33% of the lower heating value of the energy contained in the hydrogen. Table 3 shows the size and cost assumptions used for the central plant storage systems.

The cost of high-pressure H_2 gas storage is significantly higher than the cost of liquid H_2 storage. With liquid hydrogen it is possible to add significant storage and thus reliability at relatively low cost. However, the low cost of liquid hydrogen storage is offset by the high cost for liquefaction and liquid hydrogen is often preferred when large quantities of hydrogen must be stored to assure reliability. As shown in Table 3, the liquid and gaseous systems analyzed here are not completely equivalent because of the difference in central plant storage quantities and subsequent reliability.

Table 1
System components included in delivery pathways

Compressed gas trucks (G)	Liquid H_2 trucks (L)	Gas pipelines (P)
Compression and storage at H_2 plant	Liquefaction and storage at H_2 plant	Compression and storage at H_2 plant
Compressed gas trucks	LH_2 trucks	Gas pipelines
Refueling station[a] (compressor, high-pressure storage, dispensers)	Refueling station[a] (LH_2 storage, LH_2 pump, high-pressure storage, dispensers)	Refueling station[a] (compressor, high-pressure storage, dispensers)

[a] Refueling stations only included in distribution analysis, not transmission.

Table 2
Compression and liquefaction-estimated costs and energy input [1,5,6,9]

$C_x = C_0\left(\frac{S_x}{S_0}\right)^{\alpha}$	Compressor	Liquefier
Base size (S_0)	10 kW	30,000 kg/day
Base capital cost (C_0)	\$15,000	\$40,000,000
Scaling factor (α)	0.9	0.57
O&M costs (fraction of capital costs)	4%	4%
Energy use (kWh/kg)	0.7–1.0	11

Table 3
Central plant storage and cost assumptions [1,5,9]

Delivery mode	Storage amount	Storage cost
Liquid H_2 storage	200% of daily flow	\$20–40/kg
Compressed H_2 truck storage	50% of daily flow	\$400/kg
Pipeline compressed H_2 storage	50% of daily flow	\$400/kg

Table 4
Compressed gas trucks assumptions [1,5,9]

Total truck capacity:	300 kg H_2[a]
Truck P (max):	160 atm (2350 psia)
Truck P (min):	30 atm (440 psia)
Pick up/drop-off time	1 hr
Tube trailer cost:	\$150,000
Undercarriage cost:	\$60,000
Cab cost:	\$90,000

[a] The net capacity of the compressed gas tube trailers is reduced from the total truck capacity because of the minimum gas pressure in the truck at the end of dispensing. Eq. (1) provides the net capacity of the truck as a function of the maximum and minimum operating tank pressures

$$M_{\mathrm{netH_2,truck,G}} = M_{\mathrm{H_2,truck,G}}\left(1 - \frac{P_{\mathrm{min,truck}}}{P_{\mathrm{max,truck}}}\right). \tag{1}$$

With the assumptions shown in Table 4, the net H_2 delivered is 243.75 kg/truck. If higher pressures were allowed, the mass of hydrogen stored on the truck would increase.

2.2. Compressed gas trucks

The first hydrogen delivery mode considered is compressed gaseous truck transport (i.e. large semi-trucks carrying tube trailers with compressed hydrogen). Commercial tube trailers are made up of 12–20 long steel cylinders mounted on a truck trailer bed and are regulated by the US Department of Transportation. Current DOT regulations and industry standards have limited gas pressures on trucks to 160 atm (∼ 2400 psi) or less, although higher-pressure trailers (400 atm/6000 psi) have been built and received special certification. The amount of hydrogen carried by a tube trailer is relatively small (∼ 300 kg), although the capacity would increase when higher tube trailer pressures are implemented. The system also includes a stationary compressor at the central plant, which is used to fill the tube trailers to their specified pressure.

The main factors determining hydrogen delivery costs are the capital costs of the truck cabs and tube trailers, the driving distance, the driver labor cost, diesel fuel cost, and operations and maintenance (O&M) costs. Table 4 lists some of the key assumptions for the capacity, operation of and costs of a compressed gas truck delivery system.

2.2.1. Operating characteristics of tube trailer truck delivery

Tube trailers are filled to 160 atm at the central hydrogen production plant. The trailer is attached to a truck cab (also called a tractor), driven to the refueling site and "dropped off". At the refueling site, an extra compression step brings some of the hydrogen to the high pressures needed for storage onboard vehicles (350 atm), while the tube trailer storage on the truck is used as the low-pressure part of the cascade storage system. As needed, a new, full trailer is dropped off at the station and the empty trailer is collected and taken back to the central plant for refilling. We assume that the truck cabs are operated 24 h per day. Tube trailers have fairly low capital costs but also low hydrogen capacity. This makes them suitable for hydrogen markets that have small delivery requirements.

2.2.2. Estimating equipment requirements

The number of truck cabs and tube trailers required to serve a particular demand can be modeled in several ways. We assume each truck cab makes several round trips per day between the central plant and refueling sites (counting time for connecting a full trailer to the truck cab, traveling between the plant and the refueling station, dropping off a full trailer and picking up an empty one, and returning the empty trailer to the hydrogen plant). The number of truck cabs is determined by the total hydrogen demand, the truck capacity, the average time of each trip (including loading and unloading), and the truck and driver availability (i.e. capacity factor).

The number of trailers needed depends upon the type of demand. For point-to-point transmission, the simplest model is

Table 5
Liquid H_2 trucks assumptions [1,5,9]

Truck capacity (liq)	4000 kg H_2
Liq H_2 boil off	0.3%/day
Load/unload time	3 h
LH_2 tank cost	$650,000
Undercarriage cost	$60,000
Cab cost	$90,000

to assume that there are two trailers for each truck cab (one trailer at the refueling site, the other in the process of being transported or refilled). For hydrogen distribution to a network of refueling stations, it is assumed that the required number of tube trailers is equal to the number of truck cabs plus the number of refueling stations, so that a tube trailer could be left at each station (and loading and unloading would not have to occur with a truck and driver waiting) [5].

An additional system constraint on tube trailer distribution comes about when we compare the truck capacity and the refueling station size. We assume that no more than two trailer delivery per day is practical at each station (typical gasoline stations today receive fuel truck deliveries every 3–5 days). Given a truck capacity of about 250 kg (Table 1), this limits the station size served by compressed gas trucks to approximately 500 kg/d or less.[2]

These “rules” are simple generalizations and not meant to imply the correct quantity of each equipment type. The actual number of tube trailers will depend on the optimal determination in the tradeoff between increased expense for additional tube trailers and the time (and labor cost) savings for reducing driver idle/unloading time.

2.3. *Cryogenic liquid* H_2 *trucks*

The volumetric density of hydrogen can be increased significantly by liquefaction.[3] Liquid hydrogen delivery is used today to deliver moderate quantities of hydrogen medium to long distances [5]. Table 5 summarizes costs and operating characteristics for liquid hydrogen trucks.

Energy requirements and capital costs for liquefaction are much higher than for compression (Table 2). However, cryogenic liquid trucks can transport approximately 10 times more hydrogen than compressed gas trucks. This reduces the number of trucks and trips required to supply a network of stations and reduces fuel requirements for truck transport. Although liquid hydrogen tank trailers cost more than tube trailers, the trucking cost per unit of hydrogen delivered is lower, which can lead to a lower overall hydrogen delivery cost.

Table 6
General truck assumptions [1,5,9]

Fuel economy of trucks	6 mpg
Average speed	50 km/h
Driver hours	8 h/driver/day
Truck availability	24 h/day, 3 shifts/day
Driver wage	$28.75/h
Fuel price	$2/gal
CF_{truck} (availability)	80%
$CF_{H_2 production}$	90%
Truck cab lifetime (yr)	5
Truck trailer lifetime (yr)	20
Real discount rate	10%
CRF_{cab}	26%
$CRF_{trailer}$	12%
$CRF_{Compressor}$	15%
Variable non-fuel O&M	1% of total capital
Fixed operating costs (not including labor)	5% of total capital

2.3.1. *Operating characteristics of liquid hydrogen truck delivery*

Each liquid hydrogen truck consists of a truck cab and large single liquid hydrogen tank mounted on a trailer. It is not practical to leave liquid hydrogen trailers at refueling sites, so, unlike the case for compressed gas tube trailers, the number of truck cabs is always equal to the number of liquid hydrogen tank trailers. We assume that in each trip the truck visits a single refueling station, where it empties its entire load before returning to the central plant (rather than making multiple stops to off-load small quantities of liquid hydrogen at each station).

Equipment for liquefying hydrogen is capital intensive, and there are significant economies of scale associated with liquefier capacity (see Table 2). Thus, we assume a minimum liquefier size (30 tonne H_2/day). Any transmission or distribution system that demands an amount less than this minimum size is assumed to be sharing the liquefier with another transmission or distribution system. Above this size, the liquefier is sized to the amount of hydrogen transported.

2.4. *Common truck delivery operating parameters*

The major costs for truck delivery of gaseous or liquid hydrogen include the capital costs of the trucks, and a variety of fixed and variable O&M costs. In Table 6, we list assumptions for truck delivery used to estimate labor for drivers, fuel costs, and other O&M costs.

2.5. *Pipeline delivery—gaseous* H_2

Pipelines are used commercially today for large flows of hydrogen. The cost of hydrogen pipeline delivery depends on the installed capital cost of the pipeline, as well as costs for compression and storage at the central production plant.

The total installed capital cost of the pipeline includes not only materials for the pipeline, but installation costs, rights of

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[2] If higher-pressure tube trailers were used in the future it would be possible to deliver more hydrogen in each trailer, serving larger stations.

[3] The volumetric energy density is still significantly lower (approximately 70% lower) than that of gasoline. Additionally, the very low temperature requirements for liquid hydrogen (20 K or −423°F) lead to considerable energy input to cool hydrogen from ambient temperatures and super-insulated storage vessel to reduce heat transfer.

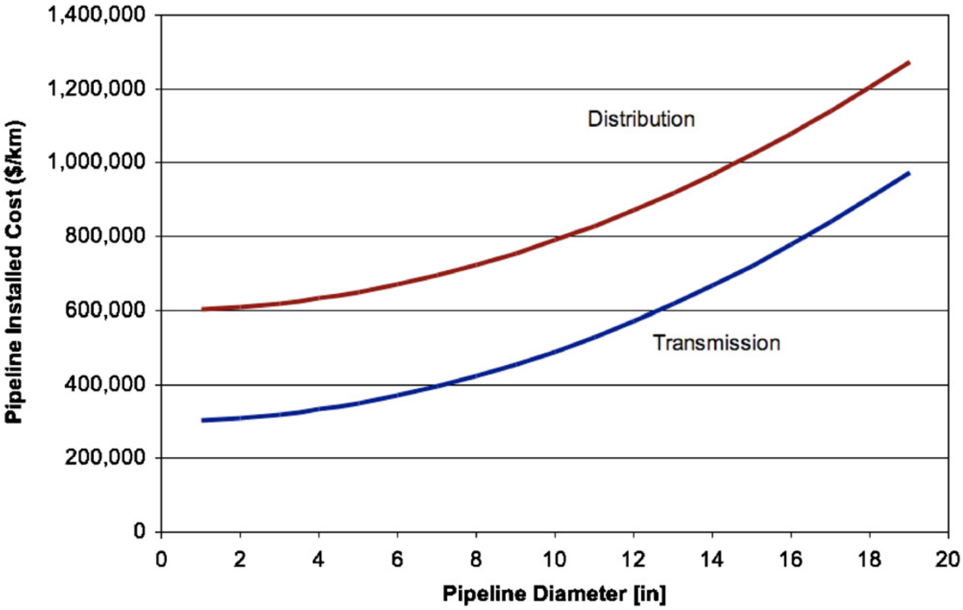

Fig. 1. Pipeline model installed cost ($/mile) dependence on pipeline diameter.

way and miscellaneous costs, all of which can vary greatly with location. The total installed capital costs that are used for this analysis are shown as a function of pipeline diameter in Fig. 1.[4] At small pipeline diameters, the installed cost per meter has little dependence on pipeline diameter. This is true because materials costs are a relatively small fraction of the total, and other costs such as installation and rights of way dominate the installed cost [10]. At the larger pipe diameter, the cost per unit length is more sensitive to pipeline diameter.

