INFRASTRUCTURE FOR HYDROGEN FUEL CELL VEHICLES: A SOUTHERN CALIFORNIA CASE STUDY

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INTRODUCTION

Motivated by concerns about urban air quality, California and several other states have enacted requirements for introduction of zero emission vehicles. Because of their potential for long range, fast refueling time and low cost in mass production, fuel cell vehicles are among the leading contenders in emerging markets for zero emission vehicles (ZEVs).

All fuel cells currently being developed for near term use in road vehicles require hydrogen as a fuel. While hydrogen can be produced onboard the vehicle by reforming methanol or gasoline, direct storage of compressed gaseous hydrogen has many attractive features. The vehicle is simpler in design, less costly and more energy efficient, refueling can be accomplished rapidly, and hydrogen can be produced from many sources. Several experimental fuel cell vehicles such as the Ballard bus and the Daimler-Benz mini-van employ compressed hydrogen gas storage. Although the energy density of compressed hydrogen gas is lower than liquid fuels, it is higher than that of electric batteries (Arthur D. Little 1994). With high efficiency fuel cell vehicles and advanced pressure cylinders, a travelling range of at least 400 km should be possible for a fuel cell automobile (Delucchi 1992, Steinbugler and Ogden 1996).

The relative simplicity of vehicle design for the hydrogen fuel cell vehicle must be weighed against the added complexity and cost of developing a hydrogen refueling infrastructure. Indeed, hydrogen infrastructure is often seen as a "show-stopper" for hydrogen vehicles.

In this paper, we examine the technical feasibility and economics of developing a hydrogen vehicle refueling infrastructure for a specific area where zero emission vehicles are being considered: Southern California. We assess several near term possibilities for producing and delivering gaseous hydrogen transportation fuel (using commercial or near commercial technologies for hydrogen production, storage and distribution). These include (see Figure 1):

* hydrogen produced from natural gas in a large, centralized steam reforming plant, and truck delivered as a liquid to refueling stations,

* hydrogen produced at the refueling station via small scale steam reforming of natural gas,

* hydrogen produced in a large, centralized steam reforming plant, and delivered via small scale hydrogen gas pipeline to refueling stations,

* hydrogen produced via small scale electrolysis at the refueling station,

* hydrogen from chemical industry sources (e.g. excess capacity in ammonia plants, refineries which have recently upgraded their hydrogen production capacity, etc.).

To compare these alternatives, we address the following questions:

* What are projected hydrogen demands, assuming hydrogen fuel cell vehicles capture some fraction of the ZEV market?

* What are existing and potential hydrogen supplies in the LA Basin?

* How much would it cost to build a hydrogen infrastructure including hydrogen production capacity, hydrogen distribution systems and refueling stations?

*What is the delivered cost of hydrogen transportation fuel for various supply options and levels of demand?

*How does hydrogen compare to other fuels for fuel cell vehicles (methanol, gasoline) in terms of vehicle cost and infrastructure cost.

* How might a hydrogen infrastructure evolve to meet projected demands for hydrogen for ZEVs in Southern California?

* What are the synergisms between near term options and phasing in longer term supplies such as hydrogen from renewables?

ESTIMATED HYDROGEN DEMAND FOR REFUELING HYDROGEN VEHICLES IN SOUTHERN CALIFORNIA

Data were obtained from the South Coast Air Quality Management District for current and projected numbers of automobiles, vehicle miles traveled, and gasoline consumed in each county (Los Angeles, San Bernadino, Orange and Riverside) in the South Coast Air Basin (George, private communications 1995, 1996). By 2010, over 9 million passenger cars are projected for the Los Angeles Basin. (If light trucks are considered, a category which includes the increasingly popular "sport-utility" vehicles, the total projected number of light duty vehicles is close to 11 million.)

From this data, the ZEV population in the LA Basin can be estimated for each year, assuming that 10% of all new cars are ZEVs starting in 2003 (see Figure 2). Even though the mandate has been altered to delay introduction of ZEV cars until 2003, the cumulative number of ZEVs in the LA Basin is still projected to be over 700,000 in 2010.

Many analysts believe that fuel cell cars could be commercialized sometime between 2003 and 2010. The cumulative number of hydrogen fuel cell cars are shown in Figure 2 for commercialization dates of 2003, 2005 and 2007.

The hydrogen demand for an individual PEM fuel cell car or bus is estimated in Table 1. Given the projected number of fuel cell cars (Figure 2) and the hydrogen demand per vehicle (Table 1), the total hydrogen demand can be estimated (Figure 3). For this study we assume an aggressive commercialization scenario, where half the ZEV market is captured by hydrogen fuel cell cars starting in 2003, and 10% of all new buses are fuel cell buses starting in 1998 (the year Ballard has planned to commercialize PEMFC buses). This amounts to about 350,000 fuel cell cars (see Figure 2) and 300 fuel cell buses in the LA area in 2010. For these assumptions, a total hydrogen demand of about 55 million scf/day would develop by 2010 (almost all for cars). This is about as much hydrogen as would be produced at a good sized oil refinery today. [Hydrogen production is commonly given in units of millions of standard cubic feet of hydrogen produced per day (million scf/day). For reference one million scf/day would fuel about 800 PEMFC cars per day (or a total fleet of 6300 cars) or 80 PEMFC buses/day (or a total fleet or 140 buses). (See Table 2.)]

We now consider how the projected hydrogen demand might be met in the near term (1996-2010) from existing hydrogen supplies and potential future supplies in the LA Basin.

EXISTING AND POTENTIAL HYDROGEN SUPPLIES IN THE LOS ANGELES BASIN

Existing supplies of hydrogen

At present, the primary suppliers of hydrogen in Southern California are the industrial gas companies Praxair, Inc. and Air Products and Chemicals, Inc.

