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ABSTRACT

We compare, with respect to vehicle characteristics (design, performance, fuel economy) and infrastructure requirements (cost of producing, transporting and delivering fuel), four possible energy carrier options for use with fuel cell vehicles:

* compressed hydrogen gas
* methanol with onboard steam reforming
* gasoline with onboard partial oxidation
* synthetic middle distillates (SMD) derived from natural gas with onboard partial oxidation.

Our simulations indicate that hydrogen is the preferred fuel for fuel cell vehicles in terms of vehicle weight, simplicity, first cost and fuel economy. The total capital cost for equipment to bring hydrogen to the fuel cell (including both onboard fuel processors and off-vehicle fuel infrastructure) is comparable for methanol, gasoline and SMD, and lower for hydrogen.

INTRODUCTION

Development of refueling infrastructure is a major challenge to introducing new transportation fuels and vehicle technologies. All fuel cells currently being developed for use in vehicles require hydrogen as a fuel. Hydrogen can either be stored directly or produced onboard the vehicle by reforming a liquid fuel such as gasoline, methanol, or synthetic liquids from natural gas. The vehicle design is simpler with direct hydrogen storage, but requires developing a more complex refueling infrastructure.

Here we compare, with respect to vehicle characteristics and infrastructure requirements, four possible energy carrier options for use with fuel cell vehicles (see Figure 1):

* compressed hydrogen gas
* methanol with onboard steam reforming
* gasoline with onboard partial oxidation
* synthetic liquids (such as synthetic middle distillates) derived from natural gas with onboard partial oxidation.

Fuel cell vehicles are currently being developed which use hydrogen, methanol or gasoline. Synthetic middle distillate (SMD) is a leading contender as a low polluting fuel for advanced internal combustion engine vehicles, and it has been proposed that SMD could be used in fuel cell vehicles as well.

To estimate the performance of alternative fuel cell vehicle types, we have developed a vehicle simulation model, including detailed models of onboard fuel processors. This is used to compare the vehicle performance, fuel economy, weight, and cost for various vehicle parameters, fuel storage choices and driving cycles. Infrastructure capital costs (including the added costs of fuel production, distribution, and refueling stations), delivered fuel cost, fuel cost per kilomteter and lifecycle cost of transportation are estimated for each alternative. Considering both vehicle and infrastructure issues, possible fuel strategies leading to the commercialization of fuel cell vehicles are discussed. Flexibility would be gained by using fuels which could also serve other advanced vehicle types and are easily compatible with the existing gasoline refueling system . However, for fuel cell vehicles with onboard fuel processors, there is a trade-off in lower fuel cell vehicle fuel economy and higher cost.

COMPARISON OF ALTERNATIVE DESIGNS FOR FUEL CELL VEHICLES

SIMULATION MODEL OF FUEL CELL VEHICLES. We have developed a computer model for proton exchange membrane fuel cell vehicles, as a tool for estimating the performance, fuel economy and cost of alternative fuel cell vehicle designs. The details of the model are given in the earlier papers (Steinbugler 1996; Steinbugler and Ogden 1996; Steinbugler 1998; Ogden, Steinbugler and Kreutz 1997).

Input parameters to the model include:

* the driving schedule [the Federal Urban Driving Schedule (FUDS), Federal Highway Driving Schedule (FHDS) or others may be used]
* vehicle parameters (the base vehicle weight without the power train, the aerodynamic drag, the rolling resistance, vehicle frontal area, accessory loads),
* fuel cell system parameters (fuel cell current-voltage characteristic, fuel cell system weight),
* peak power battery characteristics

(behavior on charging and discharging, weight),

- fuel processor parameters (conversion efficiency, response time, weight, hydrogen utilization in the fuel cell).

First, the fuel cell system and peak power device are sized according to the following criteria:

- The fuel cell system alone must provide enough power to sustain a speed of 55 mph on a 6.5% grade.

- The output of the fuel cell system plus the peak power device must allow acceleration for high speed passing of 3 mph/sec at 65 mph.

These criteria are consistent with the goals set by the Partnership for a New Generation of Vehicles (PNGV).

Once the components are sized, the vehicle weight is calculated, accounting for any extra structural weight needed on the vehicle to support the power system. Then the fuel economy is calculated for a desired driving schedule. At each time step of the driving schedule the "road load" equation [1] is solved to find the total power P_D needed from the vehicle's electrical power system (fuel cell plus peak power device).

$$P_D = P_{aux} + (mav + mgC_R v + 0.5\ r\ C_D\ A_F\ v^3)/h \qquad [1]$$

where:

P_D = total electrical power demanded of vehicle's power system (Watts)
P_{aux} = power needed for accessories such as lights and wipers (Watts)
m = vehicle mass (kg)
a = vehicle acceleration (m/s^2)
v = vehicle velocity (m/s)
g = acceleration of gravity = 9.8 m/s^2
C_R = rolling resistance
r = density of air (kg/m^3)
C_D = aerodynamic drag coefficient
A_F = vehicle frontal area (m^2)
h = efficiency of electric motor, controller and gearing

If the fuel cell alone cannot supply the power needed, the peak power battery is called upon. Power demanded is allocated between the fuel cell and battery in a way that both accounts for fuel processor response time and aims to maintain the battery at a target state of charge. (The program is set up to keep the battery near its ideal state of charge, by recharging from the fuel cell during driving or via regenerative braking.) Knowing the fuel processor efficiency, the fuel consumed in each time step can be estimated. Fuel consumption is summed over the drive cycle and divided into the distance travelled to give a fuel economy, expressed in miles per equivalent gallon of gasoline.

Table 1.
Conversion Factors And Economic Assumptions

All costs are given in constant $1995.

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

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

1 million standard cubic feet (scf)
= 26,850 Normal cubic meters ($m_N{}^3$)

$1/gallon gasoline = $7.67/GJ (HHV)
$1/gallon methanol = $15.4/GJ (HHV)
$1/gallon Synthetic Middle Distillate = $ 6.85/GJ (HHV)

FUEL	HEATING VALUE
Hydrogen	343 kJ/scf (HHV) 12.8 MJ/Nm^3 (HHV) 141.9 MJ/kg (HHV) 120.2 MJ/kg (LHV)
Methanol	64,600 BTU/gallon (HHV) 22.7 MJ/kg (HHV) 19.9 MJ/kg (LHV)
Gasoline	125,000 BTU/gall (HHV) 115,400 BTU/gal (LHV) 45.9 MJ/kg (HHV)
Sythetic Middle Distillate	139,000 BTU/gal (HHV)

MODEL RESULTS: VEHICLE PERFORMANCE, FUEL ECONOMY AND COST FOR ALTERNATIVE FUEL CELL VEHICLE DESIGNS. Tables 1 and 2 summarize the assumptions used in the model. The base vehicle is a streamlined, lightweight, 4-5 passenger mid-size automobile with a 800 kg "glider", aerodynamic drag of 0.20 and rolling resistance of 0.007. Table 3 shows the results for vehicle mass, the required size for the fuel cell and peaking battery, the fuel economy and range for alternative fuel cell vehicle designs. Each vehicle is designed to satisfy identical performance characteristics.