Pipeline diameter and energy consumption are governed by turbulent pipe flow equations, which relate the inlet and outlet pressures, length, diameter and mass flow [11]. The diameter is determined by specifying the inlet and outlet pressures, pipeline length, and mass flow. The pipeline capital cost is then determined from Fig. 1. Additional costs include the compression energy cost and fixed operating costs. The electrical input energy for compression (to ~ 1000 psi) equals about 2–3% of the energy content of the hydrogen. This is considerably less than the electricity required to liquefy hydrogen (33% of the energy content of hydrogen).

In general, the design capacity of the pipeline is higher than the average flow rate to account for time variations in flow, or to allow for expansion. This leads to underutilized capital, which is modeled as an average capacity factor. Pipeline cost and operating assumptions are shown in Table 7. The cost of the right-of-way (ROW) and installation is assumed to be significantly higher for hydrogen distribution (urban) when compared to transmission (rural). The capital cost of the pipeline itself is calculated as a function of pipeline diameter, which affects the amount of material used within the pipe.

Table 7
Pipeline assumptions [1,5,9,10]

Installation and ROW cost—rural	$300,000/km
Installation and ROW cost—urban	$600,000/km
Pipeline capital costs ($/km)	$1869 $(d_{\text{pipe}})^2$
(d_{pipe} is pipeline diameter in inches)	
Maximum pipeline inlet pressure	70 atm (1029 psi)
Pipeline output pressure	35 atm (515 psi)
$\text{CF}_{\text{H}_2\text{production}}$	90%
$\text{CRF}_{\text{Pipeline}}$	15%
$\text{CRF}_{\text{Compressor}}$	15%
Fixed operating costs	5% of total capital
Compressor capital costs	$\$15,000\left(\frac{S_x}{10\,\text{kW}}\right)^{0.9}$
(S_x is compressor size in kW)	
Compression energy requirements	0.7–1.0 kWh/kg

2.6. Refueling stations model

The costs of refueling stations are included in our hydrogen delivery calculations. Each delivery mode has a different type of refueling station.

- Stations that rely on compressed gas delivery by truck or pipeline further compress hydrogen from the station delivery pressure to the assumed hydrogen vehicle storage pressure (5000 psi).
- Liquid hydrogen delivery allows for pumping of liquid hydrogen, which is lower cost than gas compression, and vaporization at the refueling pressure.

Hydrogen storage requirements vary among the different station types. The bulk of storage for stations supplied by compressed gas trucks (G) is assumed to be in tube trailers that are dropped off by trucks. A small amount of high-pressure

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[4] This dependence on pipeline diameter was based upon a statistical analysis of data for oil and gas pipelines [10].

Table 8
Compression, storage and size assumptions for refueling stations

Station type	Gas truck station (G)	Liquid H_2 station (L)	Pipeline station (P)
Station capacity (kg/day)	500	500, 1000, 1800, 3000	500, 1000, 1800, 3000
Primary storage size (% daily flow)	30%[a, b]	200%[c]	50%[a]
Secondary storage size (% daily flow)		10%[a]	
Compressor/pump size (% daily flow)	50%	100%	100%
Compression/pump energy (kWh/kg)	0.9	0.8	1.3
Station capital cost ($thousands)	$144	$144, $262, $457, $691	$248, $489, $888, $1,435
Station O&M costs ($thousands/yr)	$108	$111, $131, $168, $212	$120, $149, $201, $155

[a] High-pressure hydrogen storage (6250 psi).
[b] Storage requirements at station apart from tube trailers.
[c] Liquid hydrogen storage (20 K).

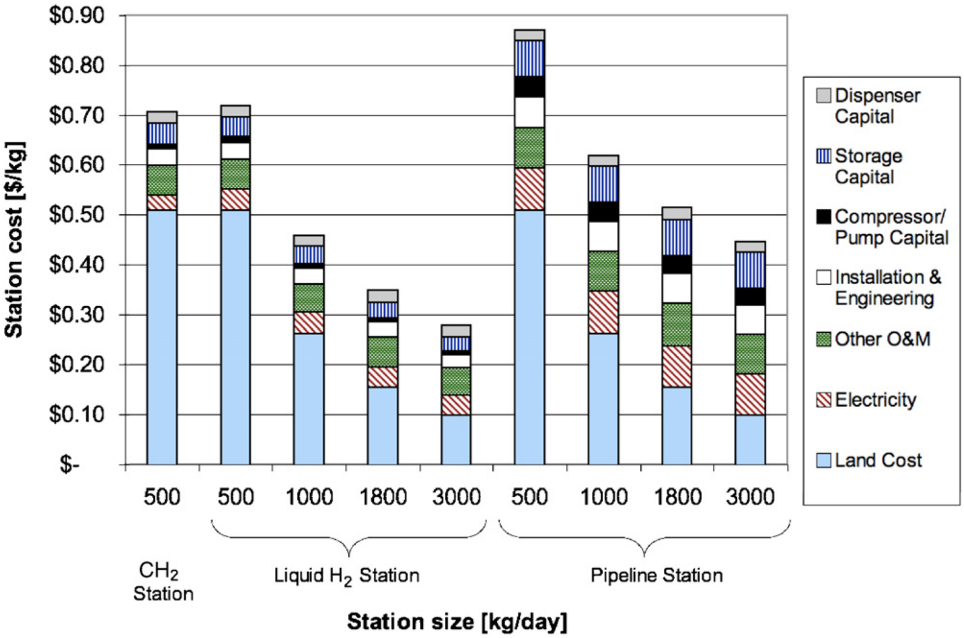

Fig. 2. Refueling station cost breakdown as a function of station size (500, 1000, 1800 and 3000 kg/day) and hydrogen delivery mode.

storage is required to "top off" the vehicles as they refuel. Similarly, stations supplied by liquid hydrogen trucks (L) store hydrogen as a liquid in large storage dewars. A small tank of high-pressure hydrogen is used for buffer storage for refueling vehicles. Finally, stations supplied by gas pipelines (P) will require a significant amount of high-pressure hydrogen storage. Other aspects of the station (dispensers, controls, land) are assumed to be equal between different station types of the same size. Table 8 lists the cost, energy and size assumptions for compression, storage and operation of the three station types determined by our detailed refueling station model.

The contribution to the hydrogen cost due to hydrogen stations (calculated per kilogram of hydrogen dispensed) is shown in Fig. 2 for three types of stations and four station sizes. Analyses of costs of current and near-term stations show very high installation, permitting and maintenance costs for H_2 stations [12]. This analysis assumes that stations are numerous and widespread so these costs would be significantly lower than for current one-of-a-kind stations. The station cost ($/kg) decreases with increasing station size. This is mainly due to the assumption that larger stations require only slightly more land than small stations while the amount of hydrogen dispensed can be significantly greater. Other station components show little economy of scale: compressed gas storage is modular and compressors have small-scale economies at this size range.

Liquid hydrogen stations have a lower cost per kg than pipeline stations. This is true because liquid storage costs less than gas storage and liquid hydrogen pumps cost less than compressors. Further, electricity requirements for pumping liquid hydrogen are less than for compressing gas (see Table 8). At small station sizes, gaseous truck delivery has lower station storage costs because the tube trailers comprise most of the storage system (only a small high-pressure buffer storage tank is used to top off the vehicles). This assumption significantly reduced the amount of hydrogen storage and compression required for compressed gas truck stations compared to pipeline stations. The installed capital costs for these stations are in close agreement with those published by the H_2A [13].

3. Transmission and distribution models

We have developed simplified idealized models for hydrogen transmission and distribution that characterize the delivery process for trucks and pipelines in terms of a few easily specified parameters. We consider two classes of delivery models: transmission (point-to-point) and local distribution to a network of refueling stations. To fully model a H_2 delivery system requires knowledge about hydrogen demand as a function of spatial, regional, daily and seasonal factors as well as the evolution of demand growth over time in response to technological, social, economic and policy changes. In our simple model, these factors and their details are distilled into several key input parameters: hydrogen flow rate (kg/day), transport distance (km), and city characteristics such as radius (km), market penetration of hydrogen vehicles and refueling station size (kg/day) and number. This allows us to estimate costs and compare among delivery modes to identify low-cost options without having to conduct a detailed regional assessment.

3.1. Transmission (point-to-point) model

We first consider the transmission of hydrogen from a single source to a single demand. We characterize the point-to-point transmission of hydrogen in terms of two parameters: hydrogen flow and transmission distance. Cost equations for the different delivery modes are used to determine the costs of transmission for each of the delivery modes, and the lowest-cost method can be identified. The transport distance is varied from 25 to 500 km and the flow of hydrogen from 2000 to 100,000 kg/day.[5] The transmission model includes central plant compression (or liquefaction) and storage, but does not include refueling stations as part of the cost or energy requirements (shown in Table 1).

3.2. Distribution model

We have developed simplified models to estimate the cost of distributing hydrogen to a network of refueling stations in a city via trucks or pipeline. Our goal is to develop models that can be applied to a range of real cities. The first part of the design problem is characterizing the demand. To simplify the analysis we have developed an idealized city model (ICM). We assume a circular city with a homogeneous population distribution.[6]

Several key parameters are used to describe the city including the city radius and the number of refueling stations. With these parameters, ICM is used to design a system layout that maximizes consumer convenience (minimizes average travel distance) and determines the following system metrics: (1) the distance that consumers must travel to refuel, (2) the length of the distribution network (pipes or trucks) to supply the refueling stations from the city gate, and (3) the distribution of demand amongst the stations within the city. Recently, Nicholas [14] has conducted a detailed geographic study of a specific region, using GIS to provide estimates of the tradeoff between the number of refueling stations and the travel time for consumers to refuel, and the exact configuration and layout of stations for consumer convenience. While ICM does not yield results at the same level of spatial detail, it permits the development of generalized “rules-of-thumb” and equations for distribution system design that can be quickly applied to a new location, in way that a detailed GIS analysis cannot.

There are a number of different configurations for a network of refueling stations [15,16] as well as numerous ways of connecting the stations to a distribution node. Even for the same number of refueling stations distributed throughout a city, the cost of the distribution network can vary significantly depending upon how those stations are arranged, the station size distribution, how the distribution system is organized, and which modes are used to deliver the hydrogen. In this paper, we make several simplifying assumptions: (1) stations are organized in concentric rings around the city center, (2) population is homogeneously distributed, (3) all refueling stations are the same size and (4) only one delivery mode is used.[7] With these assumptions, we find that the most convenient station network is laid out by evenly spreading stations throughout the city.

Fig. 3 shows the paths that the pipeline network and trucks would travel within the city. It is assumed that both delivery modes follow a rectilinear coordinate system that would approximate a grid-like street network. Pipelines are arranged in rectilinear “rings” to connect stations. Trucks are assumed to travel from the city gate to only one station and then return. Given a specified number of stations within the city, the number of rings within the city and the number of stations within each ring are easily determined. We then calculate the pipeline network length and truck travel distance for any number of refueling stations. General relationships are developed that characterize pipeline lengths and truck travel distances as a function of the city radius. This allows application of the results to different sized cities.

In Fig. 4, the delivery length for pipelines and trucks is shown as a function of the number of refueling stations.[8] The results

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[5] Higher flows are possible but do not significantly change the delivery costs ($/kg).

[6] ICM can be used to optimize station layout for non-homogeneous, radially symmetric population distributions as well.

[7] The assumed homogeneous distribution of population and stations within the idealized city leads to a conservative estimate of the average travel distance for consumers to their closest station and the distribution system delivery distances. Cities with areas of higher density population will tend to cluster stations in these areas, leading to lower distribution costs for hydrogen and shorter travel distances for the average consumer. Hydrogen stations, like gasoline stations, are likely to come in a range of sizes, which could lead to multiple delivery modes being utilized.

[8] There are significant differences between truck and pipeline delivery lengths because it is assumed that trucks will travel from the starting point at the city gate to each station individually (leading to many overlapping truck routes), while distribution pipelines can connect stations to other stations.