Praxair has a hydrogen plant in Ontario, CA which currently produces 15 ton/day of liquid hydrogen (equivalent in energy to about 5.3 million scf/day of gaseous hydrogen.) for users in the aerospace industry and to chemical industries. Although most of the current output of this plant is already committed, there may be a million scf/day or so available today for transportation fuel (Kerr 1995). The output of this plant might be increased to 28 ton/day by restarting a currently idled reformer, producing enough fuel (an extra 13 tons/day) for a fleet of about 30,000 fuel cell cars or about 600 Ballard type PEMFC urban transit buses. There is also room for expansion beyond 28 ton/day , if the market warranted (Kerr 1995). The price of liquid hydrogen in the LA area at demand levels of 0.1-2.0 million scf/day is currently about $1.1-1.5/lb or $17-23/GJ (Lenci 1995). A liquid hydrogen refueling station might add several $/GJ to this cost (Ogden et.al. 1995).

Air Products and Chemicals recently completed a new 80 million scf/day hydrogen plant (based on steam reforming of natural gas) in Wilmington, CA to provide gaseous hydrogen to nearby oil refineries (Moore 1995). The plant may still have some uncommitted capacity, which could be used for vehicle fuel. If 5 million scf/day were available, this could fuel a fleet of about 33,000 fuel cell cars or 700 fuel cell buses. The cost of hydrogen at a large reformer plant might be $7-9/GJ. With gaseous hydrogen, a pipeline distribution system would have to be built (or refueling might be done at the hydrogen plant). The distribution cost would depend on the type of pipeline system needed. A gaseous hydrogen refueling station would add $5/GJ to the delivered cost. We estimate that the cost of pipeline delivered hydrogen transportation fuel could be as low as $14/GJ for a demand near a low cost supply.

In addition, a number of oil refineries are located in the Torrance/Wilmington area. Typically oil refineries produce large amounts of gaseous hydrogen (25-100 million scf/day) using most or all of it onsite. Historically some excess hydrogen has been available, and some refineries have sold a few million scf/day of hydrogen "over the fence" to other refineries or chemical users, delivering the hydrogen by small scale pipeline. To meet 1996 requirements for Phase II reformulated gasoline, significantly more hydrogen is required by refineries. Thus, the refiners expect to be "hydrogen short" in the near future. To meet increased demands for hydrogen, several refineries are now building (or have built) extra reformer capacity or planning to buy hydrogen from the new Air Products plant. It may be possible to purchase a few million scf/day from refineries, especially those with newly expanded reformer capacity. This could be economically attractive, as the cost (at the plant site) would be quite low. If the reformer capital cost is considered to be a "sunk" cost, gaseous hydrogen might be sold for as little as $1/1000 scf ($2.8/GJ). If the reformer capital costs are counted, the price for gaseous hydrogen would be $2.5-3.0/1000 scf ($6.9-8.3/GJ) (Youngman 1995). The delivered cost to the user would depend on how long a pipeline was required, as well as the cost of the refueling station.

Hydrogen from existing sources could be significant in getting hydrogen fuel cell vehicles started. Even without building any new hydrogen production capacity, the total available from all existing sources might be 5-15 million scf/day or enough for 30,000-100,000 fuel cell cars or 700-2000 fuel cell buses. Of course, there would be significant costs to build new distribution systems and refueling stations to bring the "excess hydrogen" available in the LA Basin today to consumers' vehicles.

Other potential near term sources of hydrogen in Southern California

If fuel cell vehicles capture a significant fraction of the ZEV passenger car market, demand would soon outstrip existing sources of hydrogen. (Recall that by 2010, fueling 50% of all ZEVs with hydrogen would require 55 million scf H2/day.) In this case, other near term supplies could be developed.

* If a large market for hydrogen transportation fuel were to develop, industrial gas suppliers indicated that they could build a new, large hydrogen plant based on steam reforming of natural gas in 2-3 years. A plant producing 80 million scf/H2 per day could serve a fleet of 500,000 fuel cell passenger cars. Hydrogen from such a plant could be liquified for truck delivery or delivered via a small scale pipeline system.

* It is also possible to produce hydrogen onsite at the refueling station via small scale steam reforming of natural gas. Recent improvements in small scale reformer technology are making

this option more attractive (Farris 1996, Ogden et.al. 1996). Partial oxidation of methane at the refueling station is another potentially interesting option.

* Ample natural gas resources are available in the Los Angeles area to produce hydrogen transportation fuel in the near term. Fueling a fleet of 350,000 fuel cell cars would require about 55 million scf H2/day. This amount of hydrogen could be produced via steam reforming from about 22 million scf/day of natural gas or less than 1% of the total natural gas flow through Southern California Gas's distribution system. Natural gas is widely available throughout the LA Basin. Based on experience with installing compressed natural gas vehicle refueling stations, the natural gas distribution system would not have to be modified to bring natural gas to refueling stations for onsite hydrogen production (Wayne Tanaka, Southern California Gas, private communications 1995).

* There is a large potential for using off-peak power in Southern California. Southern California Edison estimated that some 4000-6000 MW of off-peak power might available from 6 pm to 10 am. This could be used to power electrolyzers, providing some 440-660 million scf H2/day, enough to fuel a fleet of 3.5 - 5.3 million fuel cell cars. The price of off-peak power would be 4-4.5 cents/kWh for small commercial customers (50-500 kW) (Tom Burhenn, So. California Edison, private communications 1995), and 3 cents/kWh for large customers (>500 kW). Electrolyzers producing 0.1-2.0 million scf H2/day (the size range needed to serve 8-160 buses or 80-1600 cars/day) would be in the 400-8000 kW range, and might take advantage of relatively low off-peak rates.

*It has been estimated that about 1300 kg (0.52 million scf) of hydrogen per day could be produced for about 20 years at a single landfill site in the LA area (Glenn Rambach, LLNL, private communication 1995). This would be enough to refuel about 40 PEMFC buses/day. The economics would be competitive with other sources of hydrogen (Glenn Rambach, LLNL, 1995). The total resource has not been quantified, but this suggests the possibility of fuels production at landfills.

In Figure 3, we compare the projected hydrogen demand for vehicles in the LA Basin from 1998-2010 to the amount of hydrogen which could be supplied from various existing and near term supplies. Hydrogen from existing industrial and refinery sources in the LA area could fuel a fleet of perhaps 30,000-100,000 fuel cell cars or 700-2000 Ballard buses/day. Beyond this level, there is sufficient natural gas to fuel a fleet of 3-6 million FCVs (assuming that 5-10% of the current natural gas flow is used for hydrogen production), and sufficient off-peak power to produce electrolytic hydrogen for 3-5 million FCVs.