Vehicle Weight. The vehicle weight varies with the vehicle type. The various components' contributions to the total vehicle mass are shown for hydrogen, methanol and gasoline fuel cells cars in Figure 2. Vehicles with onboard fuel processors are heavier for several reasons. First, the fuel processor adds weight. Second, the fuel cell/fuel processor system is less energy efficient than a pure hydrogen system, so a larger fuel cell is needed to provide the same power output, if the fuel cell is run on reformate. Third, the mass of the vehicle support structure is increased by 15% of the additional weight it carries. The methanol fuel cell vehicle weighs about 10% more than the hydrogen vehicle, the gasoline POX vehicle about 19% more.

Table 2. Parameters Used in Fuel Cell Vehicle Modelling	
Vehicle Parameters	
Glider Weight (= vehicle - power train)[a]	800 kg
Drag Coefficient[a]	0.20
Rolling Resistance[b]	0.007
Frontal Area[a]	2.0 m^2
Accessory Load[c]	0.4 kW
Structural Weight Compounding Factor[d]	15%
Fuel Cell System	
Operating pressure	3 atm
Cathode Stoichiometry	2
System weight (including air handling, thermal and water management)[e]	4.0 kg/kW
Fuel Processor Systems	
Methanol Steam Reformer	
Gross efficiency (HHV H2 consumed in fuel cell /HHV MeOH in)	62%
Hydrogen utilization[g]	80%
Voltage Penalty for reformate operation[h]	0.06 x current (amp/cm^2)
Weight of system[i]	32 kg+1.1 kg/kW
Response time	5 sec
Reformate Composition	70% H_2, 24% CO_2, 6% N_2
Gasoline or SMD POX	
Efficiency (HHV H2 consumed/HHV gasoline in)[j]	69.4%
Hydrogen utilization[g]	80%
Voltage Penalty for reformate operation[h]	0.128 x current (amp/cm^2)
Weight of system[i]	32 kg+1.1 kg/kW
Response time	1 sec
Reformate Composition	42% N_2, 38% H_2, 18% CO_2, 2% CH_4
Peak Power Battery	
Battery type	Spiral wound, thin film, lead-acid
System weight[k]	1.0 kg/kW
Maximum charge rate	30 amps
Nominal state of charge[k]	50%
Energy stored[k]	15 Wh/kg
Motor and Controller	
Overall efficiency[b]	77%
Overall weight[l]	2.0 kg/kW
Fuel Storage	
Hydrogen[d]	5000 psi compressed gas tank total weight 50 kg, 7.5% H2 by weight
Methanol, Gasoline, SMD	12 kg tank, 13 gallon capacity,total weight 50 kg
Driving schedules	FUDS, FHDS
Regenerative braking recovery up to batt. capabilities	

Notes for Table 2

a. Based on PNGV targets. (Source: CALSTART website. http://www.calstart.org/about/pngv/pngv_ta.html)

b. Energy and Environmental Analysis, "Analysis of Fuel Economy Boundary for 2010 and Comparison to Prototypes," p. 4-11, prepared for Martin Marietta Energy Systems, Contract No. 11X-SB0824, November 1990.

c. Ross, M. and W. Wu, "Fuel Economy Analysis for a Hybrid Concept Car Based on a Buffered Fuel-Engine Operating at a Single Point," SAE Paper No. 950958, presented at the SAE Interantional Exposition, Detroit, MI, Feb 27-March 2, 1995.

d. C.E. Thomas and R. Sims, "Overview of Onboard Liquid Fuel Storage and Reforming Systems," "Fueling Aspects of Hydrogen Fuel Cell Powered Vehicles," Society of Automotive Engineers, Proceedings, Fuel Cells for Transportation TOPTEC, April 1-2, 1996, Arlington, VA.

e. Based on a Ballard-type PEM fuel cell system with a stack power density of 1 kg/kW. Other weight is due to auxiliaries for heat and water management equipment and air compression.

f. Arthur D. Little 1994. "Multi-Fuel Reformers for Fuel Cells Used in Transportation, Multi-Fuel Reformers, Phase I Final Report," USDOE Office of Transportation Technologies, Contract No. DE-AC02-92-CE50343-2.

g. This estimate was verified with fuel cell developers.

h. The voltage penalty for operation on reformate is based on models by Shimson Gottesfeld at Los Alamos National Laboratory.

i. William Mitchell, Arthur D. Little, private communications, 1997.

j. Mitchell, W. April 2, 1996. "Development of a Partial Oxidation Reformer for Liquid Fuels," Society of Automotive Engineers, Proceedings, Fuel Cells for Transportation TOPTEC, Arlington, VA.

k. Keating, J., B. Schroeder and R. Nelson 1996. "Development of a Valve-Regulated, Lead/Acid Battery for Power-Assist Hybrid Electric Vehicle Use," Bolder Technologies Corporation, Wheat Ridge, CO.

l. Chang, L. "Recent Developments of Electric Vehicles and Their Propulsion Systems," Proceedings of the 28th Intersociety Engineering Conference, vol. 2, pp. 2.205-2.210, American Chemical Society, 1993.

Power Requirements for the Fuel Cell and Peak Power Device. The peak power required is shown in Table 3 for various fuel cell vehicle designs. Roughly, the fuel cell and battery each provide about half the peak power. For hydrogen, a lower fuel cell capacity and overall peak power output is needed, because the vehicle is lighter. It is interesting to note that the power required by the FUDS and FHDS driving schedules is considerably less than the maximum fuel cell power, when the fuel cell is sized for sustained hill climbing.

Fuel Economy. The fuel economy is shown for the FUDS, FHDS, and combined driving cycles. The combined driving cycle fuel economy is defined as:

mpg (combined) = 1/(.55/mpg FUDS + .45/mpg FHDS)

The energy efficiency of the methanol, gasoline and sythetic middle distillate fuel cell vehicles is about 2/3 that of the hydrogen fuel cell vehicle. The loss of efficiency is due to several effects. First is the 15-25% energy loss in converting methanol, gasoline or SMD to hydrogen. Second, operation on reformate means that the fuel cell has a lower efficiency. Third, the vehicle weighs 10-20% more with an onboard fuel processor. Finally, for themethanol steam reformer, the 5 second response time means that a significant fraction (40-50%) of the energy must be routed through the battery, with attendant losses in charging and discharging.

Table 3. Model Results: Comparison of Alternative Fuel Cell Vehicle Designs

Fuel Storage/ H2 Gen. System	Veh. mass (kg)	Peak Power (kW) (FC/ Batt.)	FUDS mpeg	FHDS mpeg	Combined 55% FUDS 45% FHDS mpeg	range (mi)
Direct H2	1170	77.5 (34.4/ 43.1)	100	115	106	425
MeOH Steam Reformer	1287	83.7 (37.0/ 46.7)	62	79	69	460
Gasoline or SMD POX	1395	89.4 (39.4/ 50.0)	65	80	71	940

Table 4. Cost Estimates for Mass Produced Fuel Cell Vehicle Components

Component	High estimate	Low estimate
Fuel cell system[a]	$100/kW	$50/kW
Fuel processor system [b]	$25/kW	$15/kW
Hydrogen storage cylinder rated at 5000 psia[c]	$1000	$500
Motor and controller[d]	$26/kW	$13/kW
Peak power battery[e]	$20/kW	$10/kW
Extra structural support	$1/kg	$1/kg
Cost of 12 kg gasoline or methanol tank	$100	$100

Adapted from Ogden, Steinbugler and Kreutz 1997.