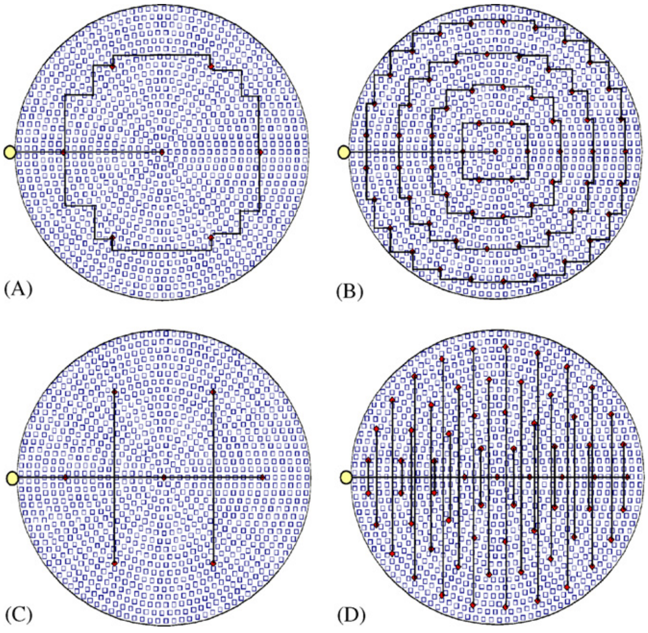

Fig. 3. Representation of idealized city with refueling station network for homogeneously distributed population. Lines show the paths for pipeline (A, B) and truck (C, D) distribution to refueling stations for 7 (A, C) and 64 (B, D) stations. The truck paths assume that trucks travel to one station only before traveling back to the hydrogen depot (the circle on the left side of the city).

for pipeline length vs station number are fit to a power function:

$$L_{\text{pipeline}} = \beta \cdot N_{\text{stations}}^{\gamma}, \tag{2}$$

where L_{pipeline} is the length of the pipeline (as a multiple of the city radius), N_{stations} is the number of stations, β is 2.43 and γ is 0.4909. For the truck delivery scenario, assuming that trucks only travel from the city gate to one station before returning, a linear equation describes this distance (one-way, in terms of city radii):

$$D_{\text{truck}} = 1.44 \cdot N_{\text{stations}}. \tag{3}$$

Thus, the average truck travel distance between the city gate and a refueling station is 1.44 times the radius of the city. The distance relationships developed in this section are coupled with the delivery mode models from the previous section to determine costs as a function of the important city parameters. From this we can determine the lowest-cost delivery mode for different levels of demand (station number is determined by total hydrogen demand and station size).

3.3. Applying idealized models to real cities

Geographic, market and operating considerations impose real constraints on the idealized city and delivery models that can impact the design of the system. There is a range of practical refueling station sizes. The maximum station size for tube trailer delivery is set equal to two trailer deliveries per day or approximately 500 kg/day. The maximum station size that is considered in this analysis is 3000 kg/day. This corresponds to a station that can serve a fleet of hydrogen cars comparable to a large gasoline station.

For a given city size, there is an upper limit on the hydrogen flow rate (set by the population and number of vehicles in the city). Most US cities have populations in the range 0.1–10 million people, and population densities of 500–3000 people/km^2 (Ni 2004). Certain combinations of parameters (such as large population combined with very low density) do not occur in any cities. Table 9 shows some values for population density and population size and city radius[9] for some real US cities.

4. Metrics and results

4.1. Hydrogen delivery metrics

We evaluate delivery modes in terms of costs, energy use and emissions.[10] The levelized cost of hydrogen delivery ($/kg) is calculated from a simple equation that describes the annual cost ($AC_{\text{equipment}}$) associated with the equipment (typically a fixed payment associated with financing of capital equipment, such as trucks, pipelines, liquefiers and/or compressors) and the annual cost of operating ($AC_{\text{operations}}$) the delivery and station equipment (associated with fuel and O&M costs, some of which can vary with output). The levelized cost of hydrogen delivery (transmission and distribution) includes all the annualized costs for equipment and operations for each type of delivery (as shown in Table 1), beginning with purified hydrogen from a central plant at 120 psi, divided by the annual mass flow of hydrogen (where M_{H_2} is the average mass flow and CF is the capacity factor)

$$LC_{H_2} = \frac{AC_{\text{equipment}} + AC_{\text{operations}}}{\dot{M}_{H_2} CF}. \tag{4}$$

In addition to the cost, we calculate well-to-wheels emissions of CO_2 according to

$$CO_{2,\text{total}} = \frac{D_{\text{totaltrips}} CO_{2,\text{unit,fuel}}}{FE_{\text{trucks}}} + W_{\text{elec}} CO_{2,\text{unit,elec}}. \tag{5}$$

The total carbon dioxide emissions (kg CO_2/kg H_2) associated with delivery and refueling are equal to the sum of fuel and electricity-related emissions.[11] Emissions are determined by: (1) fuel usage (determined by the total driving distance ($D_{\text{totaltrips}}$) and the truck fuel economy (FE_{trucks})) multiplied by the emissions associated with a unit (kg CO_2/gal) of diesel

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[9] The radius for real cities is determined by calculating the radius for a circular city with an equivalent area.

[10] There are, of course, several other potential delivery metrics, which are not discussed in detail such as system flexibility, system reliability and security, safety, criteria air pollutants and other environmental impacts, ease of expansion, community preferences and rights of way. Though these are not explicitly analyzed here, they can play a potentially large role in decision making for the transition to a hydrogen economy.

[11] Other associated emissions of CO_2 (such as those from materials and equipment manufacture) are not taken into account in this analysis.

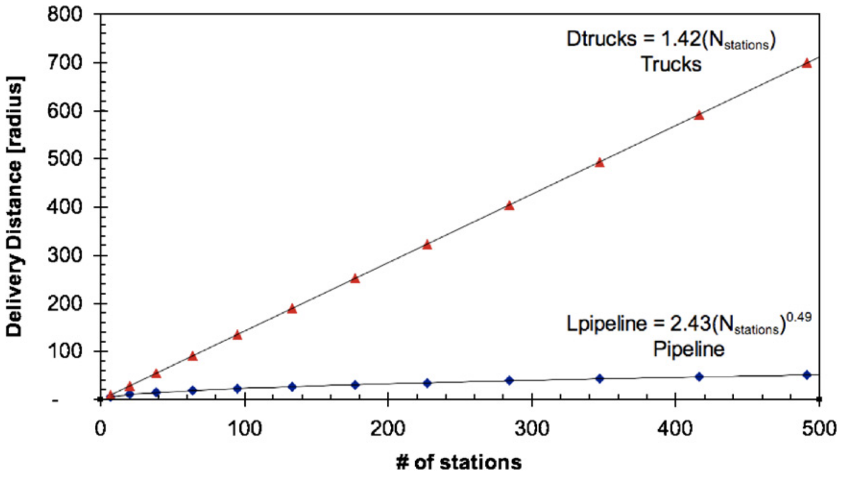

Fig. 4. The delivery length (in city radius) as a function of the total number of stations within a city for trucks and pipelines.

Table 9
Population, radius and population density for large US metropolitan regions

Metro area	Population	Radius (km)	Density (/km^2)
Los Angeles	11,789,000	37	2729
New York	17,800,000	52	2050
Miami	4,919,000	30	1702
Chicago	8,307,000	42	1511
Phoenix	2,907,000	26	1405
San Diego	2,674,000	25	1320
Washington	3,934,000	31	1313
Detroit	3,903,000	32	1195
Baltimore	2,076,000	24	1174
Houston	3,823,000	32	1140
Dallas-Fort Worth	4,146,000	34	1138
Philadelphia	5,149,000	38	1105
Seattle	2,712,000	28	1098
Cleveland	1,787,000	23	1066
Minneapolis-St. Paul	2,389,000	27	1032
Tampa-St. Petersburg	2,062,000	26	993
St. Louis	2,078,000	26	968
Boston	4,032,000	38	897
Cincinnati	1,503,000	24	864
Pittsburgh	1,753,000	26	794
Atlanta	3,500,000	40	688

fuel ($CO_{2,\text{unit,fuel}}$ including upstream emissions) and (2) electricity usage, W_{elec} (kWh/kg H_2), multiplied by the emissions from an assumed generating mix of electricity, $CO_{2,\text{unit,elec}}$ (kg CO_2/kWh) (see Eq. (5)). This electricity emissions factor can vary considerably depending on the electricity generation fuel and technology mix. To obtain a complete emissions estimate for the entire hydrogen pathway, we would have to estimate emissions at the hydrogen production plant, as well. This is planned for future work.

The energy input requirement for delivery is calculated as a percentage of the lower heating value of hydrogen (Eq. (6)). The total energy use is the sum of the rate of energy usage of the various components of the system, including fuel for trucks (W_{fuel}), electricity requirements for the liquefier (W_{liq}) and/or compressor(s) (W_{comp}). This total energy use is divided by the total energy flow (H_2 mass flow, M_{H_2}, multiplied by the lower heating value (LHV_{H_2})). Components that consume electricity are presumed to use the primary energy associated with electricity production rather than just the electricity energy content. Reducing the energy usage for hydrogen distribution and improving system-wide efficiency are important for reducing the use of energy resources and reducing environmental impact of energy use.[12]

$$W_{\%\text{input}} = \frac{\dot{W}_{\text{fuel}} + \dot{W}_{\text{liq}} + \dot{W}_{\text{comp}}}{\text{LHV}_{H_2}\dot{M}_{H_2}}. \tag{6}$$

4.2. Hydrogen transmission (point-to-point delivery)

Fig. 5 shows the point-to-point delivery costs (\$/kg H_2) over the range of transmission parameters (flow and distance) for each of the delivery modes. In Fig. 5, we show the various cost components that make up the delivery cost for each mode, for particular delivery distances (50 and 300 km), and flow rates (15 and 100 tonne/day).

Compressed gas trucks (G) costs are relatively independent of hydrogen flow rate, though there are slight economies of scale associated with compressor cost. However, the transport distance, which affects the number of trucks, O&M (mostly labor), and fuel costs, has a large effect on transmission costs and scales linearly with distance. Truck O&M (consisting of labor, as well as other non-fuel operating costs) makes up a largest component of the total compressed gas truck delivery cost.

For liquid hydrogen truck delivery (L), the large majority (80–95%) of the delivered cost is due to liquefaction. Not surprisingly, the overall costs for liquid hydrogen trucking depend strongly on the hydrogen flow, due to the economies of scale associated with the liquefaction equipment. Costs

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[12] This distribution energy requirement is only one component of the total life-cycle efficiency. Other components, not analyzed here, include hydrogen production/conversion efficiency, storage efficiency, system leakage, and hydrogen utilization/fuel cell efficiency.

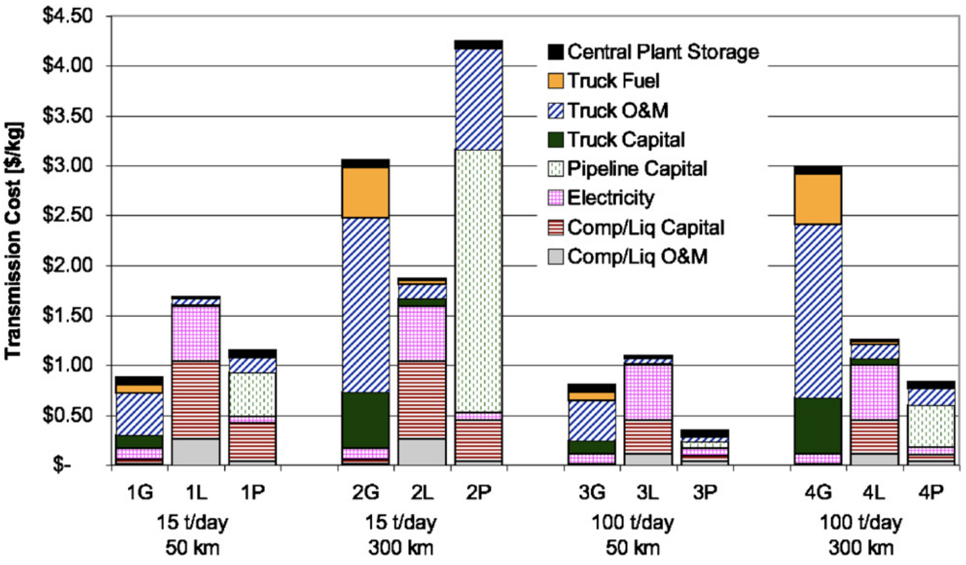


Fig. 5. Transmission costs breakdown ($/kg) for hydrogen as a function of flow and distance for the three different transport modes considered in this study.