BEYOND 2010: A TRANSITION TO RENEWABLE HYDROGEN SUPPLIES

Natural gas supplies would probably be sufficient to supply feedstock for hydrogen production for up to several million PEMFC cars, for several decades. If the entire fleet in the LA area eventually converted to ZEVs, hydrogen for some 12-14 million passenger cars might be required. Renewable and other long term options might be phased in at this time.

These include gasification of municipal solid waste (a potential resource capable of serving several million FCV cars in the LA area) or biomass, or solar (a potentially huge resource, which could meet foreseeable demands, even for a 100% ZEV transportation system). Hydrogen might also be produced from fossil fuels (natural gas or coal) or biomass with sequestering of the byproduct CO_2 in gas fields or aquifers, and piped via large scale, long distance hydrogen pipelines to users (Williams 1996). This might occur after a sufficiently large demand had built up to justify building a long distance, large scale hydrogen pipeline.

ECONOMICS OF HYDROGEN PRODUCTION AND DELIVERY

Delivered cost of hydrogen transportation fuel

We now estimate the delivered cost of hydrogen transportation fuel in Southern California for various options shown in Figure 1. A range of refueling station sizes from 0.1 to 2.0 million scf/day is considered (e.g. stations capable of refueling about 80-1600 fuel cell cars/day or 8-160 fuel cell buses/day).

Energy prices for Southern California are summarized in Table 3 based on data obtained from Southern California Gas Company (Thomas 1996) and Southern California Edison (Burhenn 1996). The delivered cost of hydrogen transportation fuel is then estimated, using data developed in our earlier studies of hydrogen transportation fuel supply options (Ogden et.al. 1995, Ogden, Dennis and Montemayor 1995, Dennis 1994).

The delivered cost of hydrogen transportation fuel for Southern California conditions is shown in Figure 4 for a variety of station sizes and supply options. The cost contributions of various factors are shown for each technology over a range of station sizes. Although all the supply options are roughly competitive, several points are readily apparent.

* Truck delivered liquid hydrogen gives a delivered hydrogen cost of $20-30/GJ, depending on the station size. This alternative would be attractive for the first demonstration projects, as the capital requirements for the refueling station would be relatively small (Ogden et.al. 1995, Ogden et.al. 1996), and no pipeline infrastructure would be required.

* Onsite production of hydrogen via small scale reforming of natural gas is economically attractive and has the advantage that no hydrogen distribution system is required. Delivered hydrogen costs are shown for onsite reforming of natural gas based on: 1) conventional small steam reformer systems and 2) advanced low cost reformers, which have just been introduced for stationary hydrogen production (Farris 1996). With conventional reformer technology, hydrogen is expensive at small station sizes, but is economically attractive at larger station sizes. As discussed in a recent report (Ogden et.al. 1996), adopting lower cost, advanced steam methane reformer designs based on fuel cell reformers could substantially reduce the delivered cost of hydrogen especially at small station size. With advanced reformers, onsite reforming is competitive with liquid hydrogen truck delivery and pipeline delivery over the whole range of station sizes considered.

* Under certain conditions, a local pipeline bringing centrally produced hydrogen to users could offer low delivered costs. Centrally produced hydrogen ranges in cost from $3/GJ (for refinery excess) to $5-9/GJ for large scale steam reforming to $8-10/GJ for hydrogen from biomass, coal or MSW). If the cost of hydrogen production is low, higher pipeline costs could be tolerated. Still, for pipeline hydrogen to be competitive with truck delivery or onsite reforming, pipeline costs can be no more than a few $/GJ. Pipeline costs depend on the pipeline length and flow rate. (The higher the flow and shorter the length, the lower the cost.) For a small scale hydrogen pipeline system to be economically competitive a large, fairly localized demand would be required. Alternatively, a small demand might be served by a nearby, low cost supply of hydrogen.

* For our assumptions, it appears that onsite electrolysis would be somewhat more expensive than other options, largely because of the relatively high cost of off-peak power in the LA area. (If the cost of off-peak power were reduced from 3 cents/kWh to 1-1.5 cents/kWh, hydrogen costs would become much more competitive.)

Capital cost of building a hydrogen refueling infrastructure

The capital cost of building a hydrogen refueling infrastructure is often cited as a serious impediment to use of hydrogen in vehicles. In Figure 5, we show the capital cost of building a hydrogen refueling infrastructure for the various options discussed in the previous section. We consider two levels of infrastructure development.

* Early development of distribution system and refueling stations to bring excess hydrogen from existing hydrogen capacity to users. We assume that no new centralized hydrogen production capacity is needed. Two refueling stations serve a total fleet of 13,000 cars, each station dispensing 1 million scf H2/day to 800 cars/day. The options for providing hydrogen include: 1) Liquid hydrogen delivery via truck from existing capacity, 2) pipeline hydrogen delivery from

a nearby large hydrogen plant or refinery, 3) onsite production from steam reforming of natural gas and 4) onsite production from electrolysis

* Development of new hydrogen production, delivery and rrefueling capacity to meet growing demands for hydrogen transportation fuel. The system serves a total fleet of 1 million cars, each station dispensing 1 million scf H2/day to 800 cars/day. Options for providing hydrogen are: 1) liquid hydrogen delivery via truck from new centralized steam reformer capacity, 2) pipeline hydrogen delivery from a new centralized hydrogen plant, 3) onsite production from steam reforming of natural gas and 4) onsite production from electrolysis.

The range of infrastructure capital costs for a system serving 13,000 fuel cell cars, is about $1.4-11.4 million or $100-900/car. The range of infrastructure capital costs for a system serving 1 million fuel cell cars, is about $400-900 million or $400-900/car.

It is important to keep in mind the results of Figure 4 for the total delivered cost of hydrogen transportation fuel, as well as the capital cost of infrastructure. Some of the lower capital cost options such as liquid hydrogen delivery, can give a higher delivered fuel cost than pipeline delivery or onsite reforming.

