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CASE STUDY OF DEVELOPING A HYDROGEN VEHICLE REFUELING INFRASTRUCTURE IN SOUTHERN CALIFORNIA

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SUMMARY

For several years, researchers at Princeton University's Center for Energy and Environmental Studies have carried out technical and economic assessments of hydrogen energy systems. Here we desribe a case study of developing a hydrogen vehicle refueling infrastructure in Southern California.

Our results can be summarized as follows:

* 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 cost of hydrogen from existing sources might be $20-30/GJ for truck delivered liquid hydrogen. Costs for gaseous hydrogen delievered by small pipeline would depend on the

level of demand and the pipeline length. This might be attractive even for small demands located near an inexpensive hydrogen source (such as refinery excess or the Air Products plant in Wilmington.) The delivered cost of hydrogen from onsite steam reforming of natural gas may rival that of existing sources, although the capital costs would be higher than for liquid hydrogen refueling stations.

* Once demand for hydrogen exceeded existing excess production capacity (perhaps 5-15 million scf/day), new production capacity would be needed. Natural gas supplies would probably be sufficient to supply feedstock for hydrogen production for up to several million PEMFC cars, for several decades. In the longer term, other hydrogen supplies might be phased such as gasification of municipal solid waste or biomass, or solar.

* For energy prices and conditions in the LA 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 and 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 this option 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 demos 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.

1.0. CASE STUDY OF DEVELOPING A HYDROGEN VEHICLE REFUELING INFRASTRUCTURE IN SOUTHERN CALIFORNIA

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1.1. INTRODUCTION

Many analysts suggest that the first widespread use of hydrogen energy is likely to be in zero emission vehicles in Southern California. California's zero emission vehicle mandate requires that starting in 2003, 10% of all new light duty vehicles must be zero emission vehicles (ZEVs.) Over seven hundred thousand zero emission automobiles are projected for the Los Angeles Basin alone by 2010, if mandated levels are implemented.

The only zero emission vehicle technologies likely to be ready in this time frame are electric battery vehicles and fuel cell vehicles. Because of their longer range, faster refueling time and potential for low cost in mass production, fuel cell vehicles are among the leading contenders in the emerging market for zero emission vehicles.

All fuel cells currently considered for road vehicles use hydrogen as fuel. While hydrogen can be produced onboard the vehicle by reforming methanol or gasoline, direct storage of compressed gaseous hydrogen has many attractions. The design of the vehicle is much simpler, the vehicle is 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, a travelling range of 400 km should be possible for a fuel cell automobile (Delucchi 1992).

The relative simplicity of the hydrogen fuel cell vehicle design must be weighed against the added complexity of a gaseous hydrogen refueling infrastructure. Unlike gasoline, natural gas or electricity, hydrogen is not widely distributed to consumers today. Assuming that hydrogen vehicles capture a significant fraction of the ZEV market, a large demand for hydrogen fuel could evolve over the next few decades.

Refueling a large number of hydrogen vehicles poses significant challenges. The question is often asked "Where is the hydrogen going to come from?" In this report, we attempt to answer that question for a specific region, where fuel cell vehicles might be introduced, the Los Angeles Basin.

There are many ways of making and delivering hydrogen tranpsortation fuel. In this study, we assess several near term options (see Figure 1.1) for producing and delivering gaseous hydrogen transportation fuel to users in Southern California including:

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

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

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

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

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

To compare these alternatives, we address the following questions:

* What are projected hydrogen demands for ZEVs and potential hydrogen supplies in the LA Basin?

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

* What is the lifecycle cost of transportation for hydrogen vehicles fueled with hydrogen from these sources?

* 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?

Our conceptual designs for hydrogen infrastructure utilize commercial or near commercial technologies for hydrogen production, storage and distribution. Our goal is to examine the hydrogen infrastructure question, with a focus on a potentially important near term market: Southern California ZEVs.

1.2. ESTIMATED HYDROGEN DEMAND FOR REFUELING HYDROGEN VEHICLES IN SOUTHERN CALIFORNIA

1.2.1. ESTIMATED NUMBER OF ZERO EMISSION VEHICLES IN THE LOS ANGELES BASIN

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 (Ranji George, private communications 1995, 1996). These are shown in Table 1.1. We see that by 2010, over 9 million passenger cars will be operating in 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 Table 1.1, the ZEV population can be estimated, assuming that mandated levels of ZEV passenger cars are introduced on the time scale shown in Table 1.2. We further assume that 1) the projected vehicle population grows linearly, 2) ZEVs have a lifetime of 10 years and 3) the number of ZEVs/year is held fixed at 10% of new vehicles sold each year between 2003 and 2010. Table 1.3 estimates the ZEVs sold per year and the cumulative number of ZEVs as a function of year from 1995-2010 under the original and revised ZEV mandates. Under the original 1990 ZEV mandate, by 2010 over 800,000 zero emission vehicles would be on the road in the LA Basin. Even though the mandate has been altered to delay introduction of ZEV cars until 2003, the cumulative number of ZEVs is still projected to be over 700,000 in 2010 (see Figure 1.2)

1.2.2. PROJECTED HYDROGEN DEMANDS

1.2.2.1. Hydrogen Demand for a Single Fuel Cell Car or Bus

The hydrogen demand for a PEM fuel cell mid-size passenger car is given in Table 1.4. The performance of the PEMFC car is based on estimates by Delucchi (Ogden, Larson and Delucchi 1994, Delucchi 1992). The annual mileage and projected annual energy use is based on average driving patterns in the Los Angeles Basin (see Table 1.1).

The hydrogen demand for a PEMFC bus is estimated in Table 1.4, based on Ballard performance estimates for a PEMFC bus (Larson et.al. 1996), and Los Angeles bus annual mileage (Chaiboonma 1996).

1.2.2.2. Scenarios for Commercialization of Fuel Cell Vehicles

It is possible that hydrogen fuel cell vehicles could capture a significant fraction of the ZEV automobile market. Many analysts believe that fuel cell cars could be commercialized sometime between 2003 and 2010.

Three possible scenarios for introducing hydrogen fuel cell vehicles are shown in Table 1.5. In the "base case" 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). For comparison, earlier and later commercialization scenarios are given (see Table 1.5 and Figure 1.3).

1.2.2.3. Total Hydrogen Demand for ZEVs in the LA Basin

The total hydrogen demand for the three scenarios above can be estimated using the information in Tables 1.3-1.5. The total hydrogen demand for fuel cell cars and buses is shown for each scenario in Table 1.6. The hydrogen demand for the base case is plotted in Figure 1.4.

For the assumptions in our base case, a hydrogen demand of about 55 million scf/day would develop by 2010. This is about as much hydrogen as would be produced at a good sized oil refinery today. Almost all the hydrogen would be for passenger cars. If 10% of the new bus market goes to PEMFCs starting in 1998, this would amount to about 300 buses by 2010 (about as many buses as would be served by a large bus depot). Fueling this many buses would require about 2 million scf/day. If all the buses in the LA Basin were fuel cell buses, this would require about 20 million scf/day.

For reference, based on Los Angeles driving patterns, one million scf/day of hydrogen would be enough to fuel 800 PEM fuel cell passenger cars per day (or a total fleet of 6500 FCV cars) or 80 PEMFC buses per day (or a total fleet of 140 PEMFC buses) (Table 1.7).

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.

1.3. EXISTING AND POTENTIAL HYDROGEN SUPPLIES IN THE LOS ANGELES BASIN

1.3.1. EXISTING SUPPLIES OF HYDROGEN

1.3.1.1. Industrial gas companies

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 (see Figure 1.5) which currently produces 15 ton/day of liquid hydrogen (15 ton/day is equivalent in energy to about 5.3 million scf/day of gaseous hydrogen.) This plant supplies liquid hydrogen to the aerospace industry and to chemical industry users. 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 Praxair plant was originally designed to produce 28 ton/day, using two reformers. With lowered demand from aerospace companies, one reformer was shut down several years ago. The output could be returned fairly easily to 28 ton/day by restarting the second reformer. There is also room for further expansion beyond 28 ton/day if the market warranted (Kerr 1995). If the second reformer were reactivated producing an additional 13 ton/day of liquid hydrogen, this could fuel a fleet of about 30,000 fuel cell cars or about 600 Ballard type PEMFC urban transit buses. 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 delivered cost of transportation fuel would depend on the type of pipeline distribution system needed.

1.3.1.2. Excess hydrogen from refineries

In addition, a number of oil refineries are located in the Torrance/Wilmington area (see Figure 1.5). 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 will be 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 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.

1.3.1.3. Summary: total hydrogen available from existing sources

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 costs to build new distribution systems and refueling stations to bring the "excess hydrogen" available in the LA Basin today to consumers' vehicles. This is discussed in Section 1.4.2. below.)

1.3.2. 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 these existing sources of hydrogen. (Recall that by 2010, fueling all 50% of ZEVs with hydrogen would require 55 million.) In this case, other near term supplies would have to be developed.

1.3.2.1. Expansion of industrial gas supplies

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 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.

1.3.2.2. Hydrogen from onsite steam reforming of natural gas

It is also possible to produce hydrogen onsite at the refueling station via small scale steam reforming of natural gas or partial oxidation. The natural gas flow through Southern California Gas's distribution system averages about 3 x 10^9 scf of natural gas/day (David Crain, private communications 1995). Fueling a fleet of 1 million fuel cell cars with LA driving patterns would require about 150 million scf H2/day. This amount of hydrogen could be produced via steam reforming from about 60 million scf of NG or about 2% of the total flow in the natural gas utility system. Natural gas is widely available throughout the LA Basin. Based on experience with installing compressed natural gas vehicle refueling stations (which would require a similar natural gas flow to hydrogen stations based on onsite reforming), pipelines of sufficient capacity are easily tapped (Wayne Tanaka, Southern California Gas, private communications 1995). The natural gas distribution system would not have to be modified to bring natural gas to refueling stations for onsite hydrogen production for ZEVs.

Recent improvements in small scale reformer technology are making this option more attractive (Farris 1996, Ogden et.al. 1996).

1.3.2.3. Hydrogen from onsite electrolyis using off-peak power

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 would be in the 400-8000 kW range.

1.3.2.4. Hydrogen from landfill gas

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.

1.3.2.5. Summary: total hydrogen available from near term sources

Hydrogen could be produced either in a centralized plant or at the refueling station from natural gas. To produce hydrogen to fuel one million FCVs would require less than 2% of the current natural gas flow in the utility system.

Onsite electrolysis is another potentially large resource. If all the available off-peak power in the LA area were devoted to electrolytic hydrogen production, a fleet of 3-5 million FCVs could be fueled.

Hydrogen from landfill gas is another possibility which might be exploited in the near term.

In Figure 1.6, 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 3-4 million FCVs.

1.3.3. 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 is 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).

1.3.3.1. Hydrogen From Municipal Solid Waste

Municipal solid waste (MSW) can be gasified to produce methanol or hydrogen. Chen (Chen 1995) has estimated that 375-500 million scf H2/day could be produced in the LA area via gasfication of MSW. This would be enough to fuel a fleet of 3-4 million fuel cell cars. The cost of hydrogen production was estimated to be about $10.2-13.3/GJ for a plant producing 26.5 million scf H2/day, assuming tipping fees of $22/tonne of raw MSW, the figure used in Los Angeles. Hydrogen plants using MSW as a feedstock would benefit from economies of scale.

The delivered cost of hydrogen to the consumer would depend on the cost of distribution via pipeline. For a 10 km, 3" diameter hydrogen pipeline costing about $1,000,000/mile, the cost of transmitting 11 million scf/day would be about $1/GJ. Assuming that the refueling station added another $6/GJ, the total delivered cost of compressed hydrogen gas transportation fuel from MSW would be about $17-20/GJ.

Hydrogen could also be produced via gasification of biomass, probably at similar costs to hydrogen from MSW. We have not specifically estimated potential biomass resources in the LA area.

1.3.3.2. Hydrogen From Solar, Wind And Geothermal

In areas with good direct insolation, solar thermal power could be used in thermochemical cycles for producing hydrogen via solar-assisted steam reforming of natural gas or via water decomposition. (Williams 1996).

Solar photovoltaic (PV) electrolytic hydrogen could be produced almost anywhere. The Los Angeles area has a good solar resource. The amount of land required to produce 113 million scf H2/day (enough to fuel a fleet of 0.8 million fuel cell cars) would be about 37 km^2 or 15 sq.mi. (assuming annual average insolation of 220 W/m^2, PV efficiency of 15% and electrolyzer efficiency of 80%). PV hydrogen systems could be centralized or stand-alone (at the refueling site). With projected improvements in the cost of mass-produced thin film PV, the delivered cost of transportation fuel might be $22-30/GJ. Ultimately, to meet the demand for 14 million fuel cell cars (levels projected for cars in the LA Basin in the early to middle part of the next century) about 250 sq.mi. of PV plants would be needed.

There are several excellent wind sites in Southern California, including sites at Tehachapi Pass and San Gorgonio Pass (on Route I-10 an hour or so east of LA). Costs for wind electrolytic hydrogen would probably be similar to those projected for PV, if long term goals are met. (Wind power is likely to offer lower costs than PV for the next 10-20 years.)

Geothermal power is another possible option in the Southern California area.

Local wind and geothermal resources have not been quantified in this study, but could be looked at in more detail.

1.3.3.3. Hydrogen From Fossil Fuels Or Biomass With Sequestering Of CO_2

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.