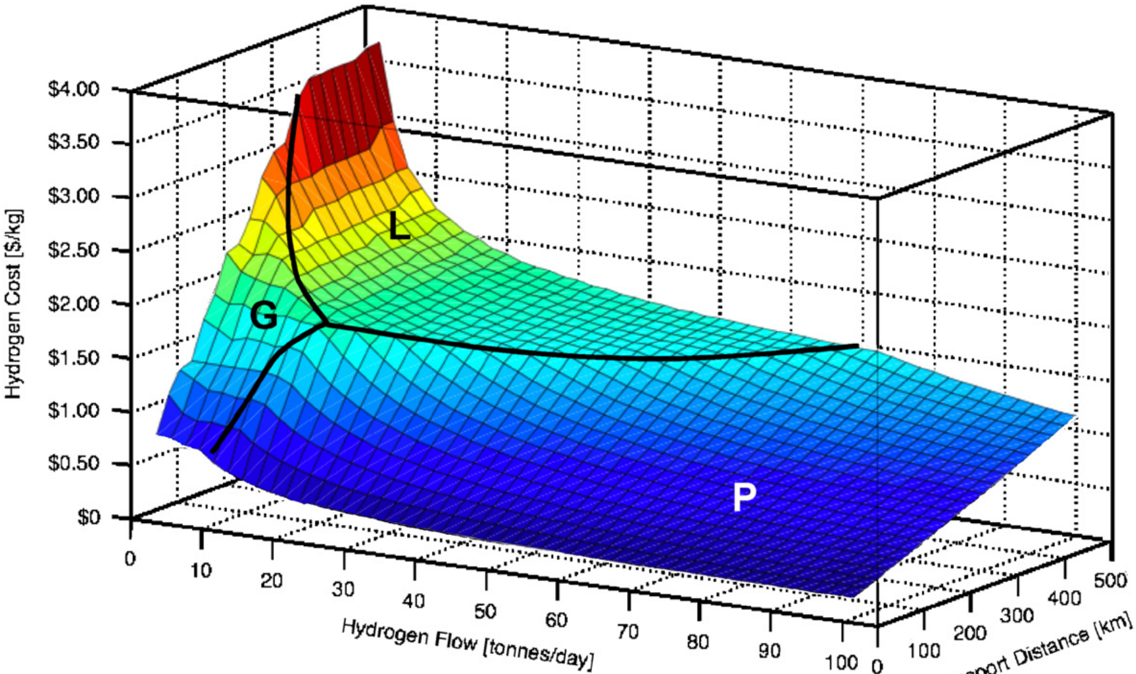
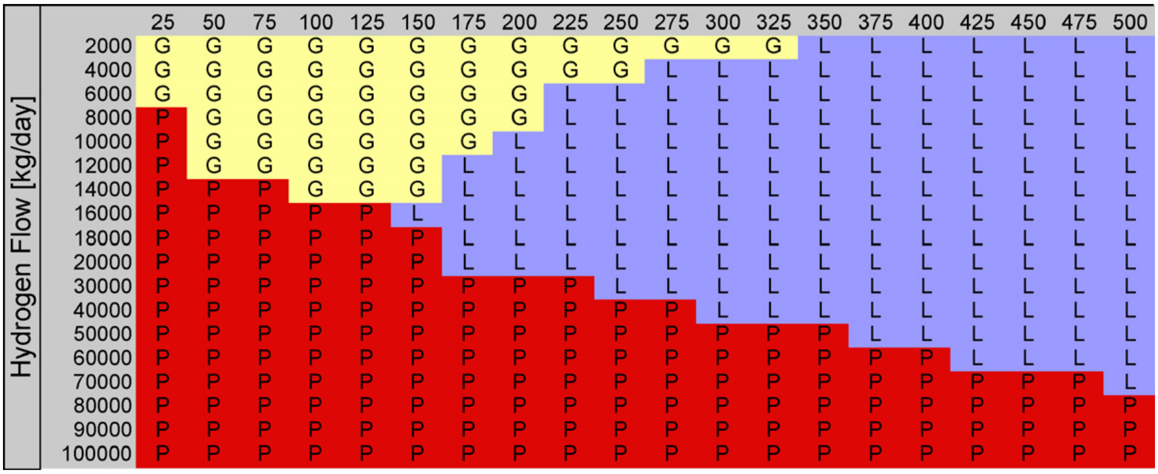


Fig. 6. Minimum hydrogen transmission costs as a function of H_2 flow and transport distance.

for liquefier capital depend upon scale, while liquefaction electricity costs ($/kg) are independent of scale. At low flow, these costs are approximately equal, while at high flow, the liquefier capital accounts for about 30% of costs while liquefier energy accounts for 50–60% of costs. Liquid truck costs have a slight dependence on transport distance but are not as sensitive as gas trucks because of the higher capacity of liquid trucks.

For pipelines (P), the costs have a very large dependence on both parameters. The pipeline capital cost is the single largest contributor to costs. The lowest costs are associated with large flows and short distances, whereas high costs are found at very low flows and long distances.

The mode that gives the lowest delivery cost depends upon the distance and flow conditions as shown in Fig. 6. The two horizontal axes correspond to transport distance (0–500 km) and flow rate (0–100 tonne/day) while the vertical axis shows delivery cost. The lowest delivery cost (per kg H_2) occurs at a very high flow rate and short distribution distance. The cost of hydrogen delivery can vary over a wide range (∼$0.10/kg to



Hydrogen Flow [kg/day]	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500
2000	G	G	G	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L
4000	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L
6000	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L
8000	P	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L
10000	P	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L
12000	P	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L	L
14000	P	P	P	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L	L
16000	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
18000	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L
20000	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L
30000	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L
40000	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L
50000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L
60000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L
70000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L
80000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
90000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
100000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

Fig. 7. Mode map describing the lowest-cost hydrogen delivery options as a function of hydrogen flow and transport distance. G, L, and P indicate compressed gas trucks, liquid trucks and pipelines, respectively. (Note: hydrogen flow rate (rows) does not change in equal increments.)

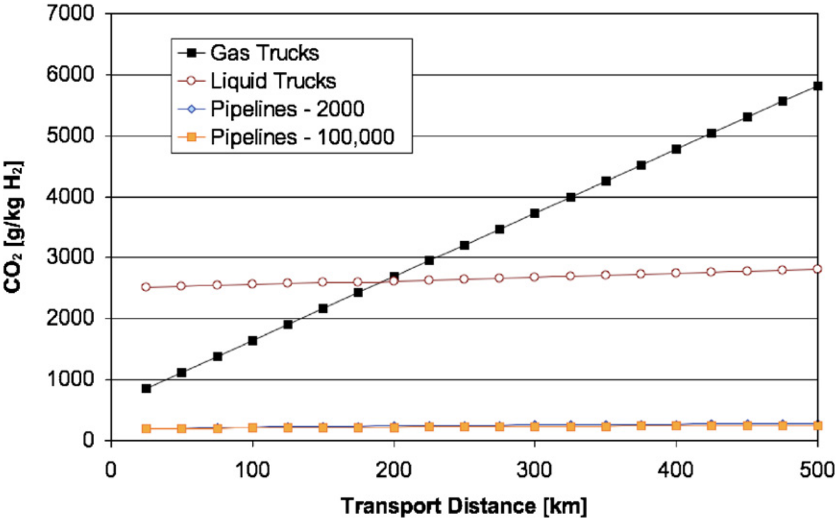


Fig. 8. Energy input requirements for hydrogen transport due to primary energy usage (from electricity and diesel fuel) as a function of transport distance for the three different delivery modes. Calculations are for a California grid mix.

nearly \$4/kg) depending upon the delivery parameters. At the larger flow rates that might be found at high market penetration levels in large cities, transmission costs could be even lower.

Fig. 7 is another representation of the lowest-cost mode for a given set of conditions (transport distance and flow rate). It shows that trucking gaseous H_2 make sense for low flow rates and short distances, but that as the delivery parameters change, other modes can become the lowest-cost method. Because the capacity of gaseous tube trailers is fairly low, liquid delivery makes more sense at longer distances, where reductions in truck usage and diesel fuel costs more than make up for increased capital and energy costs. Pipeline becomes the dominant low-cost mode, especially at short to medium transport distances, as the flow rates increase and the delivered costs are greatly reduced as the volume increases.

In Figs. 8 and 9, we estimate net energy use and CO_2 impacts of the transmission modes as function of transport distance. The energy use per kg of hydrogen for each mode is relatively constant with the flow rate of hydrogen. Fig. 8 shows energy inputs that are associated with each of the hydrogen distribution modes. Electricity is the only energy use for pipelines, while the gas and liquid truck modes use both electricity and diesel fuel. The energy requirements for electricity include the primary energy associated with electricity production. The results shown are assuming the relatively efficient ($\eta \sim 50\%$) California grid mix. The trends in energy use as a function of transport distance are different for each of the transport modes. The electrical energy required for liquefaction of hydrogen is very significant, accounting for approximately 33% of the energy contained in the hydrogen. If one looks at the primary energy requirements for the electricity generation, the primary energy associated with liquefaction can be between 60–100% of the energy in the hydrogen. There is only a slight increase in the energy use because once liquefied, the liquid hydrogen

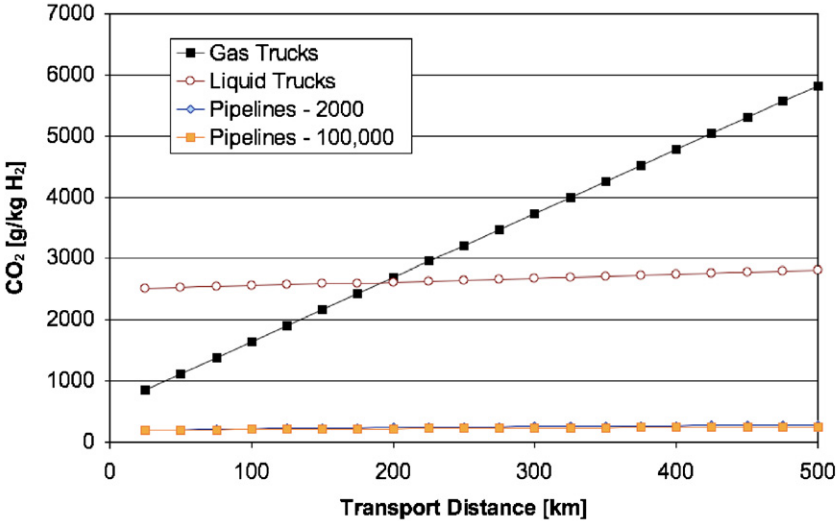


Fig. 9. CO_2 emissions (from electricity and diesel fuel) as a function of transport distance for the three different delivery modes. The CO_2 emissions associated with each of the modes are relatively constant with the flow rate of hydrogen. Electricity emissions are calculated for a California grid mix (low carbon).

is fairly energy dense and requires only a modest amount of diesel fuel to transport. Gas trucks use electricity for compression of the hydrogen and can use significant amounts of diesel fuel as transport distances increase, due to the very low capacity (300 kg) of compressed hydrogen trucks. Pipelines operate at lower pressures than compressed gas trucks and, when the pipeline is sized adequately, require very little energy input to overcome frictional losses within the pipe. The energy usage for pipelines is significantly lower than for the other modes. The energy losses (per kg of H_2) for pipeline transport are similar at a wide variety of flow rates (2–100 tonne/day), because the majority of energy use is associated with compression to the pipeline inlet pressure.

Fig. 9 shows the CO_2 emissions associated with the different transport modes and shows a very similar trend to that shown in Fig. 8. The difference between these two graphs has to do with the relative amount of CO_2 emissions associated with electricity production (assuming a particular grid mix) and diesel fuel usage. This particular result is based upon the relatively low-carbon California grid mix (~ 0.3 kg CO_2/kWh). Although pipelines give the lowest energy use and CO_2 emissions of all modes under the conditions analyzed, they are often not the least cost method to transport low volumes over moderate or long distances. The amount of CO_2 emissions from each delivery/refueling pathway can be a significant contributor to the total well-to-wheels CO_2 emissions. Given the difference in CO_2 emissions between pipelines and liquid trucks shown in Fig. 9, a carbon tax of \$100/tonne C (\$27/tonne CO_2) would add an additional cost of about \$0.10/kg H_2 to liquid trucks relative to pipelines. Thus, any economic incentives to control carbon emissions, such as carbon taxes or trading schemes, could affect the choice of the most appropriate delivery mode. The difference in cost would be even higher when considering electricity from other states with different grid compositions, since California's electricity is low carbon relative to the rest of the US.