Infrastructure costs for fuel cell vehicles: hydrogen compared to methanol and gasoline

It is often stated that use of methanol or gasoline with onboard reformers would greatly reduce (for methanol) or eliminate (for gasoline) the problem of developing a new fuel infrastructure. How does the capital cost of building a hydrogen refueling infrastructure compare to the capital cost of infrastructure development for methanol or gasoline fuel cell vehicles?

Defining "infrastructure" to mean all the equipment (both on and off the vehicle) required to bring hydrogen to the fuel cell, it is clear that gasoline and methanol fuel cell vehicles also entail extra costs -- largely for onboard fuel processing. In the case of hydrogen, the infrastructure development capital cost is paid by the fuel producer (and presumably passed along to the consumer as a higher fuel cost). In the case of methanol or gasoline fuel cell vehicles, the capital cost is paid by the consumer buying the car.

A recent study by Directed Technologies, Inc. concludes that when the total infrastructure cost (on and off the vehicle) is considered, hydrogen infrastructure capital costs are comparable to those for methanol and gasoline (Thomas 1996). Research by Kreutz, Steinbugler and Ogden (1996, 1997) indicates that gasoline POX fuel cell vehicles are likely to cost $500-1000 more than comparable hydrogen fuel cell vehicles supporting the view that the total cost for infrastructure on and off the vehicle would be about the same for hydrogen and gasoline.

DISCUSSION: IS HYDROGEN REFUELING INFRASTRUCTURE A "SHOW-STOPPER" FOR HYDROGEN VEHICLES IN SOUTHERN CALIFORNIA?

Our study suggests several reasons why hydrogen infrastructure development may not be an insurmountable obstacle to introducing hydrogen vehicles in Southern California.

* The technologies to produce, deliver and dispense hydrogen are well known. There appear to be no major technical hurdles to dispensing hydrogen transportation fuel.

* Ample supplies of hydrogen exist in the LA area. It would be possible to introduce significant numbers of fuel cell vehicles, even without building any new hydrogen production capacity. The excess hydrogen capacity available from industrial suppliers and refineries today might fuel 700-2000 PEM fuel cell buses or 30,000-100,000 PEM fuel cell cars.

* Once demand exceeded these levels, hydrogen from steam reforming of natural gas, gasification of MSW, or off-peak power could supply hydrogen for millions of FCVs.

* According to recent estimates by Directed Technologies, Inc. (Thomas 1996), and Princeton CEES (Kreutz et.al. 1996) the capital cost of building a hydrogen refueling infrastructure off the

vehicle appears to be comparable to the added cost of putting individual small hydrogen production systems (fuel processors) onboard each vehicle. Further work is needed to clarify the relative costs and other advantages of alternative fuels for fuel cell vehicles.

POSSIBLE SCENARIOS FOR DEVELOPING A HYDROGEN REFUELING INFRASTRUCTURE IN THE LOS ANGELES BASIN

Introduction of PEMFC buses

There are a number of reasons why PEM fuel cell buses might be the first users of hydrogen as a transportation fuel.

* Ballard will be demonstrating hydrogen fueled PEMFC buses in several cities starting in 1997, with commercialization planned for 1998.

* Refueling with hydrogen or any alternative fuel is easier at centralized fleet locations such as bus garages.

* The daily demand for hydrogen for a bus depot would be large enough to bring the delivered cost of hydrogen down somewhat because of economies of scale, especially for stations based on small scale reformers.

* Fuel cells might be economically competitive first in bus markets, where cost goals are not as stringent as for automobiles.

Existing industrial hydrogen sources would be sufficient to supply several hundred buses. It is interesting to note that all the urban transit bus depots in the LA area are within an hour or so of the Praxair liquid hydrogen plant. Several depots are located in the Long Beach area, possibly within pipeline distance of refineries or the Air Products plant. Alternatively, onsite production of hydrogen from natural gas might be used. A fleet of about 8 PEMFC buses could be refueled daily using a small scale reformer producing 100,000 scf H2/day. Rapid developments in small scale reformer technology are making this an increasingly attractive supply option.

Introduction of PEMFC automobiles in Southern California

Several major automobile manufacturers are conducting R&D on PEM fuel cell cars (including Chrysler, GM, Ford, Daimler-Benz, Mazda, Toyota, and Honda). A PEMFC mini-van using compressed hydrogen gas storage was demonstrated in May 1996 by Daimler-Benz, and it is likely that the first mid-size PEMFC automobiles may be demonstrated before the year 2000. The first mass-produced commercial models might be available a few years later in the 2004-2010 time frame. (Chrysler has announced plans to commercialize a gasoline POX fuel cell vehicle around 2005.]

While most in the fuel cell vehicle community would agree that widespread public use of hydrogen fuel cell cars is the ultimate aim, there is an ongoing debate about the most direct path to this goal. If onboard partial oxidation of gasoline is perfected, this might allow a rapid introduction of fuel cell cars to the general public, with attendant lowering of fuel cell costs in mass production. But onboard POX vehicles appear to have penalties in terms of vehicle cost, efficiency and emissions, which may make hydrogen vehicles an extremely attractive successor or alternative. The first hydrogen fuel cell cars would be likely to appear in centrally refueled fleets. Issues in moving beyond these initial markets may be similar to those for CNG, methanol and other alternative fuels.

If hydrogen PEMFC cars capture a significant fraction of the mandated ZEV market, the demand for hydrogen could grow rapidly, and new hydrogen production capacity and delivery infrastructure would be needed. In near term liquid hydrogen truck delivery or onsite production of hydrogen from natural gas would probably give the lowest delivered transportation fuel costs to the consumer. Because of the high cost of building small scale gaseous pipelines, development of new, large scale, centralized production capacity with pipeline distribution would require a fairly large, localized hydrogen demand. This might not develop until a larger fraction of the automotive population were hydrogen-fueled. (Exceptions might be found, where gaseous distribution was more attractive, e.g.a cluster of fleet cars in an industrial area.) Onsite electrolysis appears less economically attractive than steam reforming in the LA area, because of the relatively high cost of off-peak power (3 cents/kWh). If lower cost electricity supplies were available this alternative would be more competitive.