Notes for Table 4.

a. Based on a range of estimates found in the literature. For example, GM/Allison projects a fuel cell "electrochemical engine" cost of $3899 for a 60 kW system including the fuel cell, fuel processor (methanol reformer), heat and water management. This is about $65/kW (at the rated power of 60 kW) or $46/kWpeak. About 45% of the cost per peak kW ($21/kW) is for the fuel cell stack, 28% ($13/kW) for the methanol reformer and the rest for auxiliaries. This cost assumes large scale mass production. (Allison Gas Turbine Division of General Motors December 16, 1992).

Mark Delucchi of Institute of Transportation Studies at UC Davis estimates a retail cost of $2954 for a mass produced 25 kW hydrogen/air PEM fuel cell system or about $120/kW. (The manufacturing cost is $59/kW, with a materials costs for the fuel cell stack plus auxiliaries estimated to be $41/kW, and the labor cost $18/kW.) (J. M. Ogden, E.D. Larson and M.A. Delucchi May 1994).

A recent study by Directed Technologies, Inc. and Ford Motor Company estimated fuel cell stack manufacturing costs of $19-27/kW using conventional manufacturing techniques, assuming production of 500,000 units per year. (F.D. Lomax, B.D. James and R.P. Mooradian, "PEM Fuel Cell Cost Minimization Using Design for Manufacture and Assembly Techniques," Proceedings of the 8th National Hydrogen Association Meeting, Alexandria, VA, March 11-13, 1997, pp. 459-468.)

Chrysler estimates that even with current fuel cell manufacturing technology, mass produced costs would be $200/kW (Chris Boroni-Bird, private communications 1997).

b. W. Mitchell, J. Thijssen, J.M. Bentley, "Development of a Catalytic Partial Oxiidation Ethanol Reformer for Fuel Cell Applications," Society of Automotive Engineers, Paper No. 9527611, 1995.

c. C.E. Thomas and R. Sims, "Overview of Onboard Liquid Fuel Storage and Reforming Systems," "Fueling Aspects of Hydrogen Fuel Cell Powered Vehicles," Society of Automotive Engineers, Proceedings, Fuel Cells for Transportation TOPTEC, April 1-2, 1996, Arlington, VA.

d. Derived from estimates in B. James, G. Baum, I. Kuhn, "Development Goals for Automotive Fuel Cell Power Systems," ANL-94/44, August 1994.

e. Based on PNGV goals

Range The vehicle range exceeds the PNGV goal of 380 miles, for all the fuel cell vehicle cases considered in Table 3.

Vehicle Capital Cost Table 4 summarizes our cost assumptions for fuel cell vehicle drive train and fuel storage components in high volume mass production, based on a range of estimates in the literature. Two sets of cases are shown, one corresponding to a low range of values for fuel cell, fuel processor, battery and hydrogen storage mass produced costs, the other to a high range of values. Using projected mass produced component costs in Table 4 and component sizes from Table 3, we estimate the total capital cost of drive train and fuel storage components for each case (Figure 3). The total cost ranges from about $3600 to over $7000, depending on the assumptions. Fuel cell vehicles with onboard fuel processor systems have a higher first cost than those with direct hydrogen storage. This is due to extra costs for the fuel processor and because a larger capacity (and more costly) fuel cell is needed to achieve the same performance. The first cost of fuel cell vehicles with onboard methanol steam reformers would be higher than that for hydrogen fuel cell vehicles by about $500-600/car. We estimate gasoline or SMD POX fuel cell cars would cost $850-1200/car more than hydrogen fuel cell vehicles. (This does not include the cost of off-vehicle refueling infrastructure, which is estiumated in later sections.)

Summary In summary, for the same performance, hydrogen fuel cell vehicles are likely to be simpler in design, lighter, more energy efficient, and less expensive than methanol, gasoline or SMD fuel cell vehicles. Moreover, the tailpipe emissions will be strictly zero under all operating conditions

COMPARISON OF REFUELING INFRASTRUCTURE REQUIREMENTS FOR FUEL CELLS FUELED WITH HYDROGEN, METHANOL, GASOLINE AND SYNTHETIC MIDDLE DISTILLATES

PROJECTED ENERGY DEMAND FOR FUEL CELL VEHICLES. Refueling infrastructure requirements depend on the amount of energy which must be delivered, which can be calculated from the number of vehicles in use and the average energy consumption per vehicle. Table 5 describes the assumed annual fuel consumption of PEM fuel cell automobiles fueled with hydrogen, methanol, gasoline and synthetic middle distillates. The annual energy use is lowest for hydrogen fuel cell vehicles, as they have the highest fuel economy. Although methanol, gasoline and SMD fuel cell cars are projected to have about the same fuel economy (about 2/3 that of the hydrogen fuel cell vehicle), roughly twice as many gallons of methanol would be needed per year, because of its lower volumetric energy density compared to gasoline or SMD.

DEVELOPMENT OF REFUELING INFRASTRUCTURE FOR HYDROGEN VEHICLES The relative simplicity and lower cost of the hydrogen fuel cell vehicle must be weighed against the added complexity and cost of developing a hydrogen refueling infrastructure. Hydrogen infrastructure is often cited as a "show-stopper" for hydrogen vehicles. Recent studies have shown that the issue is not technical feasibility. Large quantities of hydrogen are produced and delivered routinely for chemical applications today (Heydorn 1995), and the technologies to produce, store and transport hydrogen are mature, well established and commercially available. However, the cost of hydrogen infrastructure is widely regarded as much higher than that for other fuels. Here we summarize results of our previous studies dealing with the technical feasibility and economics of developing a hydrogen vehicle refueling infrastructure (Ogden, Dennis, Steinbugler and Strohbehn 1995, Ogden, Cox and White 1996, Ogden 1997, Ogden 1998).

Table 5. Assumed Characteristics of PEM Fuel Cell Automobiles

Fuel:	Hydrogen Gas @ 5000 psi	Methanol	Gasoline	SMD PEMFC
Fuel economy a,b	106 mpg gasoline equiv.	69 mpg gasoline equiv.	71 mpg gasoline equiv.	71 mpg gasoline equiv.
Mile/yr[c]	11,000	11,000	11,000	11,000
Fuel stored onboard	1550 scf H2 (3.75 kg)	13 gallons methanol	13 gallons gasoline	13 gallons SMD
Range (mi)	425	460	940	1049
Energy use per year (GJ/yr)[a]	13.6	20.9	20.3	20.3
Fuel use per year[d]	40,000 scf H2/yr	307 gallons methanol/yr = 919 kg/yr	155 gallons gasoline/yr =3.69 bbl/yr	138 gallons SMD/yr = 3.28 bbl/yr

Notes for Table 5

a. The mile per gallon gasoline equivalent efficiency for a fuel cell vehicle is estimated assuming that 1 gallon of gasoline contains 125,000 BTU = 0.1308 GJ (HHV), 1 gallon of methanol contains 64,600 BTU = 0.068 GJ (HHV); 1 gallon of synthetic middle distillate contains 0.146 GJ, and that 1 scf of hydrogen contains 343 kJ (HHV).

b. Based on our estimates for a PEMFC automobile fuel economy and range. (See Table 3).

c. Typical annual mileage for a passenger car in the LA Basin. (R. George, SCAQMD, private communications 1998).

d. The specific weight of methanol is assumed to be 791 kg/m^3; 42 gallons = 1 barrel (bbl)

A number of near term possibilities exist for producing and delivering gaseous hydrogen transportation fuel, which employ commercial technologies for hydrogen production, storage and distribution. These include (see Figure 4):

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

(b) hydrogen produced in a large, centralized steam reforming plant, and delivered via local, small diameter hydrogen gas pipeline to refueling stations,

(c) hydrogen from chemical industry sources (e.g. excess capacity in refineries which have recently upgraded their hydrogen production capacity, etc.), with pipeline delivery to a refueling station.