4.3. Hydrogen distribution (delivery to a refueling station network)

Fig. 10 shows the breakdown of costs for several different hydrogen distribution cases for San Jose and Cincinnati, which both have a population of about 1.5 million people but have different population density (2300 people/km^2 vs 900 people/km^2). Also analyzed is the effect of station size and market penetration of hydrogen fuel cell vehicles. At the small station size (500 kg/day) for both cities, the compressed gas truck is the lowest-cost option and pipelines are the highest-cost option, though truck O&M (i.e. labor) and fuel costs are higher for Cincinnati which is less dense and has greater driving distances. Pipeline capital is very large because the small station size cannot give the high flow rates that help reduce pipeline costs per kg of H_2. At the larger station size (1800 kg/day), pipelines are lower cost in San Jose (i.e. the smaller, denser city) while liquid H_2 trucks are lower cost in the larger (less dense) city. Doubling the radius of the city leads to a doubling of the delivery distances (which doubles pipeline capital and truck fuel). However, changing the radius does not really affect the total delivered cost for liquid H_2 trucks because fueling comprises only a small part of the total cost (most of which is associated with liquefaction of the hydrogen).

As with the transmission of hydrogen, the cost of distributing hydrogen to a network of refueling stations can vary tremendously depending upon the physical size of the city (i.e. the city radius) and the number of stations (i.e. how dispersed a network the delivery infrastructure must support). Fig. 11 shows the cost variation as a function of these two parameters for a station size of 1800 kg/day. Gas trucks are not considered for this delivery case because the large station size would require too many deliveries. Costs decrease with increasing numbers of stations and decreasing city radius. As station numbers increase the flow of hydrogen also increases, which gives scale economies. As the city radius decreases, the city becomes

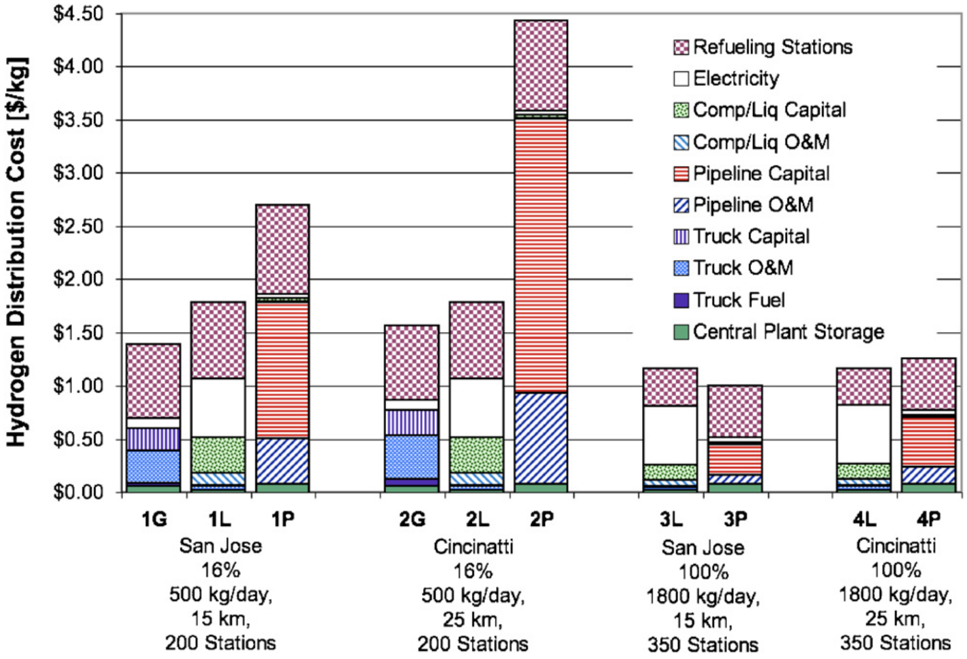


Fig. 10. Hydrogen distribution cost breakdown ($/kg) for the three delivery modes to a network of refueling stations in San Jose and Cincinnati (population 1.5 million): (1 and 2) 500 kg/day station size and 16% market penetration, (3 and 4) 1800 kg/day and 100% market penetration.

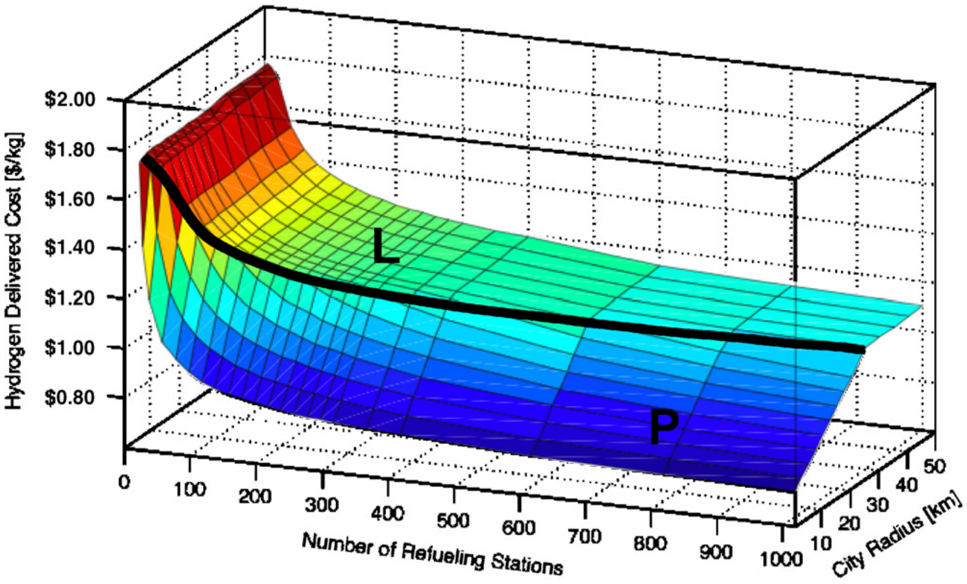


Fig. 11. Hydrogen distribution cost ($/kg) to a network of refueling stations (1800 kg/day capacity) as a function of the number of refueling stations in the network and the radius of the circular city.

more dense, which allows a switch to pipelines and lower costs.

The delivery scenario with the lowest cost occurs in a small, dense city with a large number of stations. It is important to realize that there are regions of the graph, specifically where there are large numbers of refueling stations and low city radii that are very unlikely. Certain conditions may not be possible in an actual city and care should be exercised when using the graph to estimate delivery costs.

Fig. 12 shows the distribution costs for a station of 500 kg/day. In this delivery scenario, the predominant delivery mode occurs via compressed gas trucks. The cost of delivery is proportional to the city size and is relatively independent of numbers of stations. Five hundred kg/day represents a very small station compared to the average size of current gasoline stations. It is highly unlikely that large numbers of these small stations would be built in a city when networks of larger stations are more cost-effective. When comparing Fig. 11 with

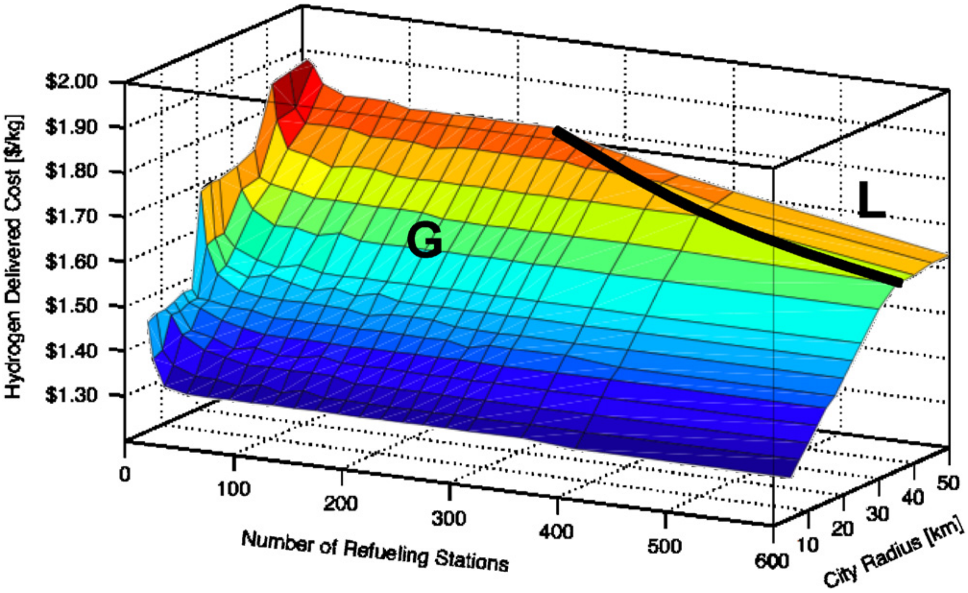


Fig. 12. Hydrogen distribution cost ($/kg) to a network of refueling stations (500 kg/day capacity) as a function of the number of refueling stations in the network and the radius of the circular city.

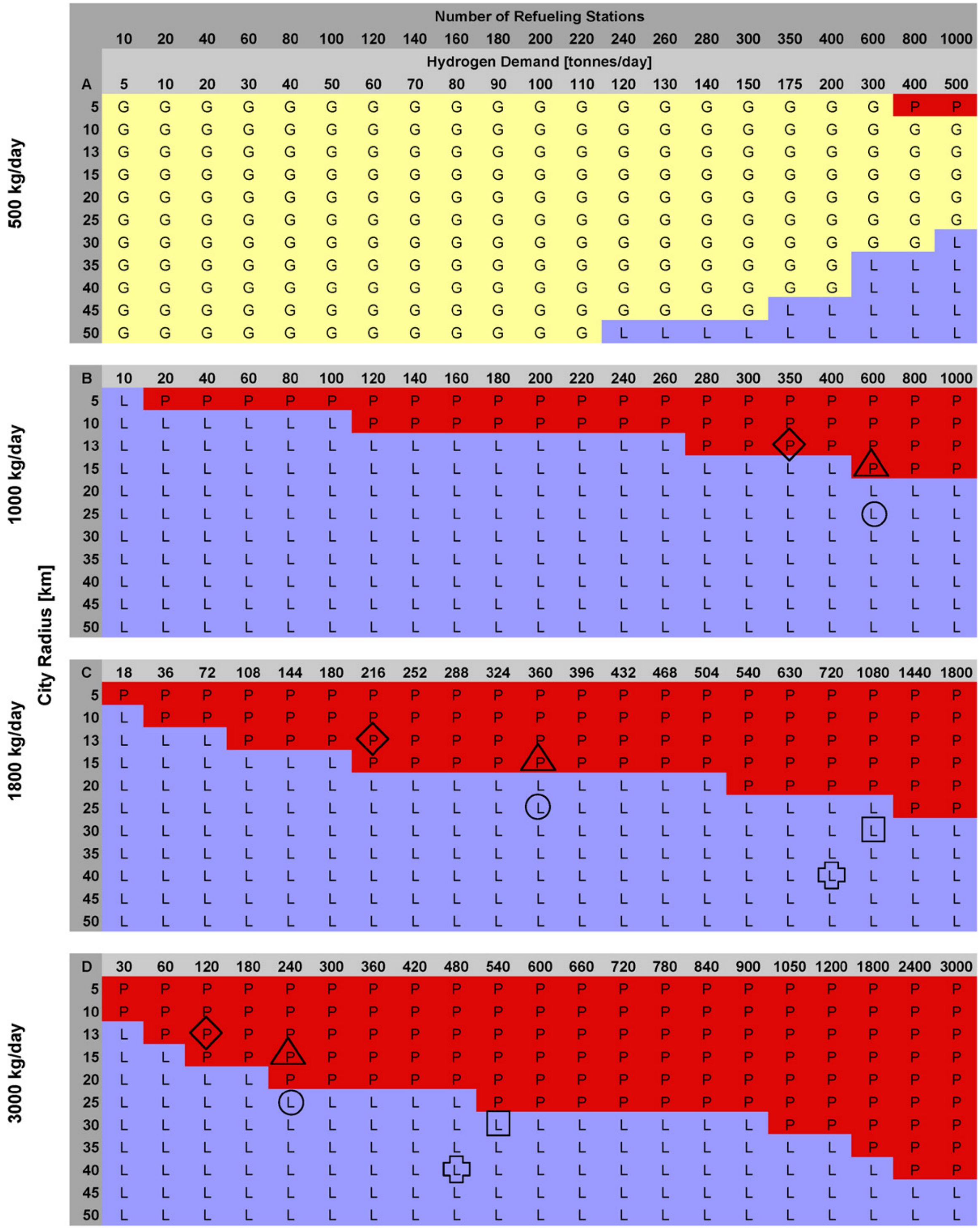
Fig. 12, it is clear that as the size of refueling stations increase, costs are reduced (which is also shown in Fig. 2).