1.3.3.4. Summary of Long Term Options for Hydrogen Production

Local renewable options in the LA area would be sufficient to meet foreseeable needs for hydrogen fuel cell cars. Once a sufficiently large demand for hydrogen had developed, long distance hydrogen pipelines might be built to bring in lower cost sources of hydrogen to the user.

1.4. ECONOMICS OF HYDROGEN PRODUCTION AND DELIVERY

1.4.1. DELIVERED COST OF HYDROGEN TRANSPORTATION FUEL

We now estimate the delivered cost of hydrogen transportation fuel in Southern California for various options.

Energy prices for Southern California are summarized in Table 1.8, 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).

We consider a variety of near term refueling infrastructure options including (Figure 1.1):

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

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

* hydrogen produced at the refueling station via small scale steam reforming of natural gas, both conventional and fuel cell type steam reformers are considered (Ogden et.al. 1996)

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

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

A range of refueling station sizes from 0.1 to 2.0 million scf/day is considered (e.g.about 80-1600 fuel cell cars/day or 8-160 fuel cell buses/day). The details of the refueling system design and economics are discussed in earlier reports (Ogden et.al. 1995, Ogden, Dennis and Montemayor 1995, Dennis 1994). We have included a summary of equipment costs for developing a hydrogen refueling infrastructure (e.g. costs for hydrogen production, distribution and refueling station technologies for each option above in Appendix 1.A.)

1.4.1.1. Economic Comparison of Hydrogen Supply Options in Southern California

The delivered cost of hydrogen transportation fuel for Southern California conditions is shown in Figure 1.7 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. The capital cost of refueling stations is shown in Figure 1.8.

Although all the supply options are roughly competitive, several points are readily apparent.

* For our assumptions, it appears that onsite electrolysis would be somewhat more expensive in 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. See Chapter 2 of this report for further discussion of the conditions where electrolysis would be more competitive.)

* 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 demo 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.

* In Figure 1.9b, 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. In Figure 1.9a, we compare the capital cost of small scale hydrogen plants based on conventional and fuel cell steam methane reformers. We see that if fuel cell type reformers

are used, the reformer capital cost might be reduced by about 25-70% for station capacities of 0.1-2.0 million scf/day. As shown in Figures 1.7 and 1.9b, this reduction in reformer capital cost makes onsite reforming competitive with liquid truck delivery and pipeline delivery over the whole range of station sizes considered. The delivered cost of hydrogen is reduced by about 40% for a station serving 80 cars/day and 20% for a station serving 800 cars/day. Onsite production has the advantage that no hydrogen distribution system is required.

* Under certain conditions, pipeline hydrogen could offer low delivered costs. The capital cost of building a small (3" diameter) hydrogen pipeline would be about $1 million per mile in the heavily populated Los Angeles area (Lenci 1995). Figure 1.10 shows the cost of hydrogen pipeline delivery in a 3" diameter pipeline as a function of the pipeline flow rate and the distance. The levelized cost of pipeline delivery in Los Angeles is about

Ppipeline($/GJ)
= $1.2/GJ x distance (in km)/flow rate (in million scf H_2/day).

The levelized cost of pipeline delivery depends on the flow rate and the length of the pipeline (see Ogden et.al. 1995). The higher the flow rate, the lower the cost.

* 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 wth truck delivery or onsite reforming, pipeline costs can be no more than a few $/GJ. 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 example, from Figure 1.10, if we want a transmission cost of $1/GJ, we could have a flow rate of 10 million scf/day (an amount which could serve a total fleet of 65,000 cars (see Table 1.7)) over a pipeline distance of about 10 km (e.g. an entire small city converts to hydrogen fuel cell cars, supplied by a hydrogen plant within 10 miles). Another scenario giving

a levelized pipeline cost of \$1/GJ is a single refueling station serving a fleet of 6500 cars located 1 km from a large hydrogen plant (e.g. 10% of the cars in a small city convert to hydrogen fuel cells, and the refueling station is located near a hydrogen plant).

1.4.2. 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 this section, we estimate 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.

1) Early development of distribution system and refueling stations to bring excess hydrogen from existing hydrogen capacity to users. We assume that no new hydrogen production capacity is needed. Stations are assumed to serve 80-1600 cars or 8-160 buses per day: hydrogen demands are in the range 0.1-2.0 million scf/day.

2) Development of new hydrogen production capacity to meet growing demands for hydrogen transportation fuel. Expansion of hydrogen delivery system and increased number of hydrogen refueling stations. Introduction of onsite steam reformers or electrolyzers.

These two cases are shown in Tables 1.9a and 1.9b. (See Appendix 1.A for a discussion of capital costs for equipment used in building hydrogen infrastructure: hydrogen production, delivery and refueling station systems.)

In Table 1.9a, we assume that a total fleet of 13,000 fuel cell cars are operating in the Los Angeles area. Two refueling stations serve these cars, each station dispensing 1 million scf H2/day to 800 cars/day. The options for providing hydrogen to these cars include:

1) Liquid hydrogen delivery via truck from existing capacity. There is no capital cost for developing new capacity or for

new delivery trucks. The only cost is for two new refueling stations. The infrastructure capital cost per car is about $105.

2) Pipeline hydrogen delivery. This would not be economically feasible unless the demand was located near a large hydrogen plant or refinery with excess hydrogen. There is no charge for developing new capacity. However, the pipeline is expensive. The cost is for two new compressed gas hydrogen refueling stations is higher than for stations with LH2 delivery. The total infrastructure cost per car is about $740.

3) Onsite production from steam reforming of natural gas involves only refueling station costs. The station cost is high, because hydrogen is produced onsite. Capital costs per car for onsite production from conventional small scale reformers is about $830/car. This is reduced to about $530/car for fuel cell type reformers.

4) Capital costs for onsite production from advanced electrolysis using off-peak power, would be about $880/car.

In Table 1.9b, we estimate the capital cost of infrastructure to refuel 1 million fuel cell cars. Here we assume that new centralized production capacity is built. Infrastructure capital costs per car range from $440 for liquid hydrogen truck delivery, to $810 for pipeline delivery, to $500-800 for onsite reforming to $870 for onsite electrolysis using off-peak power.

We see that centralized steam reforming with liquid hydrogen delivery gives the lowest overall infrastructure capital cost. [It is important to recall the the delivered cost of hydrogen for this option is still higher than some others (Figure 1.7), since liquifaction requires substantial electrical energy input.]

Infrastructure costs for pipeline hydrogen are more costly because of the higher cost of the refueling stations, and because of the high costs of building hydrogen pipelines in LA.

Onsite production via electrolysis is fairly expensive.

Conventional small scale steam methane reforming is also capital intensive. However, if low cost, compact, fuel cell type steam reformers are used, it appears that onsite steam reforming could be a relatively low cost alternative.

It is important to keep in mind the results of Figure 1.7 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 LH2 delivery, can give a higher delivered fuel cost than pipeline delivery or onsite reforming.

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 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?

Redefining "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 cost is paid by the fuel producer. In the case of methanol or gasoline fuel cell vehicles, the cost is paid by the consumer buying the car.

A recent study by Directed Technologies, Inc. supports the view 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). In future work , we plan to make more detailed estimates of methanol and gasoline infrastructure costs.

1.4.3. LIFECYCLE COST OF OWNING AND OPERATING A HYDROGEN FUEL CELL CAR OR BUS COMPARED TO ALTERNATIVES

As we have shown in earlier work, the cost of owning and operating a hydrogen fuel cell automobile would be comparable to that of a gasoline internal combustion engine vehicle and other alternatives, assuming mass production cost goals for PEM fuel cells are reached (Ogden, Larson and Delucchi 1994). Performance and cost assumptions for alternative fueled vehicles are outlined in Table 1.10, comparing fuel cell automobiles to gasoline automobiles and fuel cell buses to Diesel buses (see also Larson, Worrell and Chen 1996). Using the data in Figure 1.7 for the delivered cost of hydrogen transportation, fuel, the lifecycle cost of transportation can be estimated. This is shown for a PEMFC bus in Figure 1.10. The capital cost of the vehicles is higher, but the efficiency is higher, so that the overall cost of transportation could be similar to that of today's vehicles.

For a PEMFC car, lifecycle costs are shown in Figures 1.12a-c. Figure 1.12a shows the delivered cost of hydrogen from various sources as compared to gasoline, natural gas and methanol. Figure 1.12b shows the fuel cost per km for alternative vehicles run on gasoline, methanol and hydrogen. The total lifecycle cost of transportation is given in Figure 1.12c. For details the reader is refered to (DeLuchi 1992 and Ogden, Larson and Delucchi 1994)

1.5. 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.

What about the cost of building a hydrogen infrastructure? Wouldn't other fuel cell vehicle options such as onboard reforming of methanol or gasoline entail smaller capital costs? According to recent estimates by Directed Technologies, Inc. (Thomas 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.

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

1.6.1. 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 this year, 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.

To understand the potential for fuel cell buses in the Los Angeles area, we gathered data on the bus system (Chaiboonma 1996). A total of about 3000 Diesel buses operate in the LA area. Typically, buses are driven 50,000 miles/year, and have a fuel economy of about 3.5 miles per gallon of Diesel, and a range of 350 miles. The lifetime of a typical Diesel bus is about 10 years (500,000 miles). Buses are refueled overnight where they are garaged (at depots). Typical sizes for bus depots in LA are about 60-200 buses.

Major bus depots are shown in Figure 1.13. 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.

Assuming a replacement rate for Diesel buses of 10% per year, about 300 new buses would be needed in LA every year. If fuel cell buses made up 10% of the new buses about 30 new fuel cell buses per year would be required. Existing industrial hydrogen sources would be sufficient to supply several hundred buses.Hydrogen could be trucked in as a liquid or piped short distances to bus depots near the Long Beach refinery area. 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.

1.6.2. INTRODUCTION OF PEMFC AUTOMOBILES IN SOUTHERN CALIFORNIA

Several major automobile manufacturers are conducting R&D on PEM fuel cell cars (including GM, Ford, Chrysler, 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.

If PEMFC cars capture a significant fraction of the mandated ZEV market, the demand for hydrogen could grow rapidly (Figure 1.4), and new hydrogen production capacity and delivery infrastructure would be needed. In near term (1998-2010) 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.)

1.7. CONCLUSIONS

If hydrogen fuel cell vehicles captured a significant fraction of the projected ZEV market, a large demand for hydrogen could develop over the next 15 years. If PEMFC cars accounted for half the mandated ZEV population, there would be about 350,000 fuel cell cars on the road in the LA Basin by 2010, requiring 55 million scf of hydrogen per day.

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 any 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 from existing sources might be $20-30/GJ for truck delivered liquid hydrogen. Costs for gaseous hydrogen delievered by small pipeline would depend on the level of demand and the pipeline length. This might be attractive even for small demands located near an inexpensive hydrogen source (such as refinery excess or the Air Products plant in Wilmington.) The delivered cost of hydrogen from onsite steam reforming of natural gas may rival that of existing sources, although the capital costs would be higher than for liquid hydrogen refueling stations.

Once demand for hydrogen exceeded existing production capacity (perhaps 5-15 million scf/day), new production capacity would be needed. Natural gas supplies would probably be sufficient to supply feedstock for hydrogen production for up to several million PEMFC cars, for several decades. In the longer term, other hydrogen supplies might be phased such as gasification of municipal solid waste or biomass, or solar.

For energy prices and conditions in the LA area, it appears that in the near term, truck delivery of liquid hydrogen and onsite production via small scale steam reforming offer the lowest delivered hydrogen costs and 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, capable of producing H2 for 3-4 million fuel cell cars. However, hydrogen produced via small scale electrolysis 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. 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 demos 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 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.

1.8 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.