(d) hydrogen produced at the refueling station via small scale steam reforming of natural gas, (in either a conventional steam reformer or an advanced steam reformer of the type developed as part of fuel cell cogeneration systems)

(e) hydrogen produced via small scale water electrolysis at the refueling station,

In the longer term, other methods of hydrogen production might be used including gasification of biomass, coal or municipal solid waste, or electrolysis powered by off-peak hydropower, wind, solar or nuclear power (Figure 5). Sequestration of byproduct CO_2 (for example, in deep aquifers or depleted gas wells) might be done to reduce greenhouse emissions from hydrogen derived from hydrocarbons (Williams 1996).

<u>Delivered cost of hydrogen transportation fuel</u> The levelized cost of compressed gas hydrogen transportation fuel, delivered to the vehicle at 5000 psi, is estimated in Figure 6 for various near term supply options. The cost contributions of various factors are shown for each technology over a range of typical refueling station sizes from 0.1 to 2.0 million scf/day (e.g. stations capable of refueling about 65-1300 fuel cell cars/day or 8-160 fuel cell buses/day). Delivered fuel costs are given in $/GJ. (On a higher heating value basis, the energy cost of $1/gallon gasoline is equivalent to $7.7/GJ -- see Table 1.) In this example, we have used energy prices in the Los Angeles area, where the natural gas cost is low ($2.8/GJ), and the cost of off-peak power is relatively high (3 cents/kWh). A capital charge rate of 15% is assumed.

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

* The delivered cost of hydrogen transportation fuel is about $12-35/GJ (or $1.6-4.8/gallon gasoline equivalent), substantially higher than for today's untaxed gasoline, which is perhaps $0.70/gallon.

* Onsite production of hydrogen via small scal steam reforming of natural gas is economicall attractive and has the advantage that no hydrogen distribution system is required. Delivered hydrogen costs are shown for advanced low cost reformers, which have recently been introduced for stationary hydrog production (Farris 1996, Halvorson et.al 1997). With advanced reformers, onsite reforming is competitive with liquid hydrogen truck deliver and pipeline delivery over the whole range of station sizes considered.

* Truck delivered liquid hydrogen gives a delivered hydrogen cost of $20-30/GJ, dependi on the station size. This alternative would be also attractive for early 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 development would be required.

* Under certain conditions, a local gas pipeline bringing centrally produced hydrogen to users could offer low delivered costs. Our example assumes that it costs $7/GJ to produce hydroge centrally and $5/GJ to distribute it by local pipeline. However, centrally produced hydroge 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 The cost of pipeline distribution depends on th distance between supply and demand and size the demand. (The cost of pipeline delivery increases with pipeline length, and decreases with increased flow rate through the pipeline.) 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. 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.

* It appears that onsite electrolysis would be somewhat more expensive than other options, largely because of the relatively high cost of off-peak power (3 cents/kWh) assumed in the study. If the cost of off-peak power were reduced from 3 cents/kWh to 1-1.5 cents/kWh (costs which are available in a few places with off-peak hydropower), hydrogen costs would become more competitive.

From Figure 6, it is apparent that the cost of hydrogen depends on the prices of natural gas and electricity, as wel as the station size, and (for centrally produced hydrogen) the proximity of hydrogen supply and demand. The relativ costs shown in Figure 6 are based on Southern California energy prices, and will vary for different cost assumptions. It is important to note that in this range of hydrogen demand (0.1-2.0 million scf hydrogen/day), no one supply option is favored for all energy price conditions. [For our assumptions (low cost natural gas, and relatively high cost off-peak power), onsite steam reforming gives the lowest delivered cost at all station sizes. But onsite electrolysis might be favored in a location such as Brazil with high natural gas prices and low off-peak power prices.]

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 7, 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 a 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 18,400 cars, each station dispensing 1 million scf H2/day to 650 cars/day. (Alternatively, this level of infrastructure development could serve 2 bus garages each housing 140 PEMFC buses.) 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. This is consistent with a recent study of hydrogen supply in the Southern California area which indicated that as much as 5-15 million scf/day might be available from excess industrial hydrogen production capacity and refinery excess (Ogden 1998).

* Development of new hydrogen production, delivery and refueling capacity to meet growing demands for hydrogen transportation fuel. The system serves a total fleet of 1.41 million cars, with 153 refueling stations, where each station dispensing 1 million scf H2/day to 650 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 18,400 fuel cell cars, is about $1.4-11.4 million or $80-620/car. The range of infrastructure capital costs for a system serving 1.41 million fuel cell cars, is about $440-870 million or $310-620/car.

It is important to keep in mind the results of Figure 6 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. Onsite small scale steam reforming is attractive as having both a relatively low capital cost (for advanced fuel cell type reformers), and a low delivered fuel cost.

DEVELOPING A REFUELING INFRASTRUCTURE FOR METHANOL FUEL CELL VEHICLES At present (as of 1995) the worldwide methanol nameplate production capacity is about 28 million metric tonnes per year. About 23 million metric tonnes were actually produced in 1995, yielding a capacity factor of about 83%.

Although the number of retail methanol fuel outlets is small, a significant methanol distribution already system exists for chemical applications. Of total world production, roughly half or 12 million metric tonnes were shipped to remote users, 70% by sea and 30% by rail, tank wagon or barge (Glyn Short, 1997). Typically, tank ships transport methanol from production plants sited near inexpensive sources of natural gas to marine terminals. At the terminals, the methanol is loaded into tank trucks and delivered to users.

About 90% of methanol is produced from natural gas, although it would be possible to produce methanol via gasification of coal, heavy liquids, biomass or wastes. The main uses of methanol today are production of formaldehyde, MTBE and acetic acid.

If the entire 1995 methanol production capacity were dedicated to producing fuel for methanol fuel cell cars, we estimate that about 31 million cars could be fueled. Since the capacity is not fully utilized at present, this suggests that excess production capacity might be enough to fuel up to a few million methanol fuel cell cars worldwide.

Initially, to serve small numbers of methanol fuel cell cars, it would probably be possible to provide methanol transportation fuel using the existing methanol distribution system without building new terminals or tank trucks. In this case the only capital cost associated with developing a methanol refueling infrastructure would be conversion of gasoline refueling stations to methanol. This has been estimated to cost between $6000-52,500 for a station dispensing 1100 gallons of methanol per day (DOE 1990). Such a station might serve a total fleet of 1300 methanol fuel cell cars. The capital cost per car would be a modest $6-40/car (see Table 6).