Fig. 13 shows maps of the optimal mode for different refueling stations sizes (500, 1000, 1800, and 3000 kg/day) as a function of city radius and number of refueling stations. As station size increases, from 1000 to 3000 kg/day, pipeline delivery becomes more favorable compared to liquid delivery trucks. Also included in the figure are several representative cities at 100% market penetration of fuel cell vehicles. The number of refueling stations is estimated based upon the station size, and combined with the equivalent city radii, these cities are plotted on the figure and the optimal mode can be predicted.

Fig. 14 shows maps of the optimal mode and costs as a function of city population (from 0.1 to 10 million), population density, and market penetration of hydrogen (10, 25, 50 and 100%). This is a different set of parameters than in Fig. 13, which focused on city radius and number of refueling stations. Given a city of a certain population and population density and assuming a fixed station size, it is possible to see what modes make sense at various market penetrations of fuel cell vehicles. In general, the cities with lower populations and population density, small refueling station sizes and low market penetration will tend to favor compressed gas trucks. Liquid hydrogen trucks are favored in cities with larger populations, lower population density, and smaller refueling stations. Pipelines make sense in cities with high density, high market penetration, and large refueling stations. It is apparent, at least when considering only the cost perspective, that pipelines are not the most appropriate delivery mode for all cities, even at 100% market penetration (i.e. low density cities such as Atlanta, Washington DC and Cincinnati shown in Fig. 13).

Fig. 15 displays the sensitivity of the compressed gas delivery costs to changes in a number of parameters, including changes in energy prices (electricity and diesel fuel), and storage parameters (number of tube trailers, cost of storage and capacity of the truck). The sensitivity analysis includes the following: the electricity price increases from $0.05 to $0.075/kWh, the diesel fuel price increases from $2 to $3/gallon, the tube trailer requirements increase from one per station to two, the cost of storage (on the truck, at the central plant and station) is cut in half from $400/kg to $200/kg, and the tube trailer operating pressure is doubled (from 160 to 320 atm) while keeping tube trailer price constant. The cost of delivery for the base case is linearly dependent upon the city radius. Altering parameters such as the number of tube trailers, the cost of electricity and the cost of storage lead to changes in capital cost so that the delivery costs are shifted up or down (parallel to the base case), while parameters such as the cost of diesel fuel and the capacity of the truck can change the marginal cost per kg per mile (i.e. the slope). The largest impact on the delivery cost occurs when switching to higher-pressure tube trailers (i.e. double capacity at the same cost) because it reduces the number of truck trips, thereby lowering capital costs and reducing the amount of fuel required. These trucks are being developed and certified for H_2 delivery in the US and throughout the world.

In Fig. 16, liquid hydrogen delivery costs are examined as a function of market penetration for a specific city. The effect of an increase in fuel price is significantly lower (<$0.01/kg) than for compressed gas trucks since liquid trucks can carry more hydrogen and require significantly less driving overall. The reduction in liquid storage costs (tank trailer and storage at the central plant and refueling station) also has a very small impact on the overall delivery cost. The costs are most sensitive to a 50% increase in cost of electricity (from $0.05 to $0.075/kWh) because liquefaction electricity is a large component of the overall price (see Fig. 10).



500 kg/day

	Number of Refueling Stations																			
	10	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	350	400	600	800	1000
	Hydrogen Demand [tonnes/day]																				
A	5	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	175	200	300	400	500
5	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	P	P
10	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
13	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
15	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
20	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
25	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
30	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	L
35	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	L	L	L
40	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	L	L	L
45	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L
50	G	G	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L

1000 kg/day

B	10	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	350	400	600	800	1000
5	L	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
10	L	L	L	L	L	L	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
13	L	L	L	L	L	L	L	L	L	L	L	L	L	L	P	P	◇P	P	P	P	P
15	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	△P	P	P
20	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
25	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	○L	L	L
30	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
35	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
40	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
45	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
50	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

1800 kg/day

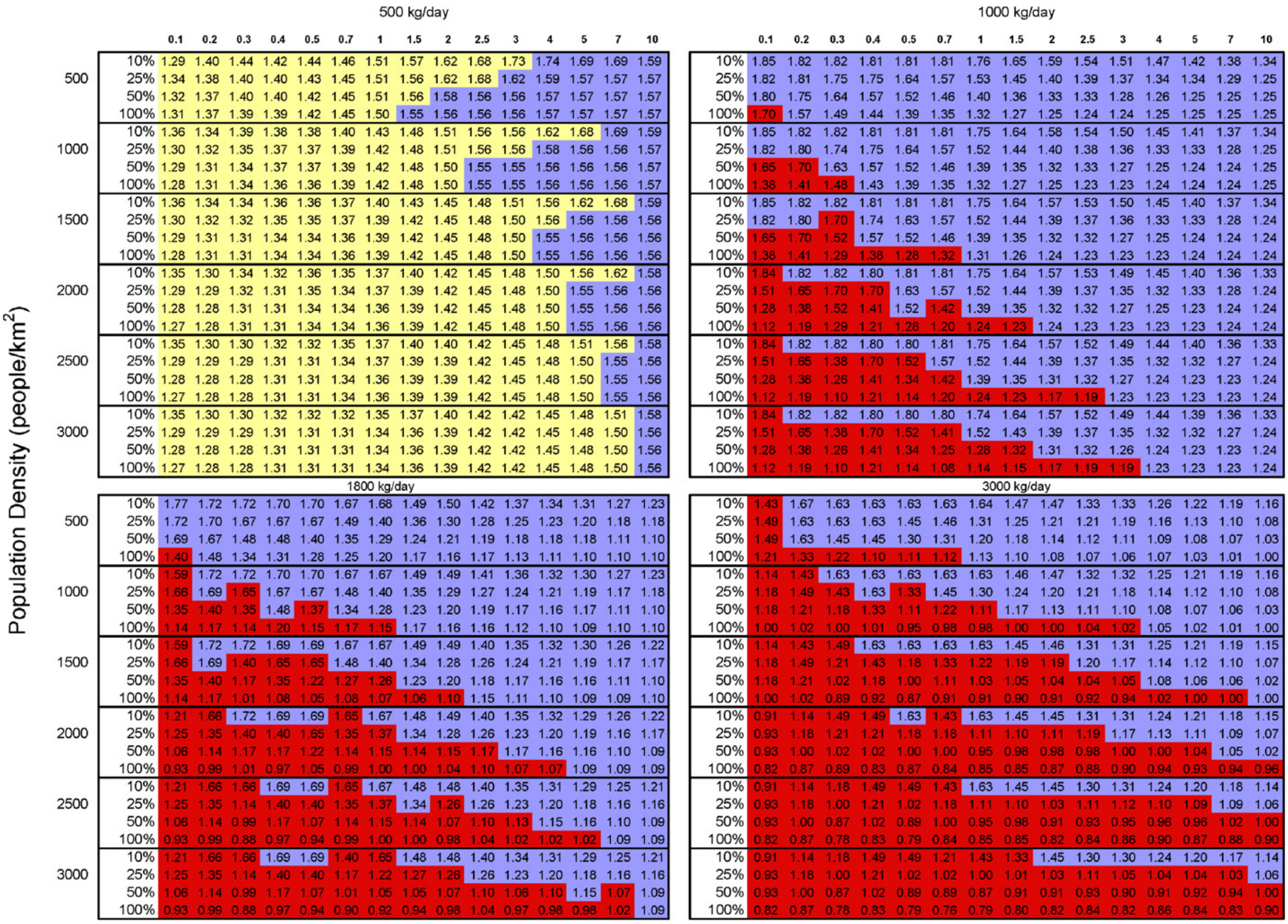
C	18	36	72	108	144	180	216	252	288	324	360	396	432	468	504	540	630	720	1080	1440	1800
5	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
10	L	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
13	L	L	L	P	P	P	◇P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
15	L	L	L	L	L	L	P	P	P	P	△P	P	P	P	P	P	P	P	P	P	P
20	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	P	P	P	P	P	P
25	L	L	L	L	L	L	L	L	L	L	○L	L	L	L	L	L	L	L	L	P	P
30	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	□L	L	L
35	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
40	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	✚L	L	L	L
45	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
50	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

3000 kg/day

D	30	60	120	180	240	300	360	420	480	540	600	660	720	780	840	900	1050	1200	1800	2400	3000
5	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
10	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
13	L	P	◇P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
15	L	L	P	P	△P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
20	L	L	L	L	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
25	L	L	L	L	○L	L	L	L	L	P	P	P	P	P	P	P	P	P	P	P	P
30	L	L	L	L	L	L	L	L	L	□L	L	L	L	L	L	L	P	P	P	P	P
35	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	P	P	P
40	L	L	L	L	L	L	L	L	✚L	L	L	L	L	L	L	L	L	L	L	P	P
45	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
50	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

Fig. 13. Lowest-cost distribution mode for cities with specified city radius (y-axis) and number of stations (x-axis) for different station sizes. (A) 500 kg/day, (B) 1000 kg/day, (C) 1800 kg/day, (D) 3000 kg/day, (G) compressed gas trucks, (L) liquid trucks, and (P) pipelines, (□) Washington DC, (○) Cincinnati, OH, (◇) Salt Lake City, UT, (△) San Jose, CA, (✚) Atlanta, GA.

Fig. 17 shows the sensitivity of pipeline distribution costs for a city of 2.8 million people and a radius of 30 km for a range of market penetration levels to factors including different sized stations from 500 to 3000 kg/day and electricity and storage costs. In all cases, as the market penetration increases, the cost of pipeline delivered hydrogen decreases, mainly due to economies of scale for the pipeline network. Smaller station sizes (500 and 1000 kg/day) require more stations to meet the same market penetration and more pipelines for hydrogen distribution to those stations and, as a result, have higher delivery costs. Larger stations (3000 kg/day) reduce the amount of pipeline needed but fewer stations may impact station



500 kg/day

		0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5	3	4	5	7	10
500	10%	1.29	1.40	1.44	1.42	1.44	1.46	1.51	1.57	1.62	1.68	1.73	1.74	1.69	1.69	1.59
	25%	1.34	1.38	1.40	1.40	1.43	1.45	1.51	1.56	1.62	1.68	1.62	1.59	1.57	1.57	1.57
	50%	1.32	1.37	1.40	1.40	1.42	1.45	1.51	1.56	1.58	1.56	1.56	1.57	1.57	1.57	1.57
	100%	1.31	1.37	1.39	1.39	1.42	1.45	1.50	1.55	1.56	1.56	1.56	1.57	1.57	1.57	1.57
1000	10%	1.36	1.34	1.39	1.38	1.38	1.40	1.43	1.48	1.51	1.56	1.56	1.62	1.68	1.69	1.59
	25%	1.30	1.32	1.35	1.37	1.37	1.39	1.42	1.48	1.51	1.56	1.56	1.58	1.56	1.56	1.57
	50%	1.29	1.31	1.34	1.37	1.37	1.39	1.42	1.48	1.50	1.55	1.55	1.56	1.56	1.56	1.57
	100%	1.28	1.31	1.34	1.36	1.36	1.39	1.42	1.48	1.50	1.55	1.55	1.56	1.56	1.56	1.57
1500	10%	1.36	1.34	1.34	1.36	1.36	1.37	1.40	1.43	1.45	1.48	1.51	1.56	1.62	1.68	1.59
	25%	1.30	1.32	1.32	1.35	1.35	1.37	1.39	1.42	1.45	1.48	1.50	1.56	1.56	1.56	1.56
	50%	1.29	1.31	1.31	1.34	1.34	1.36	1.39	1.42	1.45	1.48	1.50	1.55	1.56	1.56	1.56
	100%	1.28	1.31	1.31	1.34	1.34	1.36	1.39	1.42	1.45	1.48	1.50	1.55	1.56	1.56	1.56
2000	10%	1.35	1.30	1.34	1.32	1.36	1.35	1.37	1.40	1.42	1.45	1.48	1.50	1.56	1.62	1.58
	25%	1.29	1.29	1.32	1.31	1.35	1.34	1.37	1.39	1.42	1.45	1.48	1.50	1.55	1.56	1.56
	50%	1.28	1.28	1.31	1.31	1.34	1.34	1.36	1.39	1.42	1.45	1.48	1.50	1.55	1.56	1.56
	100%	1.27	1.28	1.31	1.31	1.34	1.34	1.36	1.39	1.42	1.45	1.48	1.50	1.55	1.56	1.56
2500	10%	1.35	1.30	1.30	1.32	1.32	1.35	1.37	1.40	1.40	1.42	1.45	1.48	1.51	1.56	1.58
	25%	1.29	1.29	1.29	1.31	1.31	1.34	1.37	1.39	1.39	1.42	1.45	1.48	1.50	1.55	1.56
	50%	1.28	1.28	1.28	1.31	1.31	1.34	1.36	1.39	1.39	1.42	1.45	1.48	1.50	1.55	1.56
	100%	1.27	1.28	1.28	1.31	1.31	1.34	1.36	1.39	1.39	1.42	1.45	1.48	1.50	1.55	1.56
3000	10%	1.35	1.30	1.30	1.32	1.32	1.32	1.35	1.37	1.40	1.42	1.42	1.45	1.48	1.51	1.58
	25%	1.29	1.29	1.29	1.31	1.31	1.31	1.34	1.36	1.39	1.42	1.42	1.45	1.48	1.50	1.56
	50%	1.28	1.28	1.28	1.31	1.31	1.31	1.34	1.36	1.39	1.42	1.42	1.45	1.48	1.50	1.56
	100%	1.27	1.28	1.28	1.31	1.31	1.31	1.34	1.36	1.39	1.42	1.42	1.45	1.48	1.50	1.56