1.9. ACKNOWLEDGMENTS

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FIG 1.1. NEAR TERM GASEOUS H2 SUPPLY OPTIONS

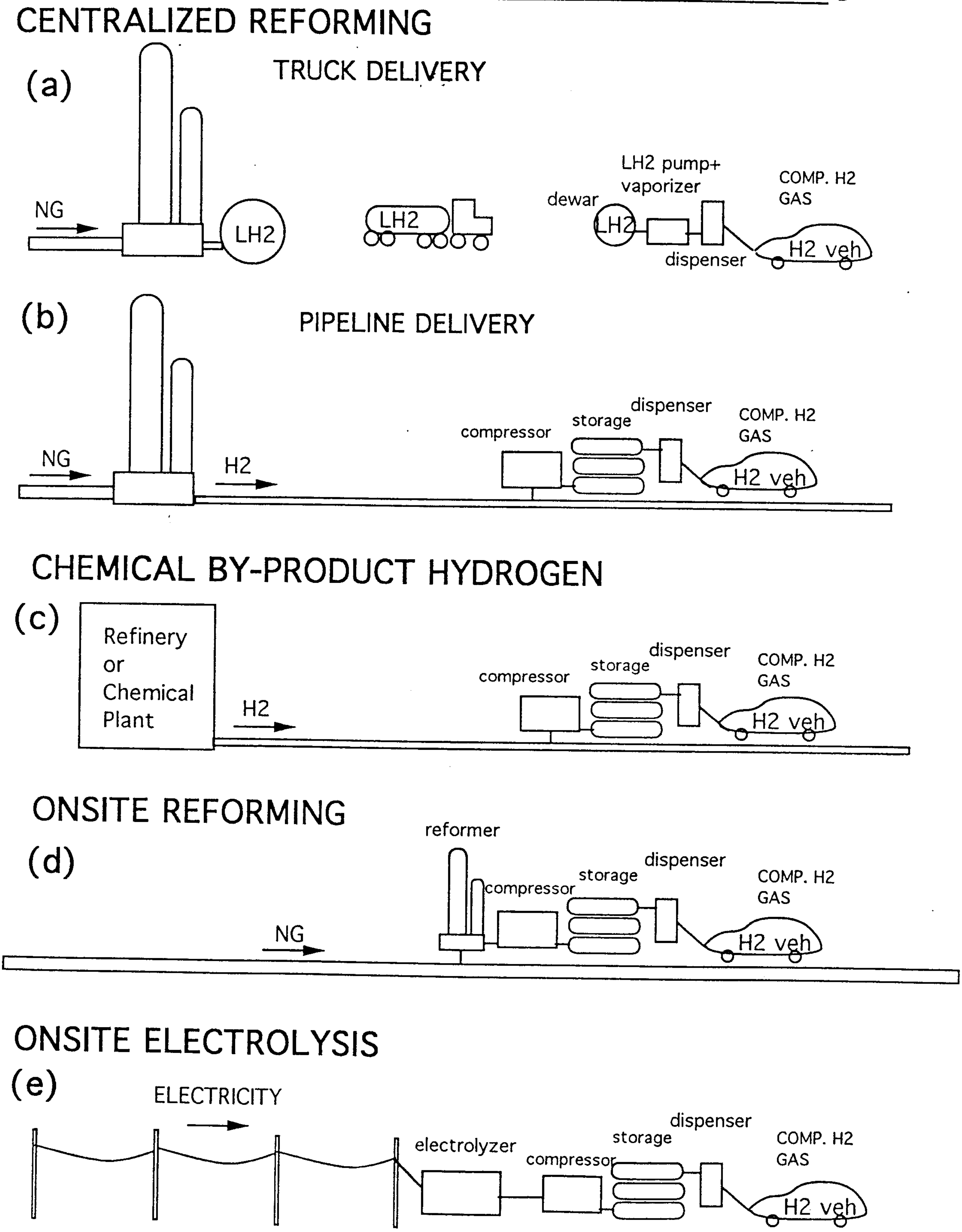


Figure 1.2.
Cumulative Number of Zero Emission Passenger Cars in the LA Basin

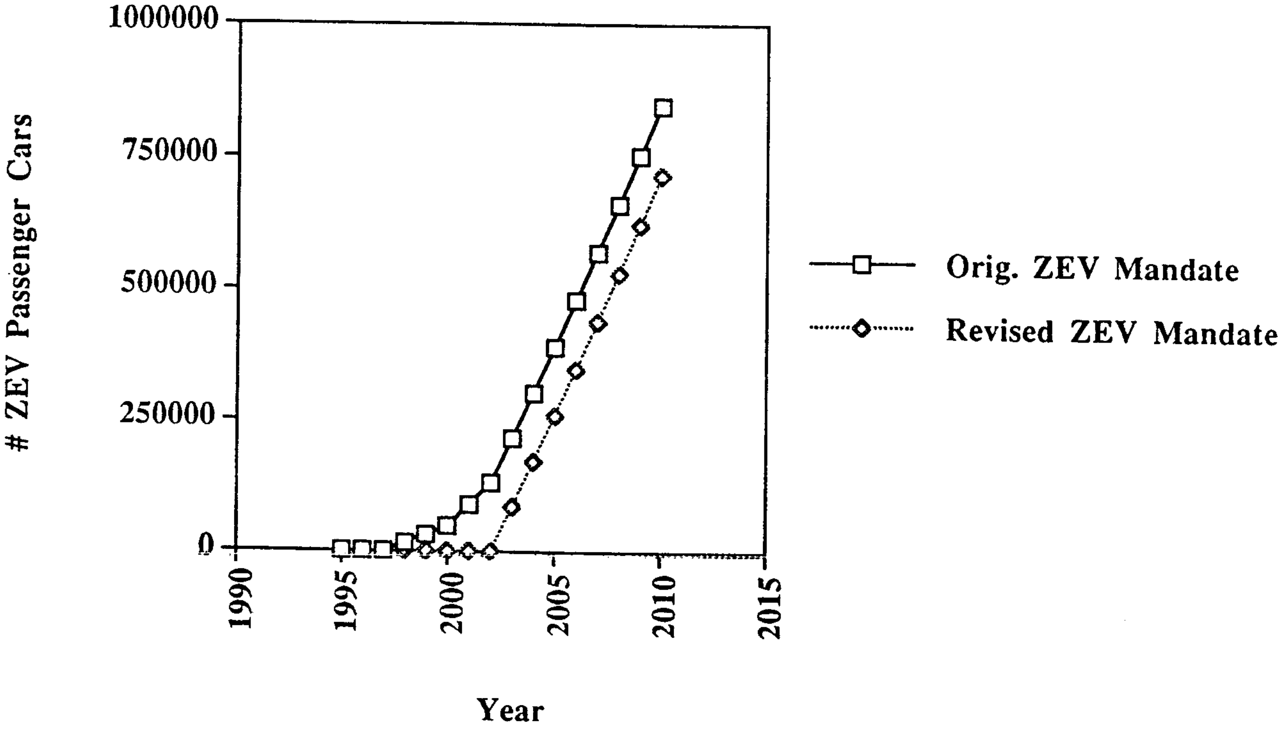


Figure 1.3.
Projections for Fuel Cell Passenger Cars in the LA Basin for Various Commercialization Scenarios (see Table 1.5)

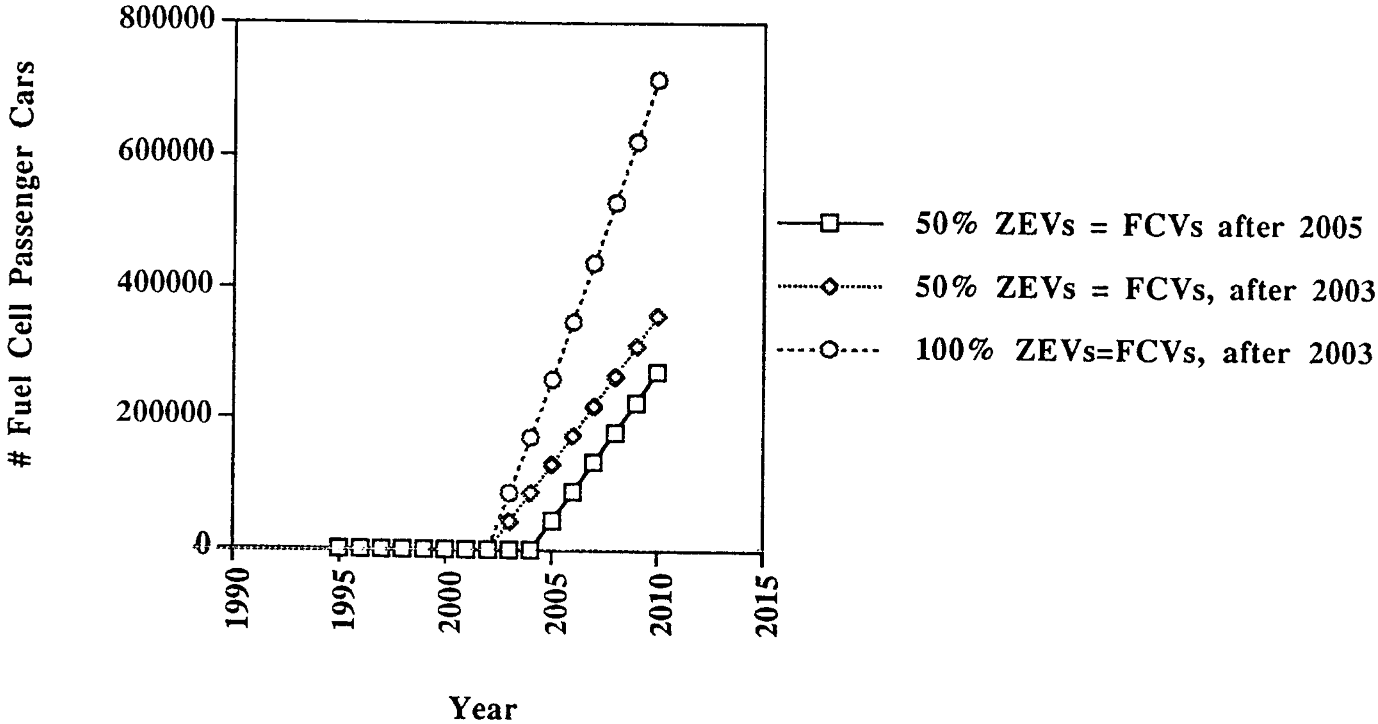
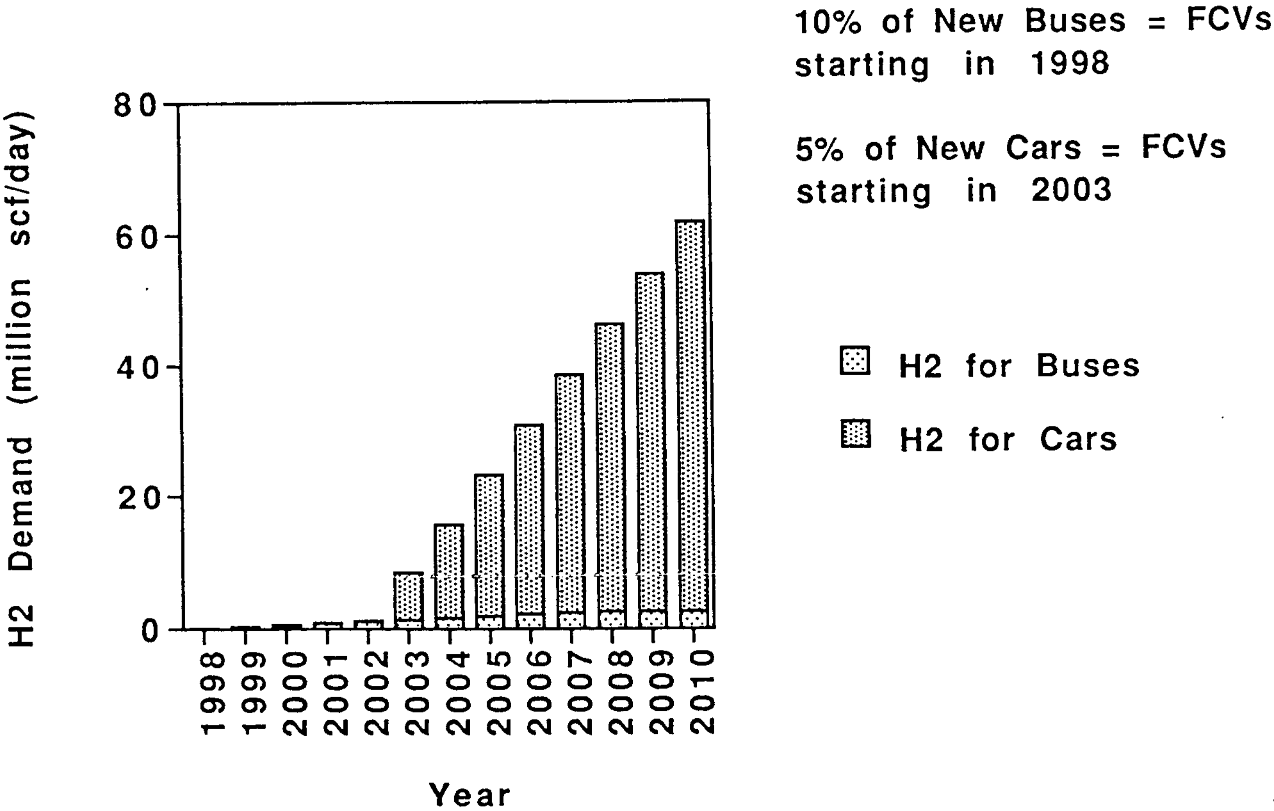


Figure 1.4.
A Possible Scenario for Introducing Fuel Cell Vehicles in the LA Basin