We recommend that demonstrations of hydrogen refueling systems (especially small scale reformers) be conducted as part of hydrogen vehicle demonstrations (bus and automotive fleets) over the next few years. (In fleet applications hydrogen fuel cell vehicles may be preferred from the beginning for reasons of vehicle simplicity and cost.) As vehicle demonstrations progress, design issues for various types of fuel cell vehicles will be better understood and the path to commercialization should become clearer.

CONCLUSIONS

If hydrogen fuel cell vehicles capture a significant fraction of the mandated zero emission vehicle (ZEV) market, a large demand for hydrogen could develop over the next 15 years. If PEMFC (proton exchange membrane fuel cell) cars accounted for half the mandated ZEV population, there would be about 350,000 fuel cell cars on the road in the Los Angeles Basin by 2010, requiring 55 million scf of hydrogen per day. (This is comparable to the amount of hydrogen produced in a typical oil refinery today.)

We found that a considerable amount of hydrogen, perhaps 5-15 million scf/day, would be available in the LA Basin from existing industrial gas supplies and from refinery excess hydrogen. Fleets of perhaps 30,000 to 100,000 fuel cell cars or 700-2000 PEM fuel cell buses might be fueled without building new hydrogen production capacity. New hydrogen distribution and refueling station capacity would be needed to bring the available hydrogen to consumers.

The delivered cost of hydrogen transportation fuel from existing sources would vary from perhaps $12 to 30/GJ. If hydrogen were trucked as a liquid to a refueling station, then vaporized and dispensed as a compressed gas, the delivered hydrogen cost to the consumer would be $20-30/GJ. Costs for gaseous hydrogen delivered by small pipeline would vary from as little as $12/GJ to more than $30/GJ, depending on the level of demand and the pipeline length. Pipeline delivery might be attractive for users located near an inexpensive hydrogen source (such as refinery excess or the Air Products plant in Wilmington, CA.) Capital costs would be lower for a hydrogen refueling station based on liquid hydrogen delivery than for a station served by pipeline.

Once demand for hydrogen exceeded existing excess hydrogen production capacity (perhaps 5-15 million scf/day), new production capacity would be needed. There are a number of possibilities for producing hydrogen in the LA region. In the near term, these include steam reforming of natural gas at the refueling station and small scale electrolysis of water using off-peak electricity. In the longer term, other hydrogen supplies might be phased such as gasification of municipal solid waste or biomass, or solar.

Natural gas supplies would probably be sufficient to supply feedstock for hydrogen production for up to several million PEMFC cars, for several decades. With conventional steam methane reformer technology, the delivered cost of hydrogen from natural gas would be about $14-40/GJ, depending on the reformer size. (For fuel cell reformers now under development the hydrogen cost might be $12-25/GJ.) The station capital costs would be higher than for liquid hydrogen refueling stations.

For energy prices and conditions in the Los Angeles area, it appears that in the near term, truck delivery of liquid hydrogen and onsite production via small scale steam reforming offer the lowest costs. Moreover, these two options would allow the addition of hydrogen production capacity in small increments, without building a new hydrogen pipeline distribution system. Improvements in small scale reformer technology might make this option even more attractive.

Off-peak power is a significant resource which could provide fuel for 3-4 million fuel cell vehicles. However, hydrogen produced via small scale electrolysis at the refueling station was somewhat more expensive than other options, largely because of the relatively high cost of off-peak power in the LA area.

In the longer term, for large, geographically concentrated demands, pipeline distribution might ultimately yield the lowest delivered fuel cost. (Although improvements in small scale steam reformer technology may make onsite production competitive with centralized hydrogen generation.) Pipeline delivery might also be prefered for a smaller demand very close to an existing low cost source of hydrogen (e.g. refinery excess).

The first hydrogen vehicles in the LA Basin are likely to be PEM fuel cell buses, which could be commercialized as early as 1998. Early bus demonstrations might be fueled from existing sources (trucked in liquid hydrogen, or piped in hydrogen for depots near the LA refinery area). Or they might use small scale fuel cell type reformer systems now being commercialized for stand-alone hydrogen production.

Once fuel cell cars were introduced, hydrogen production from natural gas would offer the lowest costs for the near term. In the longer term, other local supplies might be phased in such as hydrogen from wastes, biomass or solar. Or distant low cost sources of hydrogen might be brought in via long distance pipeline.

An estimate of infrastructure capital costs suggests that the cost per vehicle to develop a hydrogen refueling infrastructure would be perhaps $400-900/vehicle. Considering the cost of infrastructure on and off the vehicle, it appears that hydrogen fuel cell vehicles would be comparable in cost to methanol or gasoline fuel cell vehicles.

RECOMMENDATIONS

Our study suggests a number of interesting possibilities for developing hydrogen refueling infrastructure to serve hydrogen vehicles in Southern California. Demonstrations of hydrogen refueling systems should be undertaken in parallel with fuel cell vehicle demonstrations. RD&D on small scale steam reformers may be of particular interest.

It appears that hydrogen infrastructure development may not be as severe a technical and economic problem as is often stated. Further comparisons of hydrogen as a fuel for fuel cell vehicles (as compared to methanol and gasoline) should be conducted.

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TABLE 0. CONVERSION FACTORS AND ECONOMIC ASSUMPTIONS

1 GJ (Gigajoule) = 10^9 Joules = 0.95 Million BTU
1 EJ (Exajoule) = 10^{18} Joules = 0.95 Quadrillion (10^{15}) BTUs

1 million standard cubic feet (scf) = 28,300 Normal cubic meters (m_N^3) = 362 GJ (HHV)
1 million scf/day = 2.80 tons/day = 4.19 MW H_2 (based on the HHV of hydrogen)

1 scf H_2 = 362 kJ (HHV) = 344 BTU (HHV); 1 lb H_2 = 64.4 MJ (HHV) = 61.4 kBTU (HHV) = 178.5 scf
1 m_N^3 = 12.8 MJ (HHV); 1 kg H_2 =141.9 MJ (HHV) = 393 scf

1 gallon gasoline = 130.8 MJ (HHV); $1/gallon gasoline = $7.67/GJ (HHV)

All costs are given in constant $1993.