Once a larger number of methanol cars were in use, the methanol distribution network would have to be expanded to convert existing gasoline marine terminals and delivery trucks to methanol. However, this cost for this conversion would be modest as well, perhaps $9/car (DOE 1990). This strategy would work until the market for automotive methanol exceeded the excess production capacity in the system.

Table 6. Projected Capital Cost per Car Of Methanol Refueling Infrastructure			
Item	Cost	# Cars Served	Capital Cost (S/car) (adjusted from year of estimate to 1995S)
Convert Gasoline Refueling Station to Methanol (1990S)	S5,000-45,000 per station[a] (for a station dispensing 1100 gallons MeOH/day)	1309	5 - 40
Methanol Delivery truck (1990S)	No cost (use existing gasoline trucks)[a] S140,000 (per new 8500 gallon MeOH truck)[a]	10,000	0 14
Marine Terminal Bulk Storage Tank for Methanol (1990S) (for a terminal with 1.3 million bbl storage = 20 days storage) Other terminal equipment	S2.50/bbl MeOH (convert gasoline storage)[a] S15/bbl MeOH (build new MeOH storage)[a] S1/bbl MeOH	2.4 cars/bbl of storage capacity 15,400 cars (minimum)	9
Methanol Overseas Shipping Costs (1986S)	Capital cost for new 250,000 dwt tanker = S50 million[d] trans cost= 3-5 cents/gal[b,c]	3-15 million cars (if tanker makes 10-50 deliveries/yr	4-25
Methanol Production Plant (from NG) (1988S)	S880-1540 million[c] (10,000 metric tonnes/day) S330-570 million[c] (2500 metric tonne/day)	4.0 million cars 1.0 million cars	280-485 415-720

Notes for Table 6.

a. DOE/PE-0095P, "Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the US Transportation Sector," USDOE, Policy, Planning and Analysis, Washington, DC, August 1990. This assumes that the storage capacity holds 20 days worth of fuel.

b. M. Lawrence and J. Kapler, "Natural Gas, Methanol and CNG: Projected Supplies and Costs," presented to "Transportation Fuels in the 1990s and Beyond, A Conference of the Transportation Research Board, Monterey, CA, July 1988.

c. A. Krupnik, M. Walls, M. Tolman, "The Cost Effectiveness and Energy Security Benefits of Methanol Vehicles," Resources for the Future, Discussion Paper QE90-25, September 1990.

d. Jack Faucett Associates, 7300 Pearl St., Bethesda, MD, "Methanol Prices During the Transition," prepared for the Environmental Protection Agency, Report No. JACKFAU-86-322-8/11, August 1987.

To bring methanol to millions of fuel cell cars would involve increases in methanol production capacity and tanker capacity, as well. A sea-going methanol tanker would be costly, on the order of S70 million (in 1995S) for an ultra large tank ship carrying 250,000 dead weight tons (DWT) (Faucett 1987). However, it would serve a large fleet of fuel cell cars (a fleet about 3-15 million cars could be served bysuch a tanker, assuming the ship made 10-50 deliveries per year). The capital cost for new tankers would be modest on a per car basis, perhaps S4-25/car. However, the capital costs for new production capacity would be significant (Table 6). For a new 2500 tonne per day plant, serving 1.0 million methanol fuel cell cars, the capital cost would be about S415-720/car. At a larger plant size (10,000 tonnes methanol per day) serving 4.0 million cars, the capital cost would be S280-485/car (Lawrence and Kapner 1988, Krupnik, Walls and Tolman 1990).

Adding new production capacity is by far the most expensive step in developing a new methanol refueling infrastructure. If methanol fuel cell cars became a large fraction of the current light duty vehicle fleet (more than perhaps a million vehicles), new capital costs for additional production capacity would be incurred.

At low market penetrations of methanol fuel cell vehicles, infrastructure capital costs will be small (probably less than S50/car). However, once methanol is used in more than perhaps a million fuel cell vehicles, new production capacity would be needed, bringing the capital costs per car to levels similar to those for hydrogen, about S330-770/car, depending on the assumptions (see Figure 8).

This is a surprising result. One would expect that infrastructure costs for a liquid fuel like methanol would be inherently much lower than for a gaseous fuel like hydrogen. Certainly, if one compares only distribution and refueling station costs, a methanol infrastructure is much less costly to implement than a hydrogen infrastructure, a view supported by earlier studies of methanol and hydrogen infrastructure (DOE 1990). But once a large level of alternative fuel use is assumed, the picture changes. In this case, the majority (about 90% or more) of the capital cost of methanol infrastructure development is due to building new production capacity, rather than to distribution systems and refueling stations. Hydrogen production is somewhat less costly than methanol production per unit of energy output from the plant. (This is true because the conversion efficiency of natural gas to fuel is higher for hydrogen than for methanol production.) Moreover, hydrogen fuel cell vehicles are estimated to be 50% more energy efficient than methanol fuel cell cars (Table 3), so that a given energy production capacity will serve a larger number of cars. The overall effect is that even with hydrogen's much higher distribution and refueling station costs, the total capital cost of infrastructure development per car is comparable for methanol and hydrogen, once a high level of fuel cell vehicle use is achieved. The high cost of new methanol production capacity and the hydrogen vehicle's higher energy efficiency combine to level the playing field.

Although most methanol today, and for the next few decades is likely to be made from natural gas, other feedstocks such as biomass, coal or wastes could be used. The production cost of methanol has been estimated for a variety of primary energy sources (Williams, Larson, Katofsky and Chen 1995). The cost of fuel delivery is estimated to be about the same for methanol and gasoline on a volumetric basis. Given the lower energy density of methanol, truck delivery would cost about $1.9/GJ, as compared to $1.0/GJ for gasoline (Ogden, Larson and Delucchi 1994). The estimated delivered cost of methanol is shown in Figure 10 for various primary sources.

COST OF INFRASTRUCTURE FOR GASOLINE FUEL CELL VEHICLES For this study, we have assumed that there is no extra capital cost for developing gasoline infrastructure for fuel cell vehicles. This may be an oversimplification. For example, if a new type of gasoline (e.g. very low sulfur) is needed for gasoline/POX fuel cell vehicles, this would entail extra costs at the refinery. The costs of maintaining (and gradually replacing existing equipment with new) or expanding the existing gasoline infrastructure are not considered.

COST OF REFUELING INFRASTRUCTURE DEVELOPMENT FOR SYNTHETIC MIDDLE DISTILLATE FUEL CELL VEHICLES. Synthetic middle distillates are produced from natural gas. Modest sized plants producing SMD have been built, and construction of larger plants is being considered.

Shell currently operates a 12,500 bbl/day plant producing SMD from natural gas. Assuming that the energy content of SMD is the same as Diesel fuel, this plant produces 76,875 GJ/day, enough to fuel a fleet of 1.38 million SMD/POX automobiles. The capital cost is $55,000/bbl/day (or $687,500,000). The capital cost per car for the production plant is then about $500/car. The conversion efficiency from natural gas to SMD is 60% (Grimes 1998).

A proposed 50-100,000 bbl/day plant by Exxon has been estimated to cost $24,000/bbl/day (Grimes 1998). The capital cost of the production plant would be about $220/car, for this scale of production, which could serve perhaps 5.5-11 million SMD POX cars.