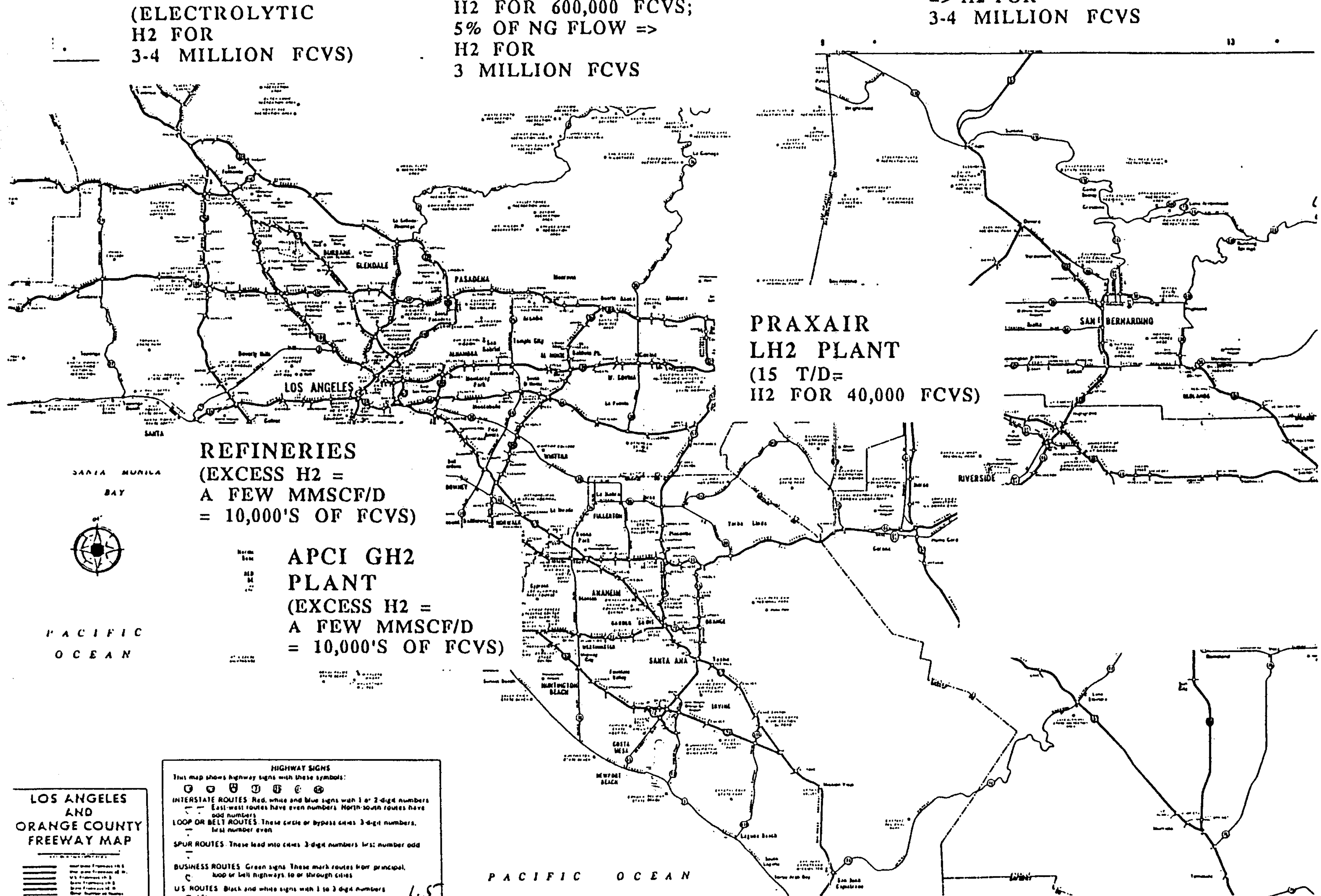


Figure ~~13~~ 1.5 Map of existing and potential hydrogen supplies in the LA Basin

Figure 1.6.
Near Term Hydrogen Supplies and Projected Hydrogen Demand in the LA Basin - Scenario I (Table 1.5)