Capital recovery factor for hydrogen production systems, distribution systems and refueling stations = 15%

TABLE 1. ASSUMED CHARACTERISTICS OF FUEL CELL VEHICLES

	PEM FC Bus	PEM FC Car
Fuel economy	52 scf H2/mile = 6.9 mpg Diesel equivalent [a]	71.4 mpg gasoline equiv.[b]
Miles/yr	50,000[c]	11,140[d]
Fuel Storage	H2 gas @3600 psi	H2 gas @5000 psi
Hydrogen stored onboard (scf)	13,000[a]	1200
Range (mi)	250[a]	250
Energy use per year (GJ/yr)[e]	976	20
Hydrogen use per year (million scf/yr)[f]	2.60	0.056

a. Based on the efficiency of the Ballard Phase II PEMFC bus (Larson, Worrell and Chen 1996). The mile per gallon gasoline equivalent efficiency for a fuel cell vehicle is estimated assuming that 1 gallon of gasoline contains 0.1308 GJ (HHV) and that 1 scf of hydrogen contains 362 kJ (HHV).

b. Based on estimates by Delucchi for a PEMFC automobile (Ogden, Larson and Delucchi 1994).

c. Typical annual mileage for a bus in the LA Basin (E. Chaiboonma, LA Metropolitan Transit Authority, private communications 1995, 1996).

d. Typical annual mileage for a passenger car in the LA Basin. (R. George, SCAQMD, private communications 1995, 1996).

e. Energy use was estimated assuming that the HHV of gasoline is 0.1308 GJ/gallon.

f. Hydrogen use was estimated based on the HHV of hydrogen, 362 GJ = 1 million scf

TABLE 2. FUEL CELL VEHICLES AND HYDROGEN USE

Hydrogen Use	FCVs refueled/day	Total Fleet Fueled
1 million scf H2/day	800 FCV cars/day	Total fleet of 6300 FCV cars
	80 FC Buses/day	Total fleet of 140 FCV Buses

The hydrogen use per for an average fuel cell vehicle is calculated as follows.

Hydrogen use per day per FCV (scf H2/day) =
Annual mileage (mi)/365 days/yr /Equiv. Fuel Economy (mi/gallon gasoline equiv. energy) x Gasoline HHV (GJ/gallon)/ H2 HHV (GJ/scf)

If a station dispenses 1 million scf/day, it could supply a fleet of FCVs given by:

FCVs in fleet = 1 million scf/day/Hydrogen use per day per FCV (scf H2/day)

The number of vehicles served daily in the refueling station can then be calculated. We assume that the vehicles refuel when the tank is close to empty. If the range of the vehicle is known, we can estimate how many times it must refuel per year, and how many vehicles are refueled on average per day.

Refuelings/year/vehicle = Annual mileage (mi)/Range (mi)
Cars refueled per day
= # Refuelings per year/365 days/year x Total fleet of vehicles served
= Annual mileage (mi)/Range (mi) /365 days/year x Total fleet of vehicles served

Annual mileage, range and fuel economy for PEMFC passenger cars and buses are taken from Table 1.

TABLE 3. ASSUMED ENERGY PRICES IN SOUTHERN CALIFORNIA

Application	Annual Average Electricity Cost ($/kWh)
Onsite Reforming Station Pipeline Hydrogen Station LH2 Station	7.2 cents/kWh
Onsite Electrolysis Station Continuous Operation Off-peak Operation	 4.8 cents/kWh 3.0 cents/kWh

Source: Southern California Edison

Natural Gas Price	$2.8/GJ

This is the price of natural gas delivered to a CNG vehicle station. Source: Southern California Gas Co.