The production cost of SMD can then be estimated as:

$$PSMD = 0.15 \times \$24{,}000/\text{bbl/day}/(365\ \text{d/y} \times 0.9\ (\text{capacity factor}) \times 6.15\ \text{GJ/bbl}) + \text{NG Price}/0.6$$

$$= 1.78 + \text{NG Price}\ (\$/\text{GJ})/0.6$$

Probably, SMD would be made at a site with low cost natural gas. We asssume that the gas price for SMD production is the wellhead price. According to the Energy Information Agency (EIA 1996), the wellhead price of natural gas was $1.88/1000 scf or $1.73/GJ in 1994 and is expected to be $2.57/1000 scf or $2.35/GJ in 2015. (assuming that the heating value of NG is 1030 BTU/scf, and that 1 million BTU = 1.055 GJ.)

For current (1994) NG prices, the cost of SMD is

$$PSMD\ (\$/\text{GJ}) = 1.78 + 1.73/0.60 = \$4.66/\text{GJ}$$

With 2015 NG prices

$$PSMD = \$5.70/\text{GJ}$$

From the EIA (EIA 1996), the cost of distribution and marketing for Diesel is about $1.06/GJ today, and is expected to rise to about $1.67/GJ in 2015. The delivered cost (without taxes) for SMD is then about

$4.66 +1.06= $5.72/GJ (today)
$5.70 + 1.67 = $7.37/GJ (in 2015)

Note that this is likely to be an overestimate if very inexpensive off shore natural gas is used as a feedstock (as is done with methanol today). The total capital cost of developing a refueling infrastructure for SMD is $220-500/car, depending on the production plant size and assuming that no extra costs are incurred at refueling stations, marine terminals or in ocean shipping.

TOTAL INFRASTRUCTURE COSTS (ON AND OFF THE VEHICLE) FOR FUEL CELL VEHICLES: A COMPARISON OF HYDROGEN, METHANOL, GASOLINE AND SYNTHETIC MIDDLE DISTILLATES It is often stated that use of liquid fuels with onboard reformers would greatly reduce (for methanol or SMD) or eliminate (for gasoline) the problem of developing a new fuel infrastructure. How does the capital cost of building a refueling infrastructure compare for hydrogen, methanol, gasoline and SMD 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, methanol and SMD fuel cell vehicles also entail extra costs. For gasoline vehicles, these costs are for onboard fuel processing. For methanol and SMD, there are "infrastructure" costs both on the vehicle (for fuel processors) and off the vehicle (for fuel production, distribution and refueling systems). In the case of hydrogen, the infrastructure development capital cost is paid by the fuel producer (and passed along to the consumer as a higher fuel cost). In the case of gasoline fuel cell vehicles, the extra capital cost is paid by the consumer buying the car. In the case of methanol and SMD both the fuel producer and the vehicle owner pay extra capital costs.

In Figure 9 we combine our estimates of the cost of alternative fuel cell vehicles (Figure 4) and off-board refueling infrastructure (Figures 7,8). Our estimates show that methanol fuel cell cars are likely to cost $500-600/car/ more and gasoline or SMD POX fuel cell vehicles $850-1200/car more than comparable hydrogen fuel cell vehicles. The added cost of off-board refueling infrastructure for hydrogen is in the range $310-620/vehicle. For methanol the off-board refueling infrastructure costs will be small (less than $50/car) until new production capacity is needed (e.g. until the methanol fuel cell car fleet exceeds perhaps 1 million cars). Once new methanol production capacity is needed, methanol infrastructure capital costs off the vehicle would be $330-770/car (Figure 8). For methanol the total on and off the car is then about $830-1370/car. For SMD, the capital cost for off-vehicle infrastructure development would be $220 - 500/car (for new SMD production plants) and $850-1200/car on the vehicle, for a total of $1070-1700/car. To within the accuracy of our cost projections, it appears that the total capital cost for infrastructure on and off the vehicle would be roughly comparable for methanol, gasoline and SMD fuel cell vehicles, with hydrogen costing somewhat less. In the longer term (once new production capacity is needed), hydrogen appears to be the least costly alternative.

LIFECYCLE COST OF TRANSPORTATION FOR ALTERNATIVE FUEL CELL VEHICLES. In Figure 10 the delivered cost of fuel (including production, delivery and refueling stations) is compared for hydrogen, methanol, gasoline (Williams, Larson, Katofsky and Chen 1995) and SMD. A variety of primary sources are considered. We see that the cost per unit of energy for hydrogen is higher than for methanol, gasoline or SMD.

The fuel cost per kilometer is shown in Figure 11. Because of the higher fuel economy of hydrogen fuel cell vehicles, we see that the cost per kilometer for a fuel cell vehicle using hydrogen from natural gas is about the same as that for a gasoline fueled fuel cell vehicle.

The total lifecycle cost of transportation with various fuels and feedstocks is shown in Figure 12. This includes the vehicle capital cost, non-fuel O&M costs, and fuel costs. All the cases shown are within a few percent of each other in total lifecycle cost. The lowest overall lifecycle cost of transportation is for a hydrogen fuel cell vehicle, with hydrogen made from natural gas. The estimated lifecycle cost for a hydrogen fuel cell vehicle is a few percent less than for a gasoline fuel cell vehicle because 1) the first cost of a gasoline vehicle is higher and 2) the fuel cost per kilometer is about the same for gasoline and natural gas-derived hydrogen.

Figure 12 suggests that factors other than the total lifecycle cost may drive fuel choice for fuel cell vehicles such as: 1) vehicle first cost, 2) performance of alternative types of fuel cell vehicles, 3) the capital cost of developing fuel production and delivery infrastructure off the vehicle, 4) environmental concerns including urban air pollution and greenhouse gas emissions, and 5) energy supply issues.

CONCLUSIONS

Our simulations indicate that for the same performance, hydrogen fuel cell vehicles are simpler in design, lighter weight, more energy efficient and have lower first cost than those with onboard fuel processors. Vehicles with onboard steam reforming of methanol or partial oxidation of gasoline or SMD have about two thirds the fuel economy of direct hydrogen vehicles. The efficiency is lower because of the conversion losses in the fuel processor (losses in making hydrogen from another fuel), reduced fuel cell performance on reformate, added weight of fuel processor components, and effects of fuel processor response time.

For mid-size automobiles with PNGV type characteristics (base vehicle weight of 800 kg -- e.g. weight without the power train and fuel storage, aerodynamic drag of 0.20, and rolling resistance of 0.007), fuel economies (on the combined FUDS/FHDS drving cycle) are projected to be about 106 mpeg for hydrogen fuel cell vehicles, 69 mpeg for fuel cell vehicles with onboard methanol steam reforming, 71 mpeg for onboard gasoline partial oxidation, and 71 mpg for onboard partial oxidation of SMD.

Based on projections for mass produced fuel cell vehicles, methanol fuel cell automobiles are projected to cost about $500-600/car more than comparable hydrogen fuel cell vehicles. Gasoline or SMD/POX fuel cell automobiles are projected to cost $850-1200 more than hydrogen fuel cell vehicles.

The capital cost of developing hydrogen refueling infrastructure based on near term technologies would be about $310-620/car depending on the type of hydrogen supply. Methanol infrastructure capital costs should be low initially (less than $50/car), but would increase to $330-770/car once new methanol production capacity was needed. For SMD the cost would be about $220-500/car, for new production capacity only. All the synthetic fuel cases (hydrogen, methanol and SMD) have a comparable range of off-vehicle long term infrastructure costs. No extra costs are assumed for developing gasoline infrastructure. Given the projected increasing demand for transportation fuels worldwide (which would require new gasoline production capacity), this may be an underestimate.