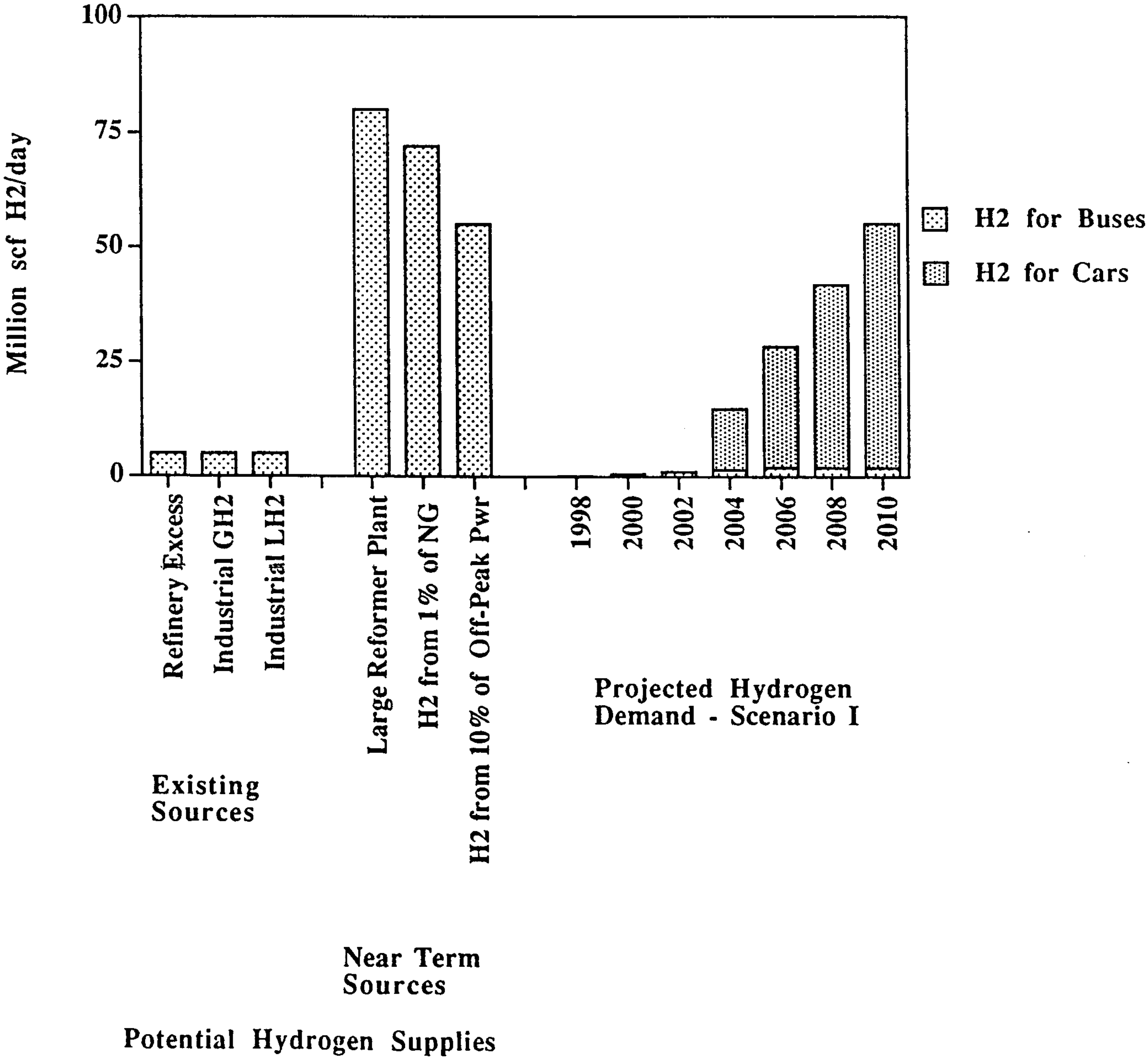


FIGURE 1.7. DELIVERED COST OF HYDROGEN TRANSPORTATION FUEL ($/GJ) VS. STATION SIZE

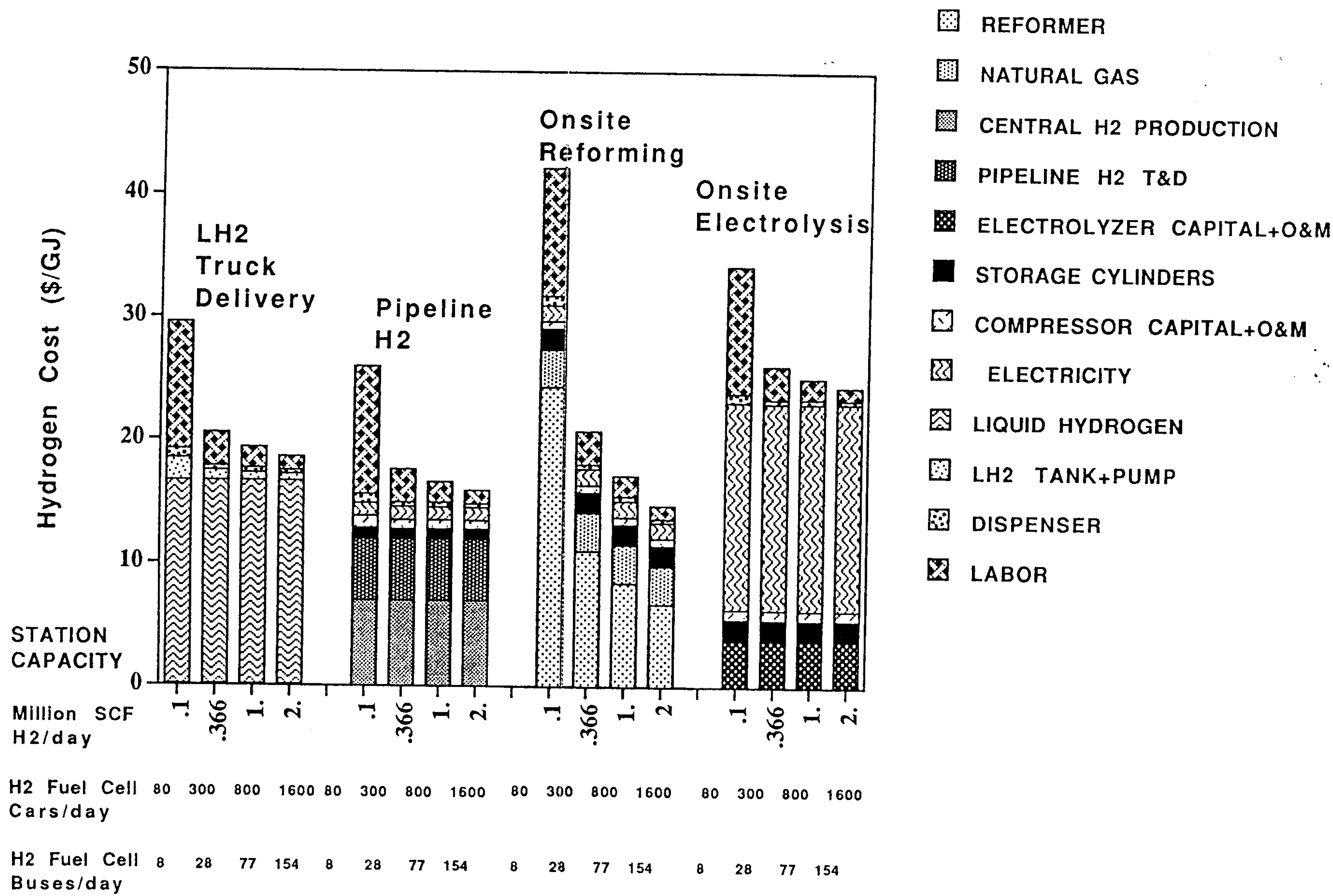


Figure 1.8.
REFUELING STATION
CAPITAL COST

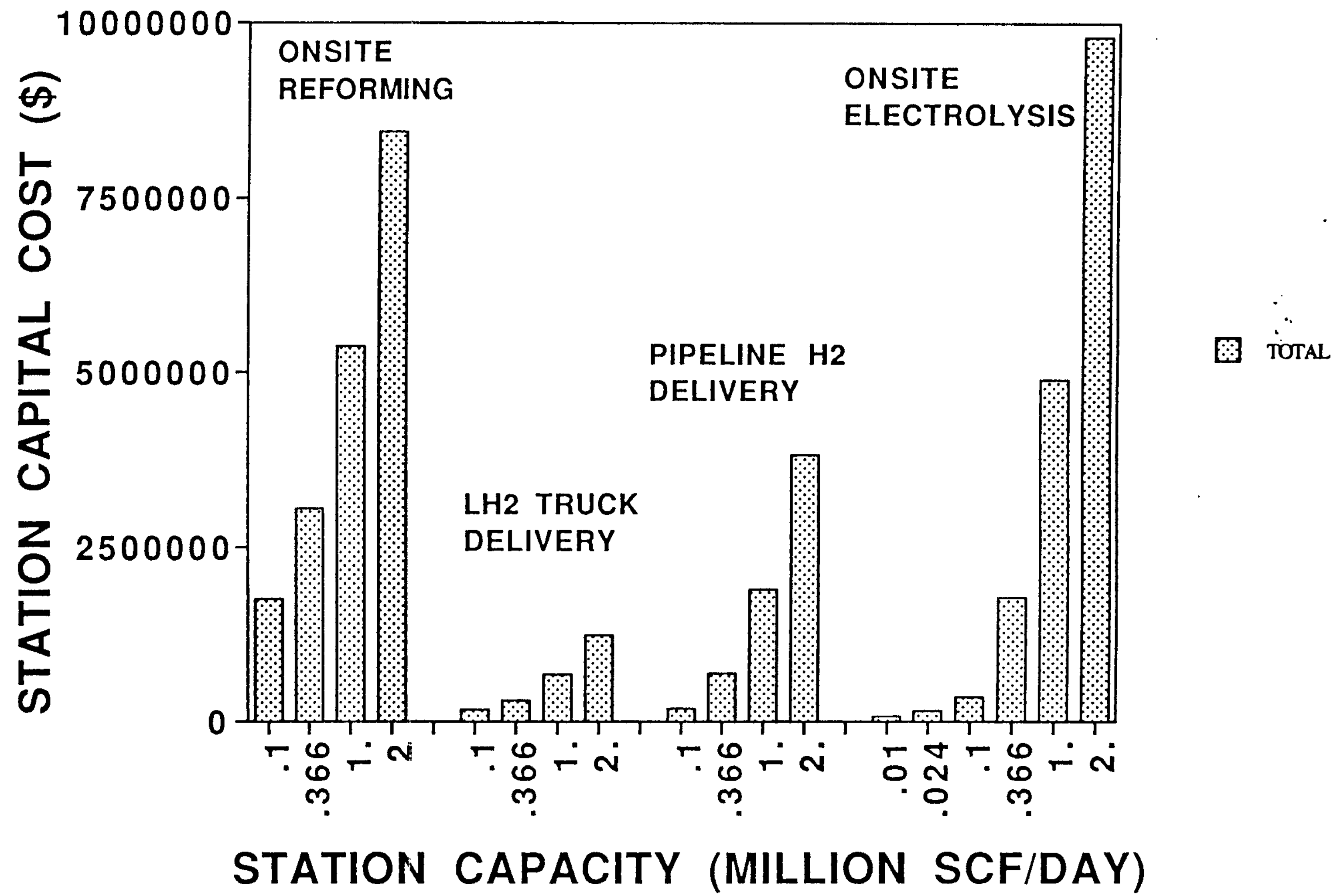
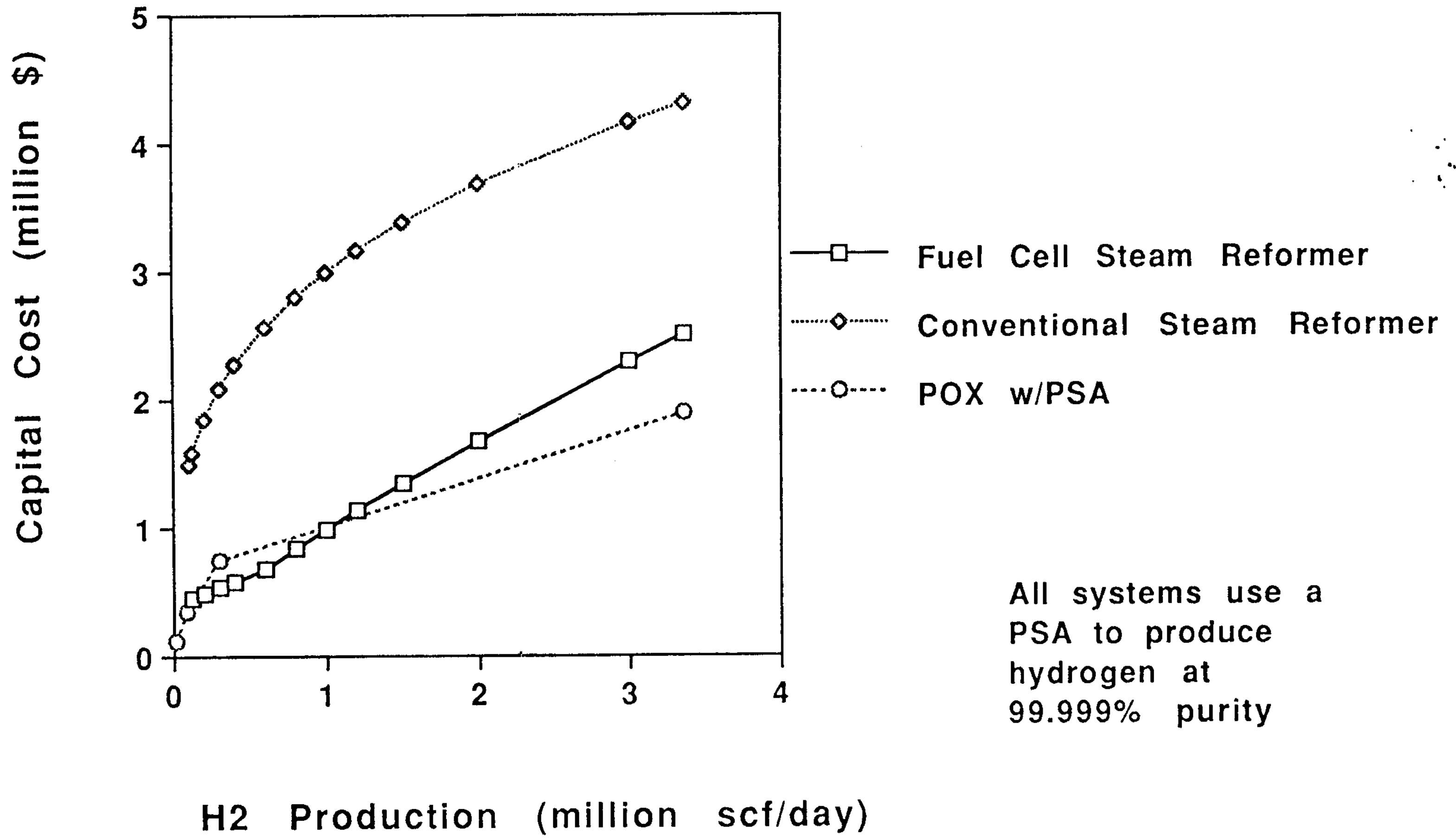


Figure 1.9a.
Capital Cost of Small Scale Hydrogen Production Plants w/Methane Reformers



All systems use a PSA to produce hydrogen at 99.999% purity

Figure 1.9b. Delivered Cost of Hydrogen Transportation Fuel: Onsite Reforming of Natural Gas

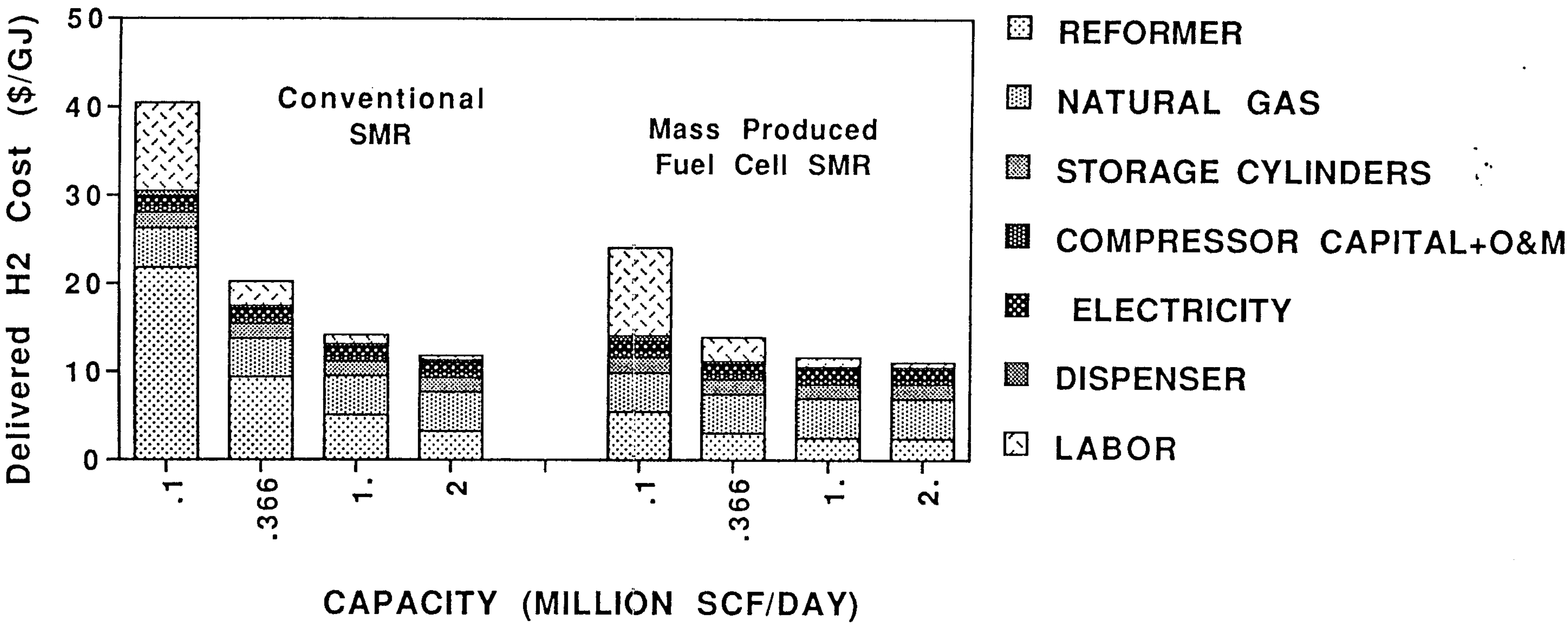


Figure 1.10
Cost of Hydrogen Pipeline Transmission vs. Pipeline Length and Flow Rate