Water Price	$0.0035/gallon

Source: Los Angeles Department of Water and Power

FIG 1. NEAR TERM GASEOUS H2 SUPPLY OPTIONS

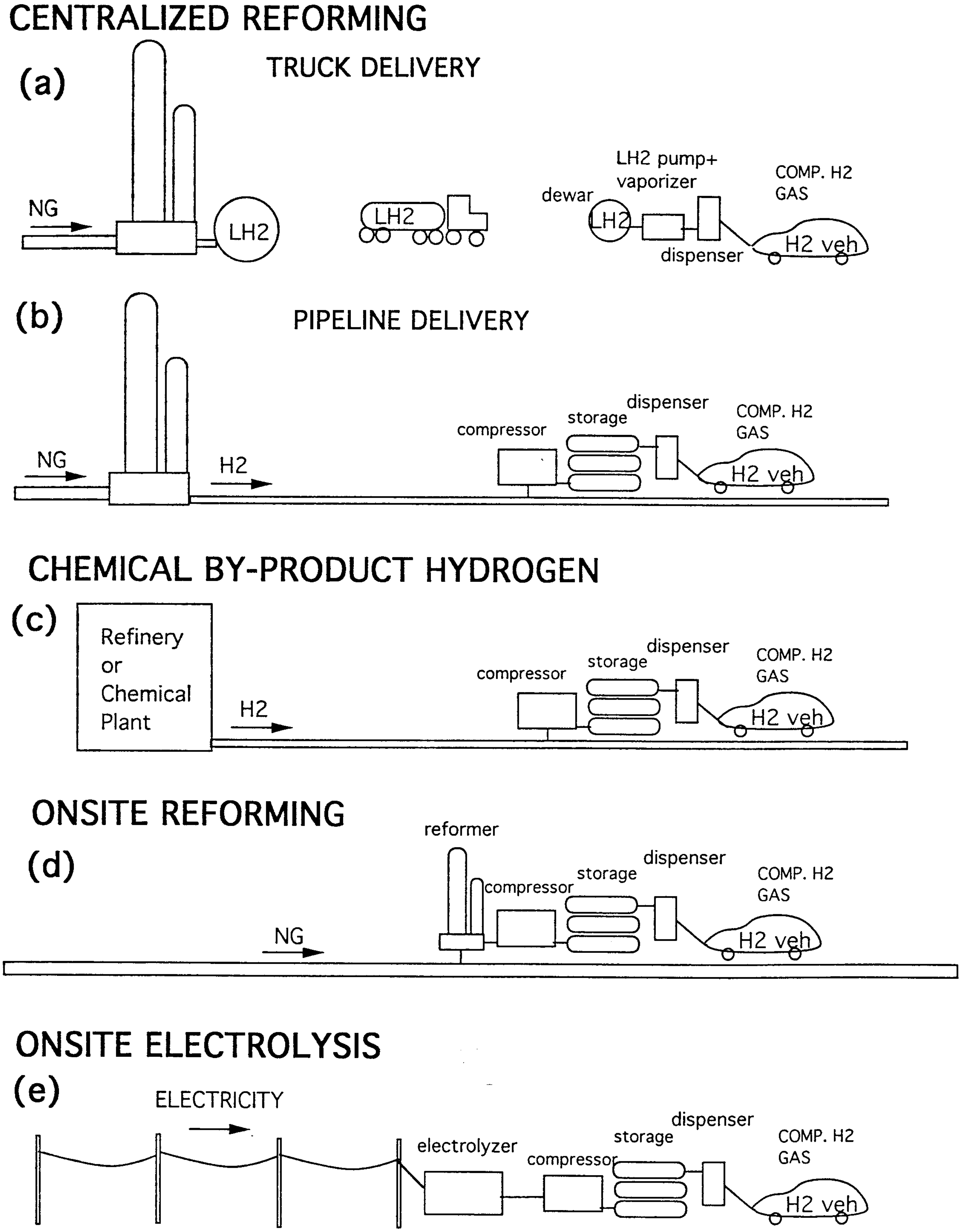


Figure 2.
Cumulative Number of Zero Emission Passenger Cars in the LA Basin

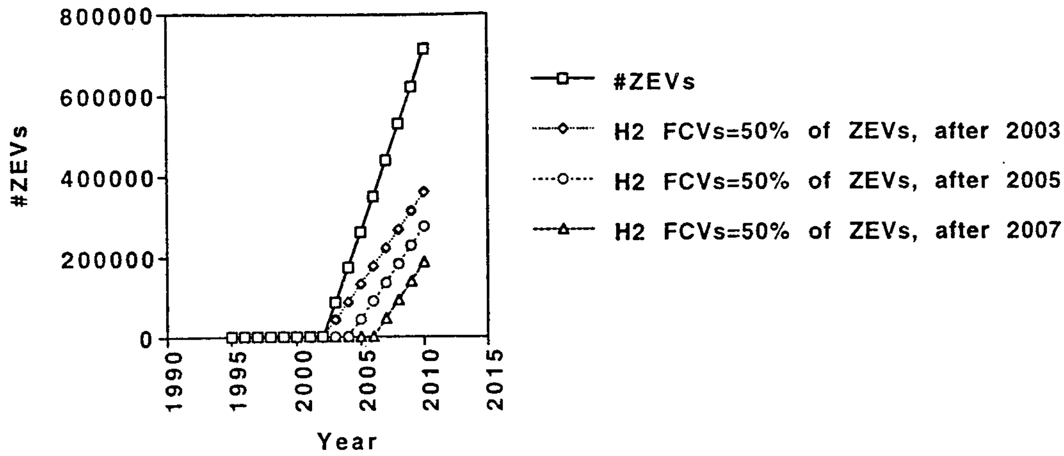


Figure 3.
Near Term Hydrogen Supplies and Projected Hydrogen Demand in the LA Basin