Defining "infrastructure" to mean all the equipment (both on and off the vehicle) required to bring hydrogen to the fuel cell, we find that the cost is roughly comparable for methanol , gasoline and SMD POX fuel cell vehicles. Surprisingly, hydrogen appears to entail the lowest overall capital costs in the longer term, when new fuel production capacity is needed for methanol or SMD.

The lifecycle cost of transportation is similar for all the cases examined (all cases are within a few percent of each other). However, the lifecycle cost is projected to be a few percent less with hydrogen made from natural gas than with gasoline, methanol, or SMD, because the vehicle first cost is lower, and the fuel economy about 50% higher.

While the flexibility they offer in being able to serve advanced internal combustion engine markets with low pollutant emission levels suggests use of synthetic liquids from natural gas in fuel cell vehicles, our simulations indicate that hydrogen is the preferred fuel for fuel cell vehicles in terms of vehicle weight, simplicity, first cost and fuel economy. Counting both fuel processors on vehicles and off-vehicle refueling infrastructure, the long term capital cost of implementing widespread use of fuel cell vehicles appears to be lowest for hydrogen. Moreover, use of hydrogen fuel opens the possibility of a future low CO_2-emitting energy system, based on renewables or on fossil sources where CO_2 is generated as a byproduct of H_2 manufacture at centralized facilities and sequestered underground, at low incremental cost (Williams 1998).

Like compressed natural gas or methanol, hydrogen faces the issue of reaching beyond centrally refueled fleet markets. In addition, technical issues remain to be resolved for fuel processors. The choice of fuel for the first generation of commercial fuel cell automobiles will be informed by data from demonstrations of alternative types of fuel cell vehicles over the next few years. Ideally, this choice should be made to give fuel cells the best chance of reaching general mass markets, paving the way for economically competitive mass produced fuel cell vehicles and long term use of hydrogen.

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FIGURES

TABLES

Figure 1: Possible Fuel Cell Vehicle Configurations

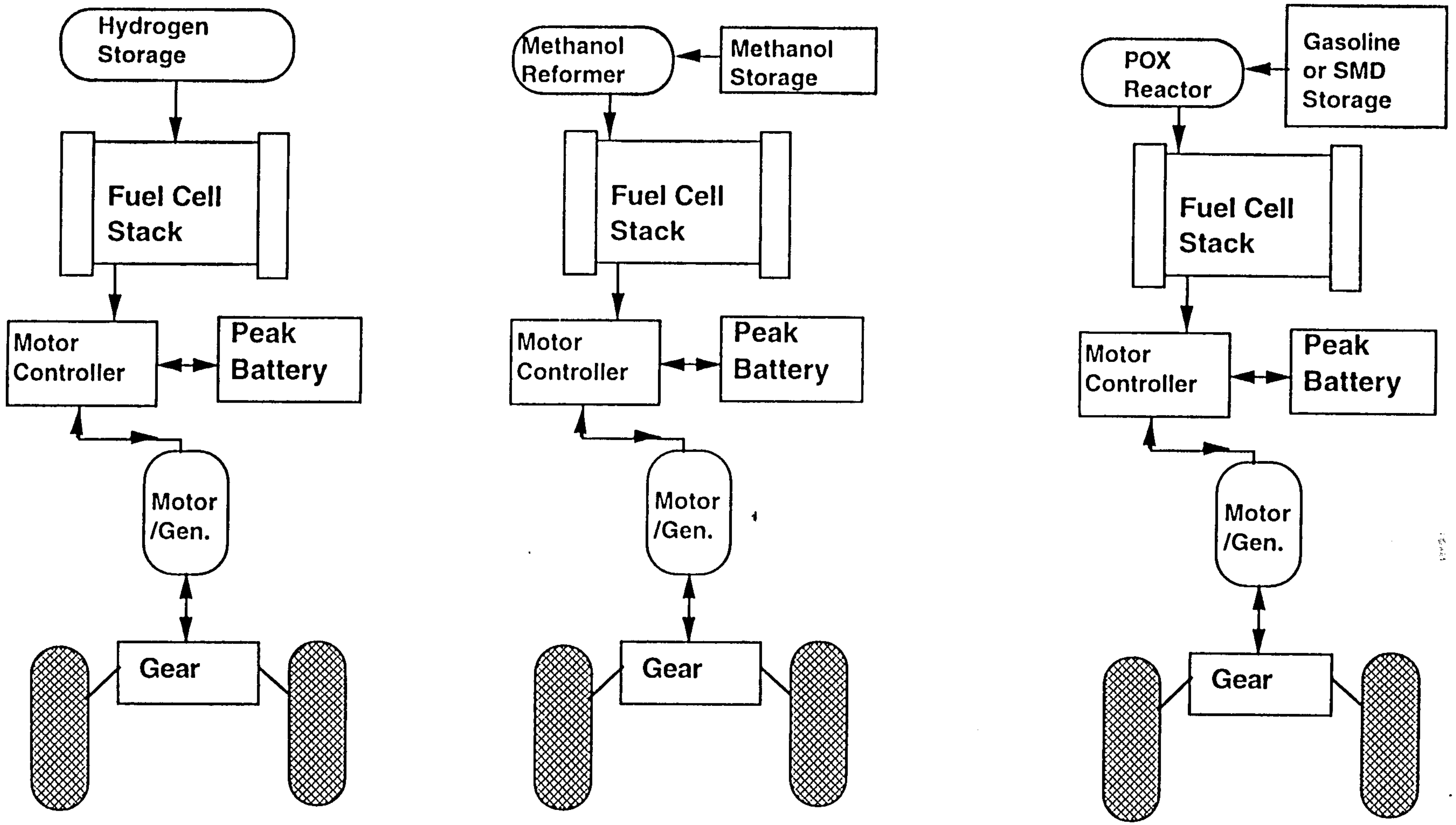


Figure 2.
Contributions to Vehicle Mass (kg)