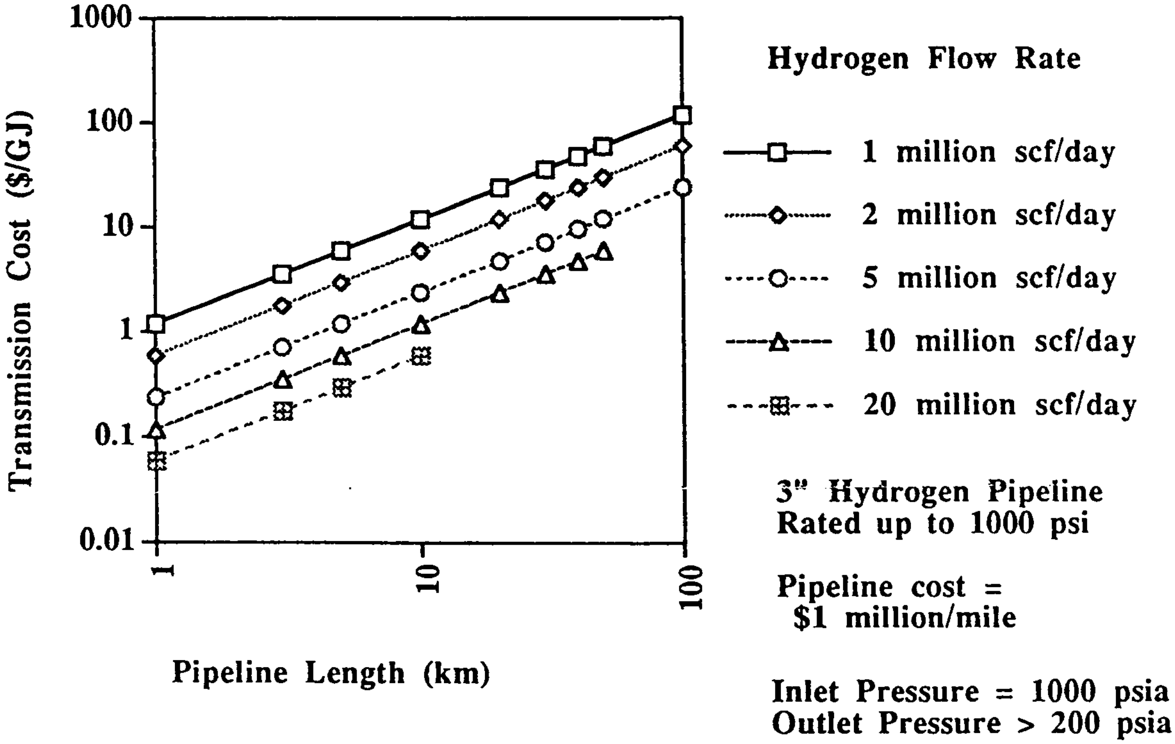


Figure 1.11.
Lifecycle Cost of Transportation for Diesel and PEMFC Buses

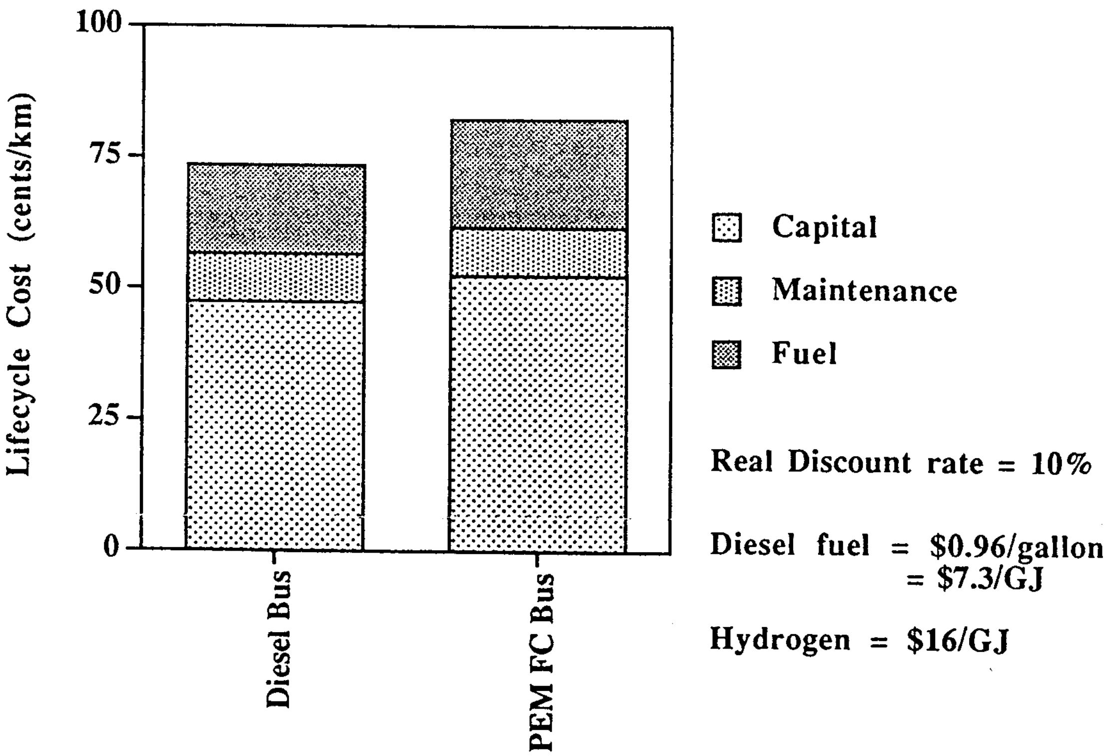
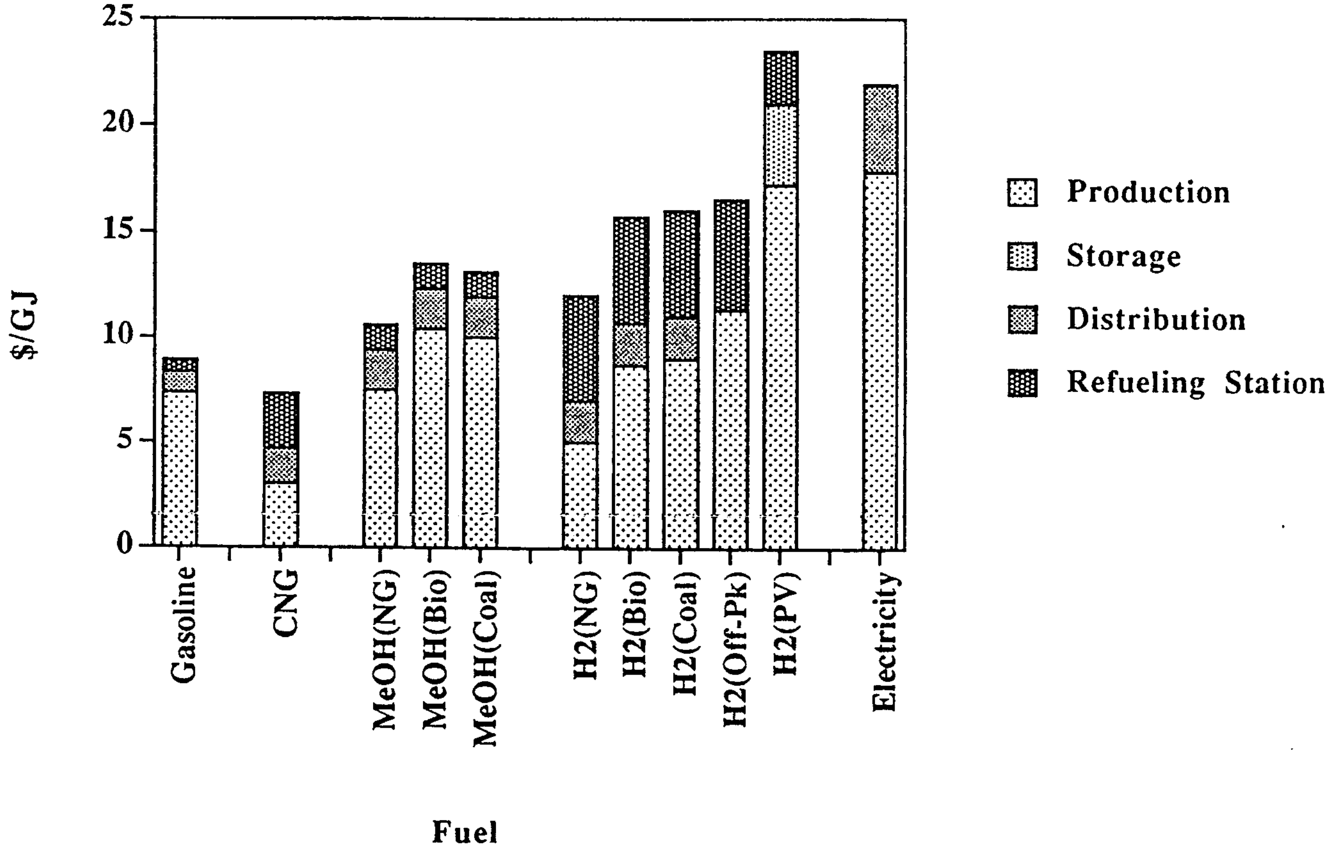


Figure 12a.
Delivered Cost of Alternative Transportation Fuels



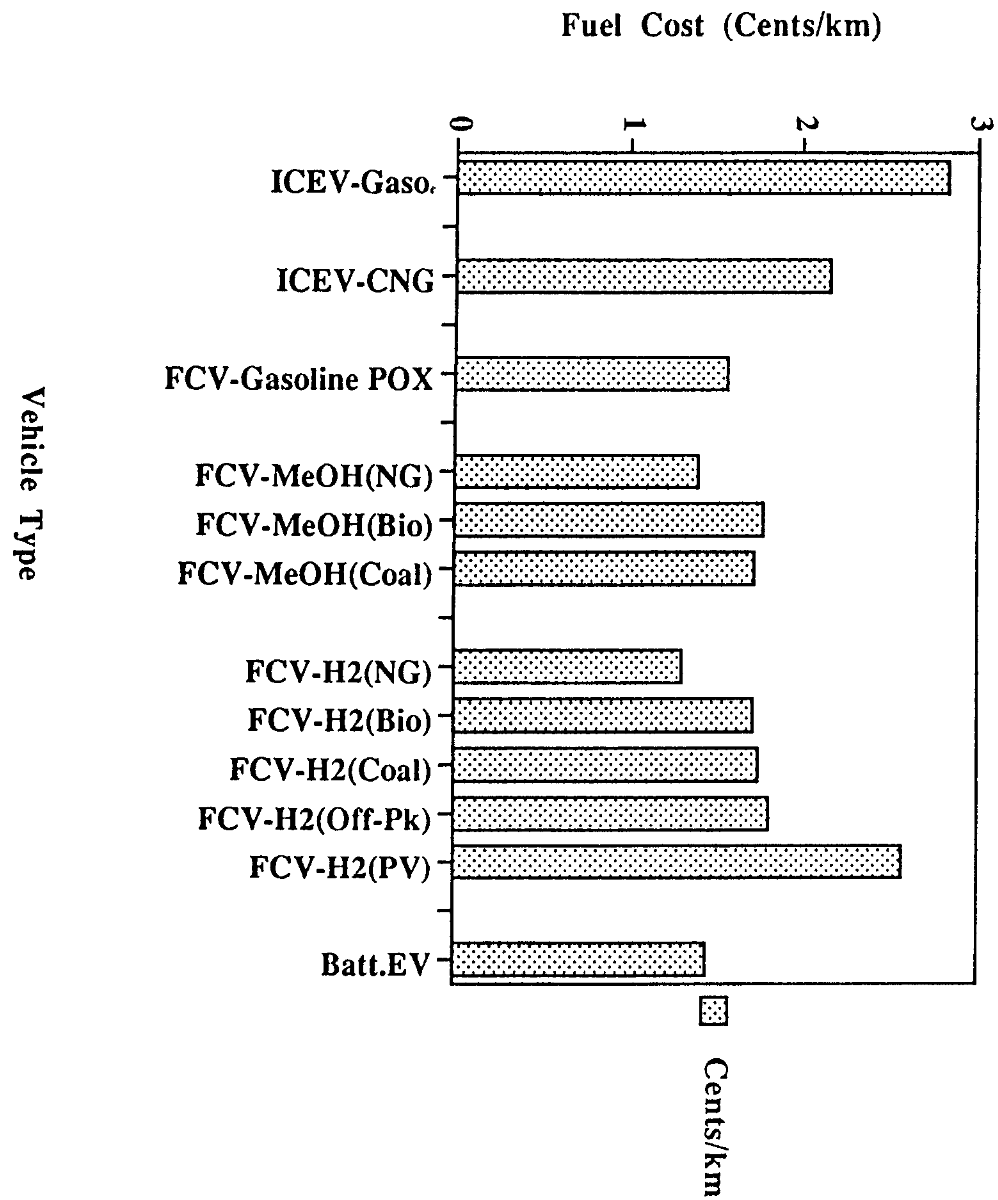


Figure 1.12b.
Fuel Cost in Cents/km for Alternative Fueled Vehicles

Figure 1.12c.
Lifecycle Cost of Transportation for Alternative Fueled Vehicles

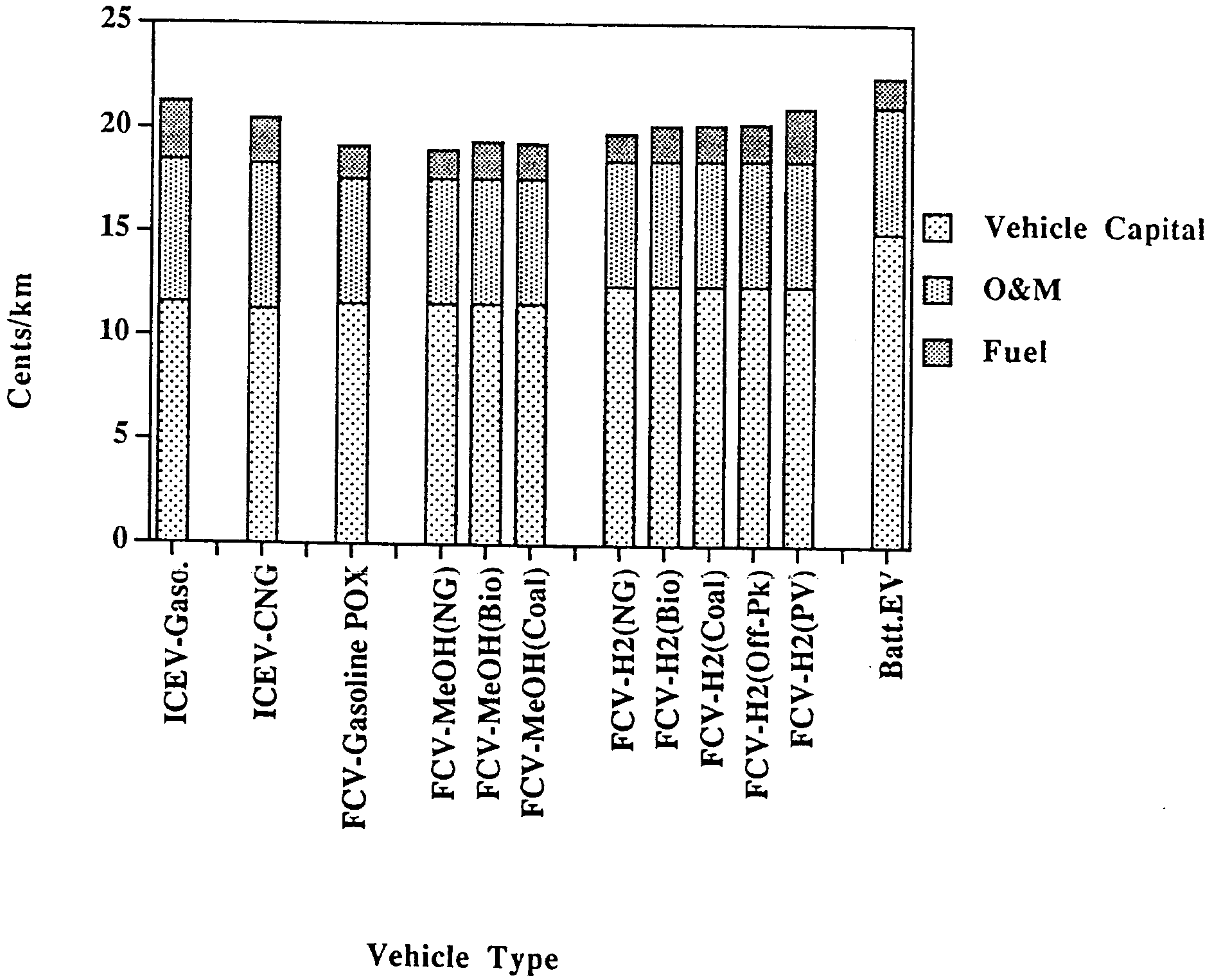


Figure [illegible]: Los Angeles MTA Bus Depots and Potential Hydrogen Supplies

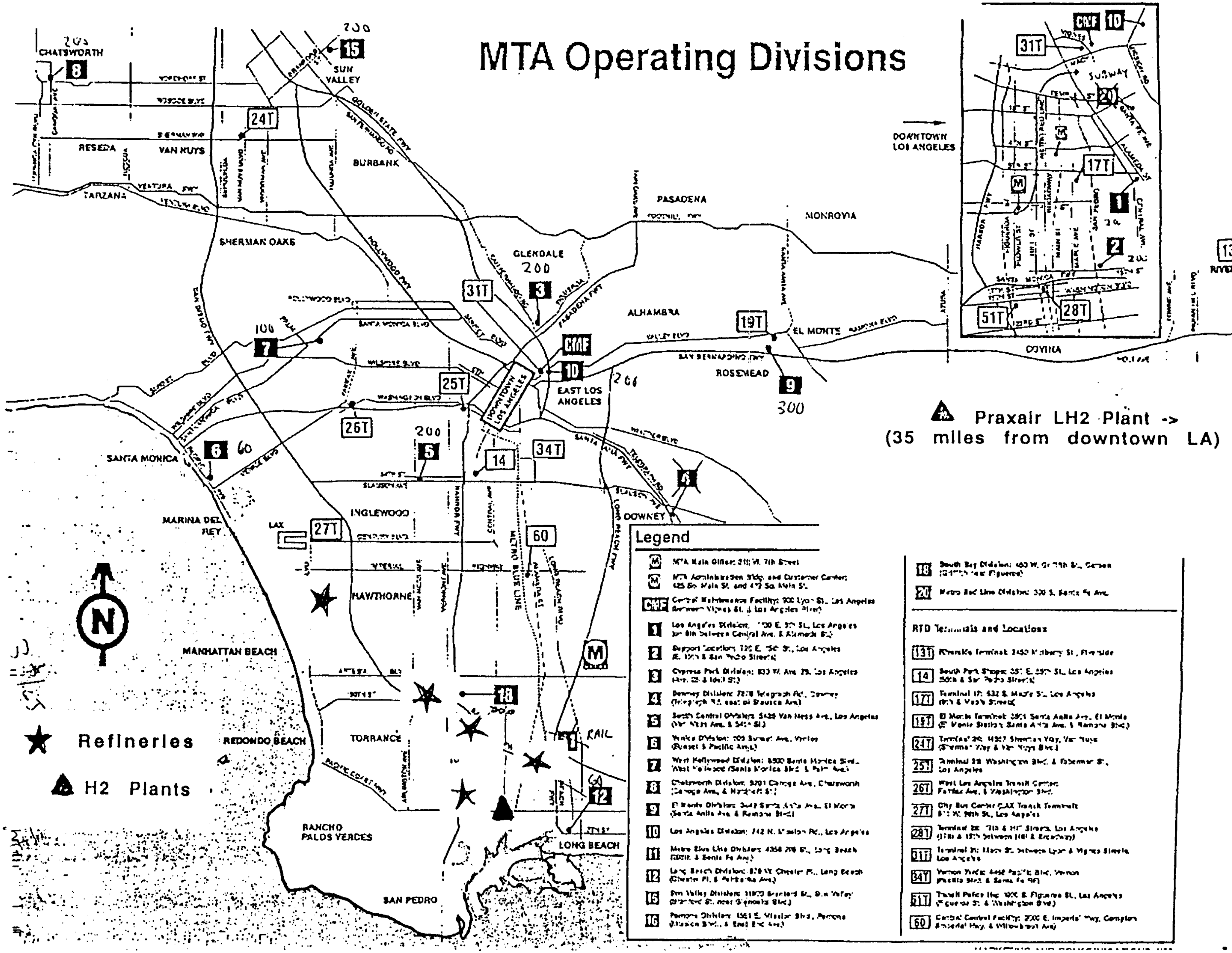


Table 1.0. Conversion Factors and Economic Assumptions

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%

Passenger car owners' real discount rate is assumed to be 3.8%
The real discount rate is taken to be 10% for urban buses.