1000 kg/day

		0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5	3	4	5	7	10
500	10%	1.85	1.82	1.82	1.81	1.81	1.81	1.76	1.65	1.59	1.54	1.51	1.47	1.42	1.38	1.34
	25%	1.82	1.81	1.75	1.75	1.64	1.57	1.53	1.45	1.40	1.39	1.37	1.34	1.34	1.29	1.25
	50%	1.80	1.75	1.64	1.57	1.52	1.46	1.40	1.36	1.33	1.33	1.28	1.26	1.25	1.25	1.25
	100%	1.70	1.57	1.49	1.44	1.39	1.35	1.32	1.27	1.25	1.24	1.24	1.25	1.25	1.25	1.25
1000	10%	1.85	1.82	1.82	1.81	1.81	1.81	1.75	1.64	1.58	1.54	1.50	1.45	1.41	1.37	1.34
	25%	1.82	1.80	1.74	1.75	1.64	1.57	1.52	1.44	1.40	1.38	1.36	1.33	1.33	1.28	1.25
	50%	1.65	1.70	1.63	1.57	1.52	1.46	1.39	1.35	1.32	1.33	1.27	1.25	1.24	1.24	1.25
	100%	1.38	1.41	1.48	1.43	1.39	1.35	1.32	1.27	1.25	1.23	1.23	1.24	1.24	1.24	1.25
1500	10%	1.85	1.82	1.82	1.81	1.81	1.81	1.75	1.64	1.57	1.53	1.50	1.45	1.40	1.37	1.34
	25%	1.82	1.80	1.70	1.74	1.63	1.57	1.52	1.44	1.39	1.37	1.36	1.33	1.33	1.28	1.24
	50%	1.65	1.70	1.52	1.57	1.52	1.46	1.39	1.35	1.32	1.32	1.27	1.25	1.24	1.24	1.24
	100%	1.38	1.41	1.29	1.38	1.28	1.32	1.31	1.26	1.24	1.23	1.23	1.23	1.24	1.24	1.24
2000	10%	1.84	1.82	1.82	1.80	1.81	1.81	1.75	1.64	1.57	1.53	1.49	1.45	1.40	1.36	1.33
	25%	1.51	1.65	1.70	1.70	1.63	1.57	1.52	1.44	1.39	1.37	1.35	1.32	1.33	1.28	1.24
	50%	1.28	1.38	1.52	1.41	1.52	1.42	1.39	1.35	1.32	1.32	1.27	1.25	1.23	1.24	1.24
	100%	1.12	1.19	1.29	1.21	1.28	1.20	1.24	1.23	1.24	1.23	1.23	1.23	1.23	1.24	1.24
2500	10%	1.84	1.82	1.82	1.80	1.80	1.81	1.75	1.64	1.57	1.52	1.49	1.44	1.40	1.36	1.33
	25%	1.51	1.65	1.38	1.70	1.52	1.57	1.52	1.44	1.39	1.37	1.35	1.32	1.32	1.27	1.24
	50%	1.28	1.38	1.26	1.41	1.34	1.42	1.39	1.35	1.31	1.32	1.27	1.24	1.23	1.23	1.24
	100%	1.12	1.19	1.10	1.21	1.14	1.20	1.24	1.23	1.17	1.19	1.23	1.23	1.23	1.23	1.24
3000	10%	1.84	1.82	1.82	1.80	1.80	1.80	1.74	1.64	1.57	1.52	1.49	1.44	1.39	1.36	1.33
	25%	1.51	1.65	1.38	1.70	1.52	1.41	1.52	1.43	1.39	1.37	1.35	1.32	1.32	1.27	1.24
	50%	1.28	1.38	1.26	1.41	1.34	1.25	1.28	1.32	1.31	1.32	1.26	1.24	1.23	1.23	1.24
	100%	1.12	1.19	1.10	1.21	1.14	1.08	1.14	1.15	1.17	1.19	1.19	1.23	1.23	1.23	1.24

1800 kg/day

		0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5	3	4	5	7	10
500	10%	1.77	1.72	1.72	1.70	1.70	1.67	1.68	1.49	1.50	1.42	1.37	1.34	1.31	1.27	1.23
	25%	1.72	1.70	1.67	1.67	1.67	1.49	1.40	1.36	1.30	1.28	1.25	1.23	1.20	1.18	1.18
	50%	1.69	1.67	1.48	1.48	1.40	1.35	1.29	1.24	1.21	1.19	1.18	1.18	1.18	1.11	1.10
	100%	1.40	1.48	1.34	1.31	1.28	1.25	1.20	1.17	1.16	1.17	1.13	1.11	1.10	1.10	1.10
1000	10%	1.59	1.72	1.72	1.70	1.70	1.67	1.67	1.49	1.49	1.41	1.36	1.32	1.30	1.27	1.23
	25%	1.66	1.69	1.65	1.67	1.67	1.48	1.40	1.35	1.29	1.27	1.24	1.21	1.19	1.17	1.18
	50%	1.35	1.40	1.35	1.48	1.37	1.34	1.28	1.23	1.20	1.19	1.17	1.16	1.17	1.11	1.10
	100%	1.14	1.17	1.14	1.20	1.15	1.17	1.15	1.17	1.16	1.16	1.12	1.10	1.09	1.10	1.10
1500	10%	1.59	1.72	1.72	1.69	1.69	1.67	1.67	1.49	1.49	1.40	1.35	1.32	1.30	1.26	1.22
	25%	1.66	1.69	1.40	1.65	1.65	1.48	1.40	1.34	1.28	1.26	1.24	1.21	1.19	1.17	1.17
	50%	1.35	1.40	1.17	1.35	1.22	1.27	1.26	1.23	1.20	1.18	1.17	1.16	1.16	1.11	1.10
	100%	1.14	1.17	1.01	1.08	1.05	1.08	1.07	1.06	1.10	1.15	1.11	1.10	1.09	1.09	1.10
2000	10%	1.21	1.66	1.72	1.69	1.69	1.65	1.67	1.48	1.49	1.40	1.35	1.32	1.29	1.26	1.22
	25%	1.25	1.35	1.40	1.40	1.65	1.35	1.37	1.34	1.28	1.26	1.23	1.20	1.19	1.16	1.17
	50%	1.06	1.14	1.17	1.17	1.22	1.14	1.15	1.14	1.15	1.17	1.17	1.16	1.16	1.10	1.09
	100%	0.93	0.99	1.01	0.97	1.05	0.99	1.00	1.00	1.04	1.10	1.07	1.07	1.09	1.09	1.09
2500	10%	1.21	1.66	1.66	1.69	1.69	1.65	1.67	1.48	1.48	1.40	1.35	1.31	1.29	1.25	1.21
	25%	1.25	1.35	1.14	1.40	1.40	1.35	1.37	1.34	1.26	1.26	1.23	1.20	1.18	1.16	1.16
	50%	1.06	1.14	0.99	1.17	1.07	1.14	1.15	1.14	1.07	1.10	1.13	1.15	1.16	1.10	1.09
	100%	0.93	0.99	0.88	0.97	0.94	0.99	1.00	1.00	0.98	1.04	1.02	1.02	1.02	1.09	1.09
3000	10%	1.21	1.66	1.66	1.69	1.69	1.40	1.65	1.48	1.48	1.40	1.34	1.31	1.29	1.25	1.21
	25%	1.25	1.35	1.14	1.40	1.40	1.17	1.22	1.27	1.26	1.26	1.23	1.20	1.18	1.16	1.16
	50%	1.06	1.14	0.99	1.17	1.07	1.01	1.05	1.05	1.07	1.10	1.06	1.10	1.15	1.07	1.09
	100%	0.93	0.99	0.88	0.97	0.94	0.90	0.92	0.94	0.98	1.04	0.97	0.98	0.98	1.02	1.09

3000 kg/day

		0.1	0.2	0.3	0.4	0.5	0.7	1	1.5	2	2.5	3	4	5	7	10
500	10%	1.43	1.67	1.63	1.63	1.63	1.63	1.64	1.47	1.47	1.33	1.33	1.26	1.22	1.19	1.16
	25%	1.49	1.63	1.63	1.63	1.45	1.46	1.31	1.25	1.21	1.21	1.19	1.16	1.13	1.10	1.08
	50%	1.49	1.63	1.45	1.45	1.30	1.31	1.20	1.18	1.14	1.12	1.11	1.09	1.08	1.07	1.03
	100%	1.21	1.33	1.22	1.10	1.11	1.12	1.13	1.10	1.08	1.07	1.06	1.07	1.03	1.01	1.00
1000	10%	1.14	1.43	1.63	1.63	1.63	1.63	1.63	1.46	1.47	1.32	1.32	1.25	1.21	1.19	1.16
	25%	1.18	1.49	1.43	1.63	1.33	1.45	1.30	1.24	1.20	1.21	1.18	1.14	1.12	1.10	1.08
	50%	1.18	1.21	1.18	1.33	1.11	1.22	1.11	1.17	1.13	1.11	1.10	1.08	1.07	1.06	1.03
	100%	1.00	1.02	1.00	1.01	0.95	0.98	0.98	1.00	1.00	1.04	1.02	1.05	1.02	1.01	1.00
1500	10%	1.14	1.43	1.49	1.63	1.63	1.63	1.63	1.45	1.46	1.31	1.31	1.25	1.21	1.19	1.15
	25%	1.18	1.49	1.21	1.43	1.18	1.33	1.22	1.19	1.19	1.20	1.17	1.14	1.12	1.10	1.07
	50%	1.18	1.21	1.02	1.18	1.00	1.11	1.03	1.05	1.04	1.04	1.05	1.08	1.06	1.06	1.02
	100%	1.00	1.02	0.89	0.92	0.87	0.91	0.91	0.90	0.91	0.92	0.94	1.02	1.00	1.00	1.00
2000	10%	0.91	1.14	1.49	1.49	1.63	1.43	1.63	1.45	1.45	1.31	1.31	1.24	1.21	1.18	1.15
	25%	0.93	1.18	1.21	1.21	1.18	1.18	1.11	1.10	1.11	1.19	1.17	1.13	1.11	1.09	1.07
	50%	0.93	1.00	1.02	1.02	1.00	1.00	0.95	0.98	0.98	0.98	1.00	1.00	1.04	1.05	1.02
	100%	0.82	0.87	0.89	0.83	0.87	0.84	0.85	0.85	0.87	0.88	0.90	0.94	0.93	0.94	0.96
2500	10%	0.91	1.14	1.18	1.49	1.49	1.43	1.63	1.45	1.45	1.30	1.31	1.24	1.20	1.18	1.14
	25%	0.93	1.18	1.00	1.21	1.02	1.18	1.11	1.10	1.03	1.11	1.12	1.10	1.09	1.09	1.06
	50%	0.93	1.00	0.87	1.02	0.89	1.00	0.95	0.98	0.91	0.93	0.95	0.96	0.96	1.02	1.00
	100%	0.82	0.87	0.78	0.83	0.79	0.84	0.85	0.85	0.82	0.84	0.86	0.90	0.87	0.88	0.90
3000	10%	0.91	1.14	1.18	1.49	1.49	1.21	1.43	1.33	1.45	1.30	1.30	1.24	1.20	1.17	1.14
	25%	0.93	1.18	1.00	1.21	1.02	1.02	1.00	1.01	1.03	1.11	1.05	1.04	1.04	1.03	1.06
	50%	0.93	1.00	0.87	1.02	0.89	0.89	0.87	0.91	0.91	0.93	0.90	0.91	0.92	0.94	1.00
	100%	0.82	0.87	0.78	0.83	0.79	0.76	0.79	0.80	0.82	0.84	0.82	0.86	0.84	0.83	0.90

Fig. 14. Optimal distribution mode and cost ($/kg) maps for cities with different populations (0.1 to 10 million), population densities (500–3000 people/km^2) and station sizes (500–3000 kg/day) as a function of market penetration (10%, 25%, 50% and 100% penetration of H_2 fuel cell vehicles).

