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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 $H_2$A 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 |
| $\beta$ | pipeline cost constant |
| $\gamma$ | 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.