TABLE 1.1.
DATA AND PROJECTIONS FOR VEHICLE POPULATIONS, FUEL ECONOMY, ANNUAL MILEAGE AND ENERGY USE FOR PASSENGER CARS, LIGHT TRUCKS AND URBAN BUSES IN THE SOUTH COAST AIR BASIN

Passenger Cars					
Year	# Vehicles	Average Fuel Economy (mpg)	Average Miles/Yr/ Vehcle	Average Energy Use/Yr/ Vehicle (GJ/yr)	Energy Use All Passenger Cars (EJ/yr)
1995	7,419,502	23.6	11,311	62.7	0.46
2000	8,141,691	25.8	11,379	57.7	0.47
2005	8,753,995	27.6	11,035	52.3	0.46
2010	9,365,800	29.0	10,724	48.4	0.45

Light Trucks					
Year	# Vehicles	Average Fuel Economy (mpg)	Average Miles/Yr/ Vehicle	Average Energy Use/Yr/ Vehicle (GJ/yr)	Energy Use (EJ/yr)
1995	1,368,212	17.1	11,854	90.7	0.12
2000	1,513,177	18.0	11,960	86.9	0.13
2005	1,639,484	18.3	11,633	83.1	0.14
2010	1,765,701	18.4	11,213	79.7	0.14

Urban Buses					
Year	# Vehicles	Average Fuel Economy (mpg)	Average Miles/Yr/ Vehcle	Average Energy Use/Yr/ Vehicle (GJ/yr)	Energy Use (EJ/yr)
1995	2926	3.5	50,646	1892	0.0034
2000	3076	3.5	50,668	1894	0.0034
2005	3188	3.5	50,720	1895	0.0033
2010	3300	3.5	50,658	1893	0.0033

Source: Ranji George, SCAQMD, private communications 1995. Passenger cars and light trucks under 3750 lb. are subject to the ZEV mandate.

TABLE 1.2. ZERO EMISSION VEHICLE MANDATE

Year	Original (1990) ZEV Mandate	Revised (1996) ZEV Mandate
1998	2%	0%
1999	2%	0%
2000	2%	0%
2001	5%	0%
2002	5%	0%
2003	10%	10%

TABLE 1.3. PROJECTED NUMBERS OF ZEV PASSENGER CARS IN THE SOUTH COAST AIR BASIN 1995-2010

WITH ORIGINAL ZEV MANDATE (1990)

YEAR	ZEVS AS % OF NEW CARS SOLD EACH YEAR	ZEV PASSENGER CARS/YR	CUMULATIVE # ZEV PASSENGER CARS
1995	0	0	0
1996	0	0	0
1997	0	0	0
1998	2%	16,137	16,137
1999	2%	16,386	32,524
2000	2%	16,635	49,158
2001	5%	42,148	91,306
2002	5%	42,709	134,016
2003	10%	86,541	220,557
2004	10%	87,663	308,220
2005	10%	88,785	397,005
2006	10%	89,908	486,913
2007	10%	91,030	577,943
2008	10%	92,152	670,095
2009	10%	93,275	763,370
2010	10%	94,397	857,767

WITH REVISED ZEV MANDATE (1996)

YEAR	ZEVS AS % OF NEW CARS SOLD EACH YEAR	ZEV PASSENGER CARS/YR	CUMULATIVE # ZEV PASSENGER CARS
1995	0	0	0
1996	0	0	0
1997	0	0	0
1998	0	0	0
1999	0	0	0
2000	0	0	0
2001	0	0	0
2002	0	0	0
2003	10%	86,541	86,541
2004	10%	87,663	174,204
2005	10%	88,785	262,989
2006	10%	89,908	352,897
2007	10%	91,030	443,927
2008	10%	92,152	536,080
2009	10%	93,275	629,354
2010	10%	94,397	723,751

Table 1.4. 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 1.5. Possible Scenarios for Introduction of Fuel Cell Vehicles in the Los Angeles Basin

Scenario I (base case)	FCVs = 50% of ZEV Market = 5% of all new passenger cars, starting in 2003 10% of new Buses = FCVs, starting in 1998
Scenario II (earlier introduction of FCVs)	FCVs = 100% of ZEV Market = 10% of all new passenger cars, starting in 2003 100% of new Buses = FCVs, starting in 1998
Scenario III (later introduction of FCVs)	FCVs = 50% of ZEV Market = 5% of all new passenger cars, starting in 2005 10% of new Buses = FCVs, starting in 2000

Table 1.6.
Numbers of ZEVs and Projected Hydrogen Demand (in Million scf H2/day) in the LA Basin for Three Demand Scenarios

Year	Scenario I				Scenario II				Scenario III			
	Cum. # Cars 1000s	H2 for Cars	Cum. # Buses	H2 for Buses	Cum. # Cars 1000s	H2 for Cars	Cum. # Buses	H2 for Buses	Cum. # Cars 1000s	H2 for Cars	Cum. # Buses	H2 for Buses
1998	0	0	30	0.21	0	0	300	2.1	0	0	0	0
1999	0	0	60	0.43	0	0	600	4.3	0	0	0	0
2000	0	0	90	0.64	0	0	900	6.4	0	0	30	0.21
2001	0	0	120	0.85	0	0	1200	8.5	0	0	60	0.43
2002	0	0	150	1.07	0	0	1500	10.7	0	0	90	0.64
2003	42.5	6.6	180	1.28	85.1	13.2	1800	12.8	0	0	120	0.85
2004	85.7	13.2	210	1.50	171	26.4	2100	15.0	0	0	150	1.07
2005	129	19.8	240	1.71	259	39.6	2400	17.1	43.7	6.7	180	1.28
2006	174	26.4	270	1.92	348	52.9	2700	19.2	88.1	13.4	210	1.50
2007	219	33.1	300	2.13	438	66.2	3000	21.3	133	20.1	240	1.71
2008	264	39.8	300	2.13	529	79.5	3000	21.3	179	26.9	270	1.92
2009	311	46.5	300	2.13	621	92.9	3000	21.3	225	33.6	300	2.13
2010	358	53.2	300	2.13	713	106.3	3000	21.3	272	40.4	300	2.13

Table 1.7. Fuel Cell Vehicles And Hydrogen Use

Hydrogen Use	FCVs refueled/day	Total Fleet Fueled
1 million scf H2/day	800 FCV cars/day 80 FC Buses/day	Total fleet of 6500 FCV cars Total fleet of 140 FCV Buses

The hydrogen use per for an average fuel cell passenger car 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)

For a passgenger car
Annual mileage = 11,400 miles
Equiv. fuel economy = 71.4 mpg gasoline equiv. (HHV basis)
Gasoline HHV = 0.1308 GJ/gallon
Hydrogen HHV = 362 kJ/scf

Hydrogen use per day (scf/day) for an average passenger car =
= 11400 mi/yr/(365 day/yr x 71.4 mpg) x (0.1308 GJ/gallon/.000362 GJ/scf H2)
= 158 scf/day

So 1 million scf/day could fuel about a total fleet of about

1 million scf/day/ (158 scf/day/car) = 6300 cars

The number of vehicles served daily in the refueling station is calculated as follows:

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

For a passenger car, the number of cars fueled per day at a station dispensing 1 million scf H2/day would be

\# Cars refueled per day = 11400 mi/250 mi/365 day/yr x 6300 cars = 790 cars/day

Similarly for PEMFC buses, where annual mileage = 50,000 miles
Range = 250 miles
Fuel Economy = 6.9 mpg equiv.,

1 million scf H2/day could fuel a fleet of 140 buses, or about 80 buses/day

Table 1.8. 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 Company

Water Price	$0.0035/gallon

Source: Los Angeles Department of Water and Power

Table 1.8. Assumed Energy Prices in Southern California Case Study

Electricity Prices	Commercial Customer 20-500 kW		Large Customer >500 kW	
	Demand Charge ($/kW)	Rate Charge ($/kWh)	Demand Charge ($/kW)	Rate Charge ($/kWh)
LA Dept. of Power and Water[a] Time of Use Rates				
Summer				
on-peak	8.63	0.0540	8.52	0.0517
mid-peak	4.21	0.0535	4.1	0.0514
off-peak	1.4	0.0411	0.8	0.0396
Winter				
on-peak	7.9	0.0540	7.8	0.0540
mid-peak	3.85	0.0535	3.76	0.0535
off-peak	1.4	0.0411	0.8	0.0411
Southern California Edison[b] Time of Use Rates				
Summer				
on-peak	21.9	0.154	41.1	0.1007
mid-peak	8.65	0.068	1.1	0.0643
off-peak	6.3	0.044	0	0.0268
Winter				
on-peak	6.3	0.162	41.1	0.1007
mid-peak	6.3	0.081	0.5	0.0635
off-peak	6.3	0.044	0	0.0286

a. Source: Los Angeles Department of Water and Power, utility for the City of Los Angeles.
On peak = 1-5pm weekdays.
Mid-peak = 10am-1pm and 5-8 pm weekdays
Off-peak = all other times.

b. Source: Southern California Edison, utility for rest of South Coast Basin.
On peak = 12 noon-6pm summer weekdays.
Mid-peak = 8am-12 noon amd 6 pm-11pm summer weekdays and 8am-9pm winter weekdays.
Off-peak = all other times and holidays.

Natural Gas Price[c]	$2.8/GJ
Water Price[d]	$0.0035/gallon

c. This is the cost of natural gas delivered to a CNG vehicle station. The natural gas flow rate to a hydrogen reforming station should be similar (Wayne Tanaka, Southern California Gas Company, private communications 1996.).

d. Source: Los Angeles Department of Water and Power

Table 1.9a. Capital Cost for Developing New Hydrogen Delivery and Refueling Station Infrastructure Serving a Total Fleet of 13,000 FCV Cars, Delivering 2 million scf H_2/day (assuming that existing production capacity is used)

	Centralized Production via Steam Reforming of Natural Gas w/LH2 Delivery	Centralized Production via Steam Reforming of Natural Gas w/Pipeline Delivery	Onsite Steam Reforming of Natural Gas: Conventional Steam Methane Reformer	Onsite Steam Reforming of Natural Gas: Fuel Cell Steam Methane Reformer	Onsite Advanced Electrolysis Using Off-Peak Power
Centralized Hydrogen Production	0 (assumed that existing capacity is used)	0 (assumed that existing capacity is used)			
Hydrogen Distribution	0 (assumed that existing trucks are used)	10 km pipeline = $6.2 million (at $1 million per mile)			
2 Refueling Stations each serving 800 cars/day	$1.4 million ($0.7 per station)	$3.4 million ($1.7 million per station)	$10.8 million ($5.4 million per station)	$6.8 million ($3.4 million per station)	$11.4 million ($5.7 million per station)
TOTAL	$1.4 million	$9.6 million	$10.8 million	$6.8 million	$11.4 million
infrastructure cost per car	$105	$740	$830	$520	$880

Table 1.9b. Capital Cost for Developing New Hydrogen Production, Delivery and Refueling Station Infrastructure Serving a Total Fleet of 1 million Fuel Cell Cars, Delivering 153 million scf H_2/day