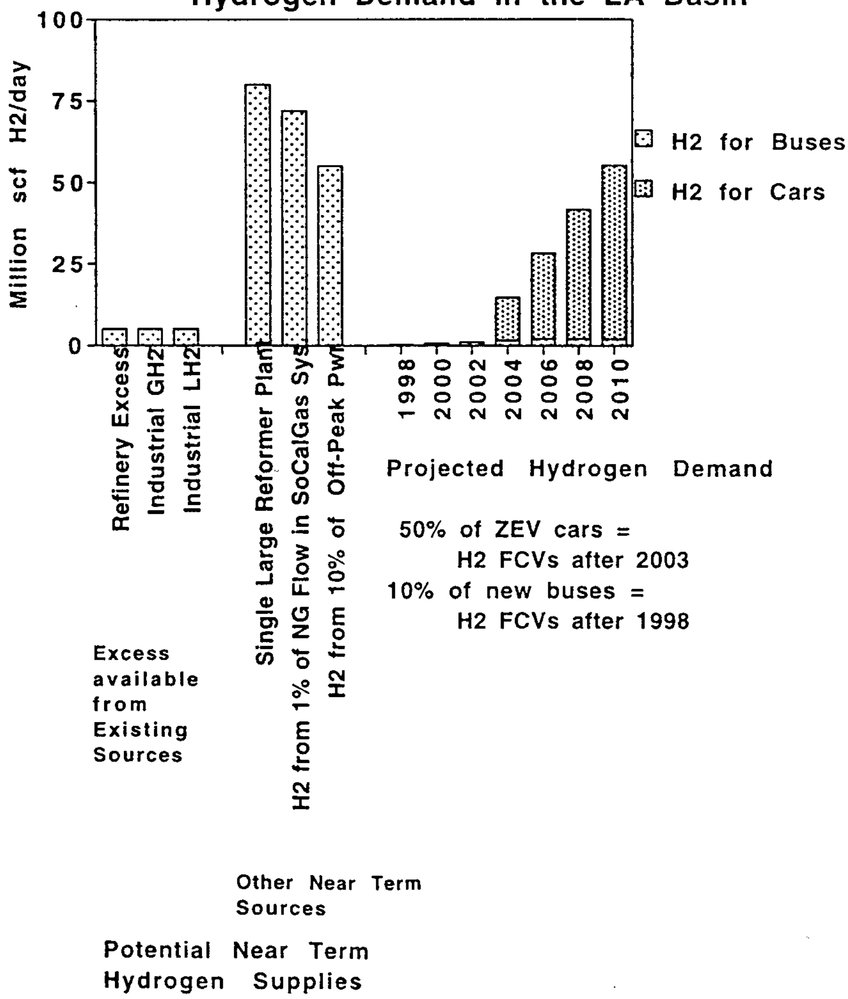


Figure 4. Delivered Cost of Hydrogen Transportation Fuel ($/GJ) vs. Station Size

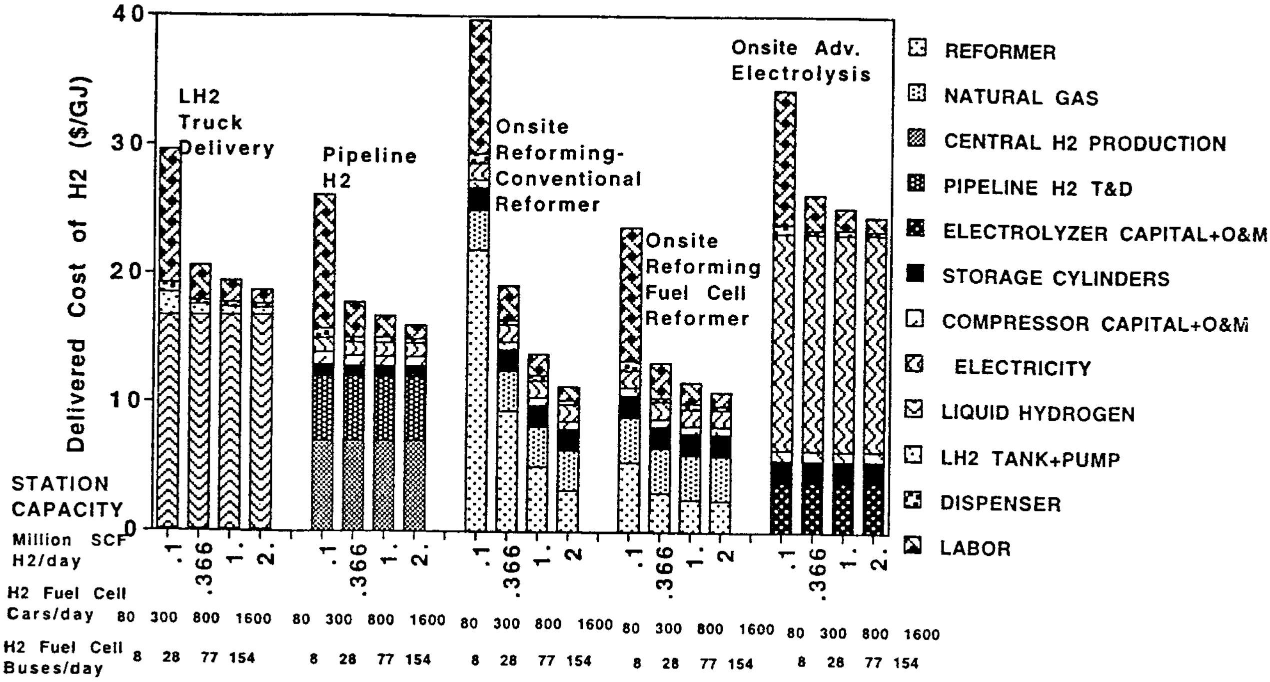
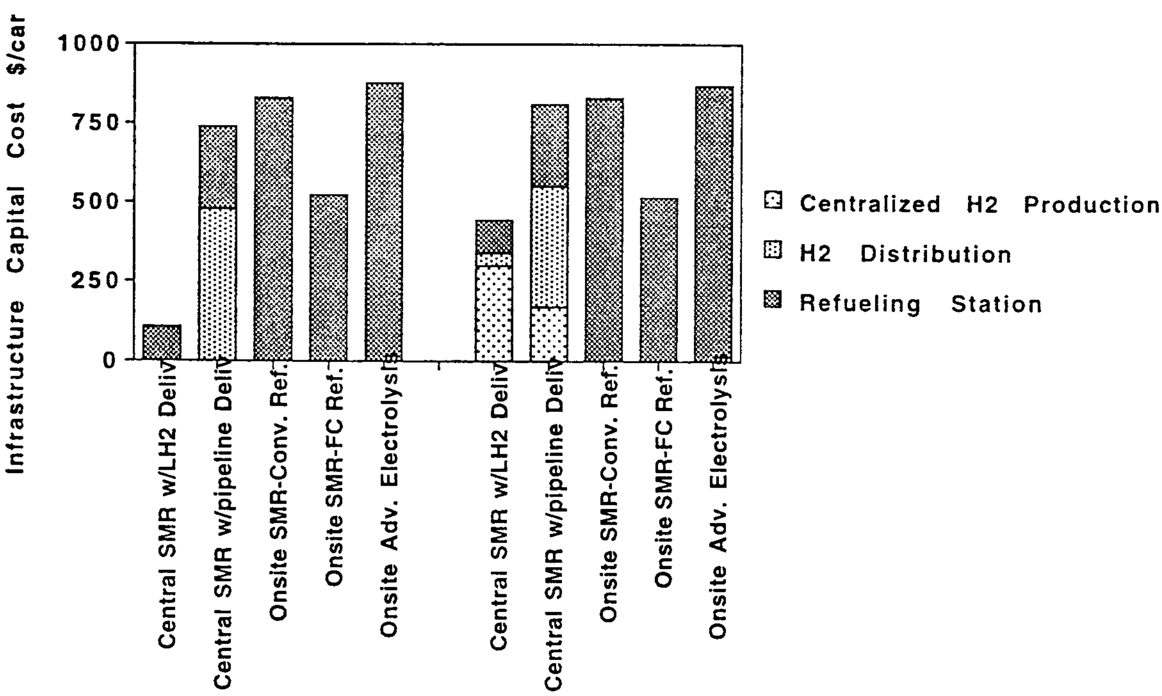


Figure 5. Capital Cost of Hydrogen Infrastructure



Early Development : Total fleet of 13,000 fuel cell cars. Centralized Options use Existing H2 Production Capacity

Extensive infrastructure development: Total fleet of 1 million fuel cell cars. Centralized options use new H2 Production Capacity