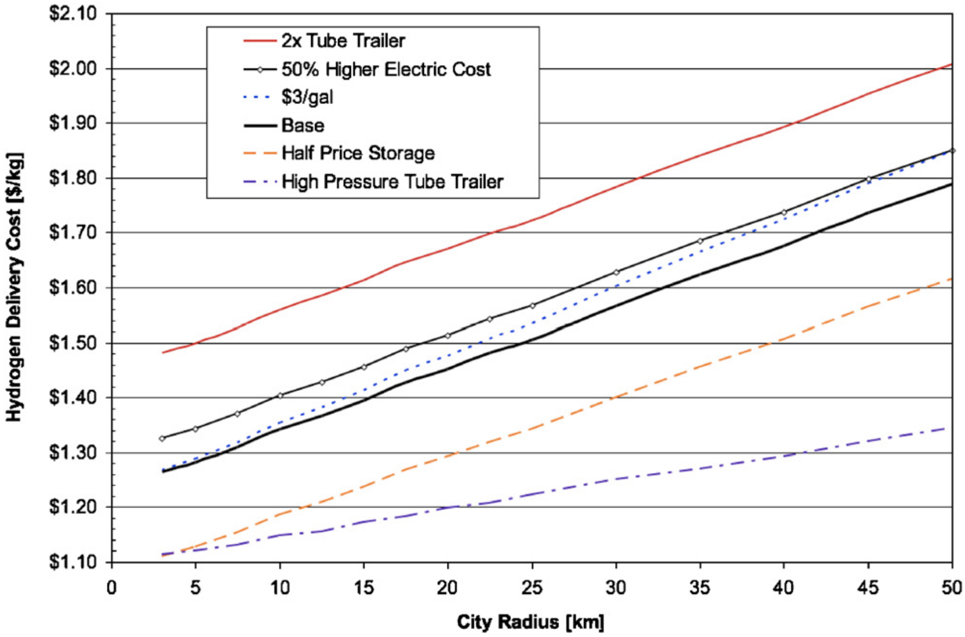


Fig. 15. Sensitivity of compressed gas truck hydrogen delivery cost as a function of the city radius for a small station size of 500 kg/day.

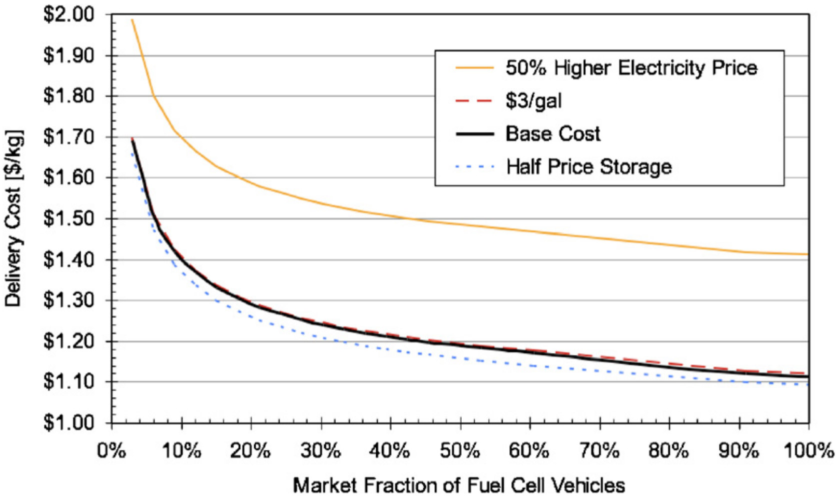


Fig. 16. Sensitivity of liquid hydrogen distribution cost as a function of market penetration for a city with 2.8 million people, a city radius of 30 km, and average station size of 1800 kg/day.

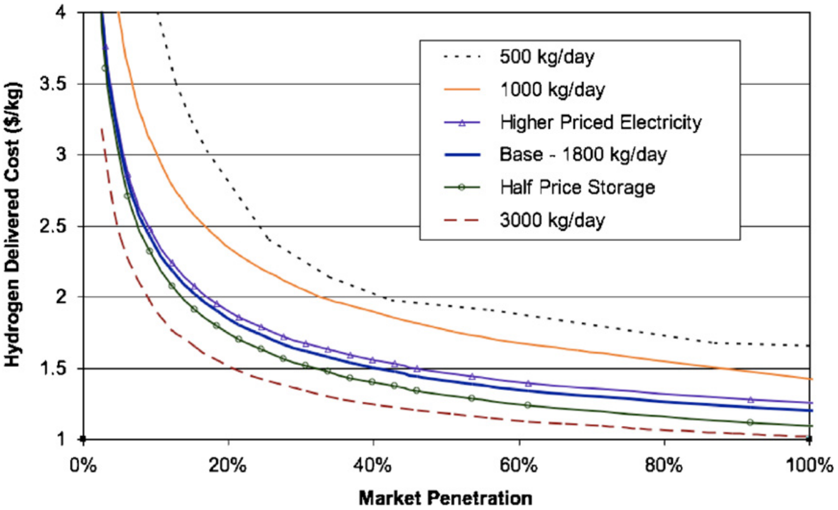


Fig. 17. Sensitivity of pipeline hydrogen distribution cost as a function of market penetration for a city with 2.8 million people and a city radius of 30 km as a function of city radius for a city with a hydrogen demand of 300 tonne/day. The sensitivity of delivered cost to electricity or storage costs is based upon a station size of 1800 kg/day.

convenience for consumers. The sensitivity to the price of H_2 storage and input electricity is based upon a station size of 1800 kg/day. Cutting the price of hydrogen storage in half lowers delivery costs by about $0.10/kg while higher electricity costs ($0.075 vs $0.05/kWh) raise delivery costs slightly (∼ $0.05/kg). The pipeline capital cost and the number and cost of refueling stations are the largest factors determining the delivered cost of stations, which is why changing the size of stations has the largest impact on cost.

5. Conclusions

Hydrogen delivery is a critical component of any hydrogen pathway that relies on hydrogen production at a large-scale central plant. Understanding the factors that contribute to delivery cost, emissions and energy use is an important step in any analysis of the economic and environmental effects of various hydrogen pathways. We have developed simplified models for the design, economics, energy use and emissions of hydrogen delivery systems serving specified types of demands. This allows us to readily estimate and compare costs for various delivery modes, for specified geographic conditions and market fractions of hydrogen vehicles, and choose the most appropriate delivery mode.

5.1. Transmission results

Hydrogen transmission (point-to-point delivery) is characterized by hydrogen flow rate and transport distance. Cost models for three delivery modes, compressed hydrogen gas trucks, liquid hydrogen trucks, and hydrogen pipelines, were developed and applied over a range of flow rates and transport distances. These costs were compared to determine the transport mode that leads to the lowest cost.

- The lowest-cost mode varies with distance and the amount of hydrogen delivered.
- For short distances and small amounts, gas trucks are preferred. The main cost factors in compressed gas truck delivery are capital costs for trucks and trailers, O&M (including labor costs), and fuel costs. Gas trucks have low capital investment for small H_2 quantities, but do not benefit from economies of scale as hydrogen flow increases. The costs also scale linearly with delivery distance.
- For medium amounts of hydrogen and long distances, LH_2 truck delivery is preferred. The largest cost factors are liquefaction equipment capital and electricity for liquefaction. There are significant scale economies associated with liquefaction so that there are significant cost reductions at high flows. Truck capital costs and operating costs such as fuel and labor are a relatively small cost, so that long distances transmission does not increase costs much. Liquefaction requires a very large primary energy input, and the cost is very sensitive to the cost of electricity and energy input and CO_2 emissions will depend upon the electricity generation grid mix.
- For large amounts of hydrogen, pipeline transmission is preferred. The pipeline capital cost is the largest single factor. Pipeline costs scale strongly with both distance and flow rate.

5.2. Distribution results

The distribution of hydrogen (point-to-network delivery) is more complicated than transmission. Specifying the layout of the hydrogen refueling station network and quantifying distribution system design and costs were accomplished with an ICM. The ICM distinguishes between truck and pipeline delivery and allows for a quick estimate of distribution network distances for cities based upon city radius and numbers of refueling stations. Once the refueling station network and distribution system are designed and distances determined, we use engineering economic models to estimate the cost, energy use and emissions. The costs depend strongly on hydrogen demand parameters such as hydrogen flow rate, city radius, population, hydrogen market penetration, population density, and station size, which can be estimated by examining the characteristics of real cities.

- The layout and cost of the distribution system depends on the city population, the city radius (or equivalently the population density), the market fraction of hydrogen vehicles and the station size.
- Compressed gas truck delivery is favored for very small station sizes of 500 kg/d or less.
- Liquid hydrogen truck delivery is preferred at smaller station sizes, low market penetration rates, and low population densities.
- Pipeline distribution can yield the lowest delivery costs for dense cities with a large population, high penetration of hydrogen vehicles, and large refueling stations. Pipelines are expected to become the least-cost delivery system in most cities, as market penetration of H_2 vehicles reaches 100%.
- Changing assumptions about electricity prices, storage costs or system design can lead to large changes in delivered cost and affect the optimal distribution mode for a given set of conditions.

5.3. Future work

Delivery of hydrogen is only one part of the hydrogen pathway. This analysis is currently being extended to include centralized hydrogen production options (such as coal gasification, natural gas reforming, biomass and other renewables) and onsite generation (distributed electrolysis from various electricity sources (e.g. renewable and grid) and natural gas reforming). This will permit the comparison of the best overall pathways under different conditions, including a variety of cities and market penetrations. Additionally, we are interested in validating the ICM against real cities. Future analyses will focus on comparisons between the layout of stations and distribution systems for real cities and for the ICM in order to improve upon the ICM and determine under which circumstances it may be most appropriately applied.

5.4. Overall conclusions

The major results from this work reinforce the idea that issues of scale and geography are critical parameters for the costs of developing hydrogen infrastructure systems. This analysis centers upon hydrogen delivery as it relates to the amounts and distances of hydrogen distribution—large demands that occur at high density are the most economical—but the same trend is also true of scale economies associated with production systems; economical hydrogen production will tend to be associated with large facilities (e.g. steam reformers, gasification plants, and electrolyzers). These trends inform our understanding of how a hydrogen economy might develop. A wide range of refueling stations exists today, but because of the large cost differences shown by the model, smaller H_2 stations may not be built in favor of fewer larger stations, especially when pipeline delivery is the major mode of distribution. Liquid H_2 may ultimately be the lowest-cost method for many cities of moderate to low density, but the large energy requirements and CO_2 emissions associated with this transport mode may prevent widespread use. The robust results from this analysis show that low-cost hydrogen systems are found in high-density urban areas, which reinforces the strategy of an initial staged or regionalized infrastructure rollout in large, dense urban areas such as Los Angeles or the San Francisco Bay Area. These sensitivities of the infrastructure and fuel costs to important parameters such as scale and geography are key results for policy-makers and industry and inform us as to how a low-cost and efficient fueling infrastructure should be built up during a transition to a hydrogen economy in the coming decades.

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