	Centralized Production via Steam Reforming of Natural Gas w/LH2 Delivery	Centralized Production via Steam Reforming of Natural Gas w/Pipeline Delivery	Onsite Steam Reforming of Natural Gas: Conventional Steam Methane Reformer	Onsite Steam Reforming of Natural Gas: Fuel Cell Steam Methane Reformer	Onsite Advanced Electrolysis Using Off-Peak Power
Centralized Hydrogen Production	$100 million for reformer + $ 200 million for liquefier + LH2 storage	$170 million for reformer + H_2 compressor			
Hydrogen Distribution	80 LH2 trucks each with a 3 tonne capacity, each making 2 local deliveries/day = $40 million	600 km pipeline = $380 million (at $1 million per mile)			
153 1 million scf H2/day Refueling Stations each serving 800 cars/day	$104 million ($0.7 million per station)	$260 million ($1.7 million per station)	$830 million ($5.4 million per station)	$516 million ($3.4 million per station)	$870 million $5.7 million per station)
TOTAL	$440 million	$810 million	$830 million	$516 million	$870 million
Infrastructure Cost per Car	$440	$810	$830	$516	$870

Table 1.10. Comparison of Projected Vehicle Performance and Lifecycle Cost

	Urban Buses		Mid-size automobiles	
	PEM FC Bus	Diesel Bus	PEM FC Car	Gasoline ICEV
Efficiency	6.9 mpg Diesel equiv.[a] = 52 scf/mile	3.5 mpg Diesel[c]	71.4 mpg gasoline equiv.[b]	26 mpg[b]
Miles/yr	50,000[c]	50,000[c]	11,140[d]	11,140[d]
Fuel Storage	H2 gas @3600 psi	Diesel Fuel	H2 gas @5000 psi	Gasoline
Range (mi)	250	250	250	400
Vehicle lifetime (years)	15	10	13.4[b]	10.7[b]
Purchase price ($)	325,000	237,000	24,550[b]	17,976[b]
Annual Maintenance Costs ($/year)	7438[e]	7438[e]	372[b]	396[b]

a. Based on the efficiency of the Ballard Phase II PEMFC bus (Ballard Power Systems, private communications 1995, 1996). The mile per gallon equivalent efficiency for a fuel cell vehicle is estimated assuming that 1 gallon of gasoline or Diesel contains 0.1308 GJ (HHV) and that 1 scf of hydrogen contains 362 kJ (HHV).

b. Based on estimates by Delucchi for mid-size (Ford Taurus) PEM fuel cell and gasoline automobiles (Ogden, Larson and Delucchi 1994).

c. Based on typical annual mileage and fuel use for a bus in the LA Basin (E. Chaiboonma, Los Angeles Metropolitan Transit Authority, private communications 1995).

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

e. For the Diesel bus, this includes annual maintenance plus upgrades at 3 and 8 years, and a major overhaul at 5 years. The maintenance for the PEM fuel cell bus is assumed to be the same (E. Larson et.al 1995).

APPENDIX 1.A.
CAPITAL COST AND PERFORMANCE ASSUMPTIONS FOR CENTRALIZED HYDROGEN PRODUCTION SYSTEMS, DISTRIBUTION SYSTEMS AND REFUELING STATIONS

1.A.1. CAPITAL COSTS OF CENTRALIZED HYDROGEN PRODUCTION SYSTEMS:

1.A.1.1. STEAM METHANE REFORMERS:

Capital costs for large, centralized steam methane reforming plants producing 160 million scf H2/day are from Katofsky 1993. The installed capital cost of the hydrogen plant is assumed to be $100 million. Compression to 1000 psi (for pipeline distribution) adds another $70 million.

1.A.1.2. HYDROGEN LIQUIFIERS AND LH2 STORAGE

In some cases, we assume that hydrogen is liquified after production. The capital cost for a liquifaction plant and associated liquid hydrogen storage is assumed to be:

Hydrogen Production Plant Capacity (million scf H2/day)	Liquifier Size (tonnes LH2 out/day)	Liquifier Capital Cost (million $)	LH2 Storage Size (tonnes)	Storage Capital Cost (million $)	Total Capital Cost for Liquifier + LH2 Storage (million $)
10.6	30	40	30	2.6	43
35	100	70	100	4.4	74
106	300	126	300	7.9	134
160[a]	450	190	450	12	202

Source: Ogden and Williams 1989, J.B. Taylor et.al 1986.

The cost for a 450 tonne LH2/day liquifier plant is estimated assuming that the cost per tonne/day is the same as for the 300 tonne/day case.

1.A.2. CAPITAL COSTS OF HYDROGEN DELIVERY SYSTEMS

1.A.2.1. LIQUID HYDROGEN TRUCKS

We assume that a liquid hydrogen truck with 3 ton capacity costs $500,000.

1.A.2.2. SMALL SCALE HYDROGEN PIPELINES

We assume that a 3" hydrogen pipeline capable of operation at up to 1000 psi costs $1 million per mile installed in the Los Angeles area.

1.A.3. CAPITAL COST OF HYDROGEN REFUELING STATIONS

Here we give cost estimates for hydrogen refueling stations dispensing 0.1 to 2.0 million scf of compressed H2 gas at 5000 psi per day. We consider:

1) Liquid hydrogen truck delivery from a centralized production plant
2) Gaseous pipeline delivery from a centralized production plant
3) Onsite steam methane reforming at the refueling station with a conventional reformer
4) Onsite steam methane reforming at the refueling station with a fuel cell type reformer
5) Onsite electrolysis at the refueling station with current electrolysis technology
6) Onsite electrolysis at the refueling station with advanced electrolysis technology

For details of the designs and costs, see (Ogden et.al 1995, Ogden et.al. 1996 and Chapter 2 of this report).

TABLE 1.A.1. SUMMARY OF ESTIMATED CAPITAL COST OF GASEOUS HYDROGEN REFUELING STATIONS

REFUELING STATION TYPE	**STATION CAPACITY SCF H2/DAY (Cars Fueled Per Day)**		
	100,000 (80 cars/day)	**366,000 (300 cars/day)**	**1,000,000 (800 cars/day)**
1) LH2 Truck Delivery	175,000	307,000	680,000
2) Pipeline H2 Delivery	200,500	620,500	1,681,500
3) Onsite Reforming (Conventional SMR)	1,769,900	3,054,740	5,379,500
4) Onsite reforming (FC SMR)	626,300	1,369,740	3,378,500
5) Onsite Electrolysis from Off-Peak Power: Current Electrolysis Technology	860,500	3,042,500	8,2455,500
6) Onsite Electrolysis from Off-Peak Power: Advanced Electrolysis Technology	608,500	2,132,500	5,745,500

Sources:
Ogden et.al 1995, Ogden et.al. 1996 and Chapter 2 of this report)

1) CAPITAL COST OF HYDROGEN REFUELING STATION: TRUCK DELIVERED LIQUID HYDROGEN

	STATION CAPACITY (SCF/D)		
REFUELING STATION INSTALLED CAPITAL COST($)	**100,000**	**366,000**	**1,000,000**
Liquid hydrogen storage tank	89,000	99,000	142,000
Liquid hydrogen pumps	30,000	90,000	240,000
Vaporizers (1 per pump)	6,000	18,000	48,000
Dispenser	50,000	100,000	275,000
TOTAL	175,000	307,000	680,000

2) CAPITAL COST OF HYDROGEN REFUELING STATION W/ H2 PIPELINE DELIVERY

	REFUELING STATION CAPACITY SCF/D		
REFUELING STATION INSTALLED CAPITAL COST($)	**100,000**	**366,000**	**1,000,000**
Storage cylinders	75,000	273,000	746,000
Storage compressor	65,000	237,000	650,000
Priority Panel and Sequencer	10,500	10,500	10,500
Dispenser	50,000	100,000	275,000
TOTAL	200,500	620,500	1,681,500

3) CAPITAL COST OF HYDROGEN REFUELING STATION W/ CONVENTIONAL STEAM METHANE REFORMER W/PSA

	REFORMER CAPACITY (SCF/D)		
REFUELING STATION INSTALLED CAPITAL COST($)	**100,000**	**366,000**	**1,000,000**
Reformer Plant	1,500,000	2,220,000	3,000,000
Storage cylinders	157,500	534,240	1,575,000
Storage compressor	51,900	190,000	519,000
Priority Panel and Sequencer	10,500	10,500	10,500
Dispenser	50,000	100,000	275,000
TOTAL	1,769,900	3,054,740	5,379,500

4) CAPITAL COST OF HYDROGEN REFUELING STATION W/ FUEL CELL STEAM METHANE REFORMER W/PSA

	REFORMER CAPACITY (SCF/D)		
REFUELING STATION INSTALLED CAPITAL COST($)	**100,000**	**366,000**	**1,000,000**
HYDROGEN PRODUCTION			
Reformer+Shift Reactors	88,000	218,000	440,000
1-stage Compressor	18,400	67,000	184,000
PSA	250,000	250,000	375,000
Sub-Total Hydrogen Production	356,400	535,000	999,000
Storage cylinders	157,500	534,240	1,575,000
Storage compressor	51,900	190,000	519,000
Priority Panel and Sequencer	10,500	10,500	10,500
Dispenser	50,000	100,000	275,000
TOTAL	626,300	1,369,740	3,378,500

5) CAPITAL COST OF HYDROGEN REFUELING STATION W/ CURRENT ELECTROLYSIS TECHNOLOGY (ASSUMES CONTINUOUS OPERATION)

REFUELING STATION INSTALLED CAPITAL COST($)	ELECTROLYZER OUTPUT SCF/D (PEAK OUTPUT kW H2 out) 100,000 (420 kW)	366,000 (1.5 MW)	1,000,000 (4.2 MW)
Electrolyzer (@$600/kW H2 out)	252,000	920,000	2,500,000
Storage cylinders	56,000	205,000	560,000
Storage compressor	75,000	275,000	750,000
Booster Compressor	36,000	132,000	360,000
Priority Panel and Sequencer	10,500	10,500	10,500
Dispenser	50,000	100,000	275,000
TOTAL	479,500	1,642,500	4,455,500

CAPITAL COST OF HYDROGEN REFUELING STATION W/ CURRENT ELECTROLYSIS TECHNOLOGY (ASSUMES OFF-PEAK OPERATION FOR 12 HOURS/DAY)

REFUELING STATION INSTALLED CAPITAL COST($)	ELECTROLYZER OUTPUT SCF/D (MAX OUTPUT IN kW H2 out) 100,000 (840 kW)	366,000 (3.0 MW)	1,000,000 (8.4 MW)
Electrolyzer (@$600/kW H2 out)	504,000	1,840,000	5,000,000
Storage cylinders	110,000	410,000	1,100,000
Storage compressor	150,000	550,000	1,500,000
Booster Compressor	36,000	132,000	360,000
Priority Panel and Sequencer	10,500	10,500	10,500
Dispenser	50,000	100,000	275,000
TOTAL	860,500	3,042,500	8,2455,500

6) CAPITAL COST OF HYDROGEN REFUELING STATION W/ ADVANCED ELECTROLYSIS TECHNOLOGY (ASSUMES CONTINUOUS OPERATION)

REFUELING STATION INSTALLED CAPITAL COST($)	ELECTROLYZER OUTPUT SCF/D (kW H2 out)		
	100,000 (420 kW)	366,000 (1.5 MW)	1,000,000 (4.2 MW)
Electrolyzer (@$300/kW H2 out)	126,000	460,000	1,250,000
Storage cylinders	56,000	205,000	560,000
Storage compressor	75,000	275,000	750,000
Booster Compressor	36,000	132,000	360,000
Priority Panel and Sequencer	10,500	10,500	10,500
Dispenser	50,000	100,000	275,000
TOTAL	353,500	1,182,500	3,205,500

CAPITAL COST OF HYDROGEN REFUELING STATION W/ ADVANCED ELECTROLYSIS TECHNOLOGY (ASSUMES OFF-PEAK OPERATION FOR 12 HOURS/DAY)

REFUELING STATION INSTALLED CAPITAL COST($)	ELECTROLYZER OUTPUT SCF/D (MAX OUTPUT IN kW H2 out)		
	100,000 (840 kW)	366,000 (3.0 MW)	1,000,000 (8.4 MW)
Electrolyzer (@$300/kW H2 out)	252,000	920,000	2,500,000
Storage cylinders	110,000	410,000	1,100,000
Storage compressor	150,000	550,000	1,500,000
Booster Compressor	36,000	132,000	360,000
Priority Panel and Sequencer	10,500	10,500	10,500
Dispenser	50,000	100,000	275,000
TOTAL	608,500	2,132,500	5,745,500

CASE STUDY OF DEVELOPING A HYDROGEN REFUELING INFRASTRUCTURE IN SOUTHERN CALIFORNIA

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ABSTRACT

Unlike gasoline, natural gas or electricity, hydrogen is not widely distributed to consumers today. Assuming that hydrogen vehicles capture a significant fraction of the ZEV market, a large demand for hydrogen fuel could evolve over the next few decades. In this report, we examine the hydrogen infrastructure question for a specific region, where fuel cell vehicles might be introduced, the Los Angeles Basin.

We assess several near term options for producing and delivering gaseous hydrogen transportation fuel to users in Southern California including: 1) hydrogen produced from natural gas in a large, centralized steam reforming plant, and truck delivered as a liquid to refueling stations, 2) hydrogen produced in a large, centralized steam reforming plant, and delivered via small scale hydrogen gas pipeline to refueling stations, 3) hydrogen produced at the refueling station via small scale steam reforming of natural gas, 4) hydrogen produced via small scale electrolysis at the refueling station, and 5) hydrogen from low cost chemical industry sources (e.g. excess capacity in refineries which have recently upgraded their hydrogen production capacity, etc.).

To compare these alternatives, we address the following questions:

* What are projected hydrogen demands for ZEVs and potential hydrogen supplies in the LA Basin?

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

* What is the lifecycle cost of transportation for hydrogen vehicles fueled with hydrogen from these sources?

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