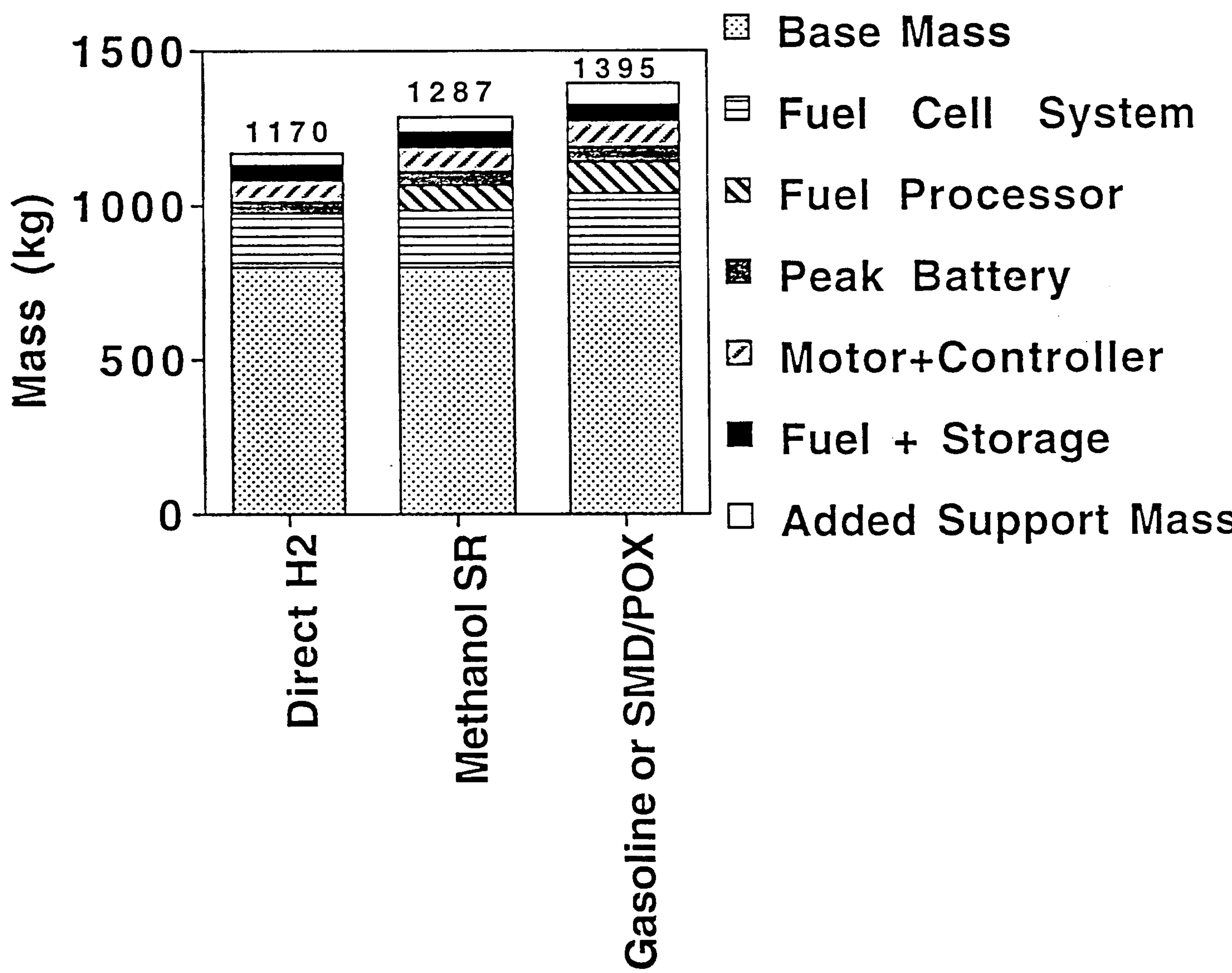
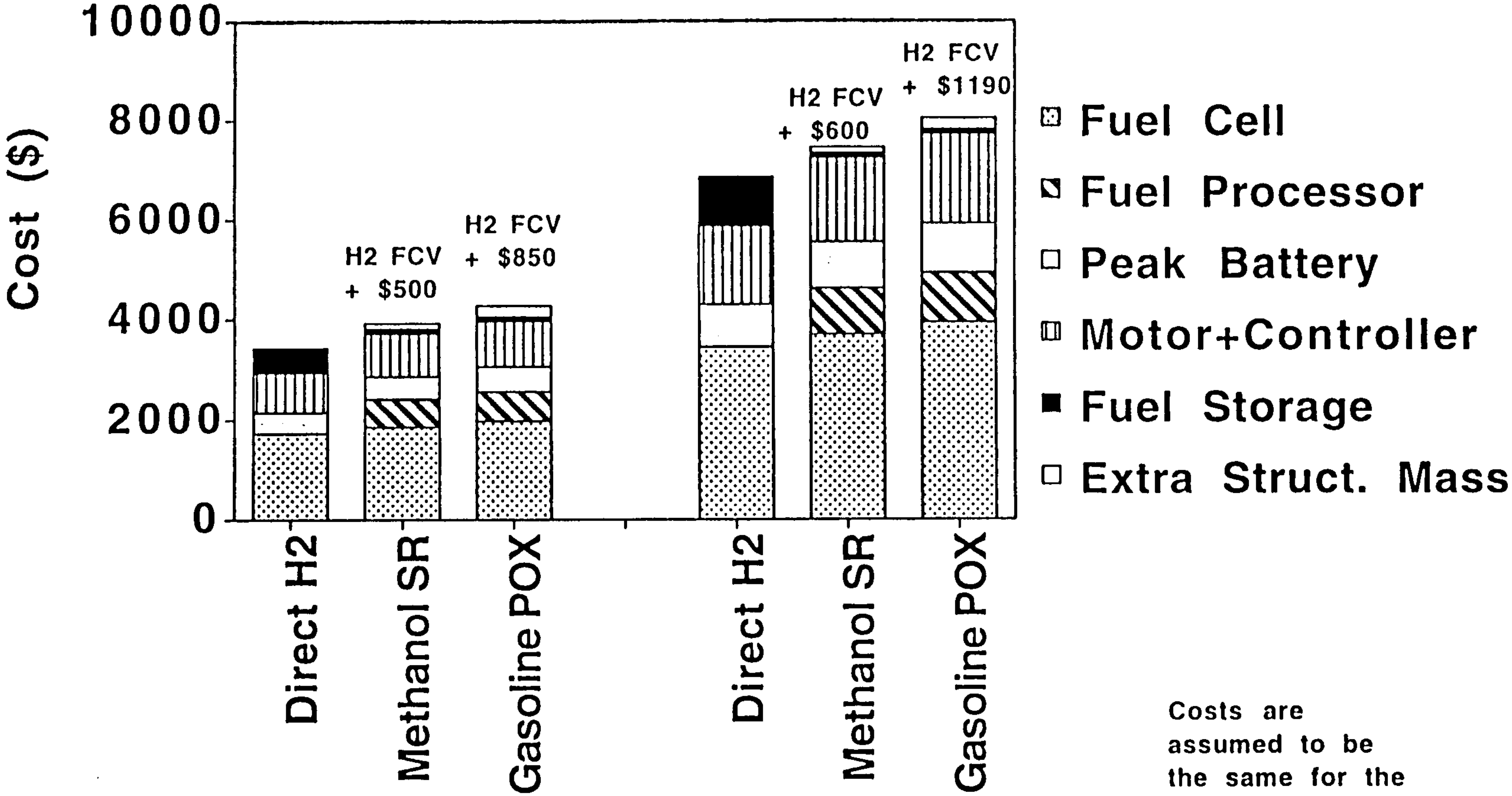


Figure 3. Capital Cost of Fuel Cell Vehicle Drive Train and Fuel Storage Components ($)



Costs are assumed to be the same for the gasoline and SMD POX vehicles

Fuel Cell = $50/kW
Fuel Processor=$15/kW
Peak Battery = $10/kW
H2 Cylinder = $500
Motor+Controller=$13/kW

Fuel Cell = $100/kW
Fuel Processor = $25/kW
Peak Battery = $20/kW
H2 Cylinder = $1000
Motor+Controller=$26/kW

Gasoline, SMD or MeOH Tank = $100
Extra Structural Mass = $1/kg

Figure 4. Near Term Gaseous H2 Supply Options

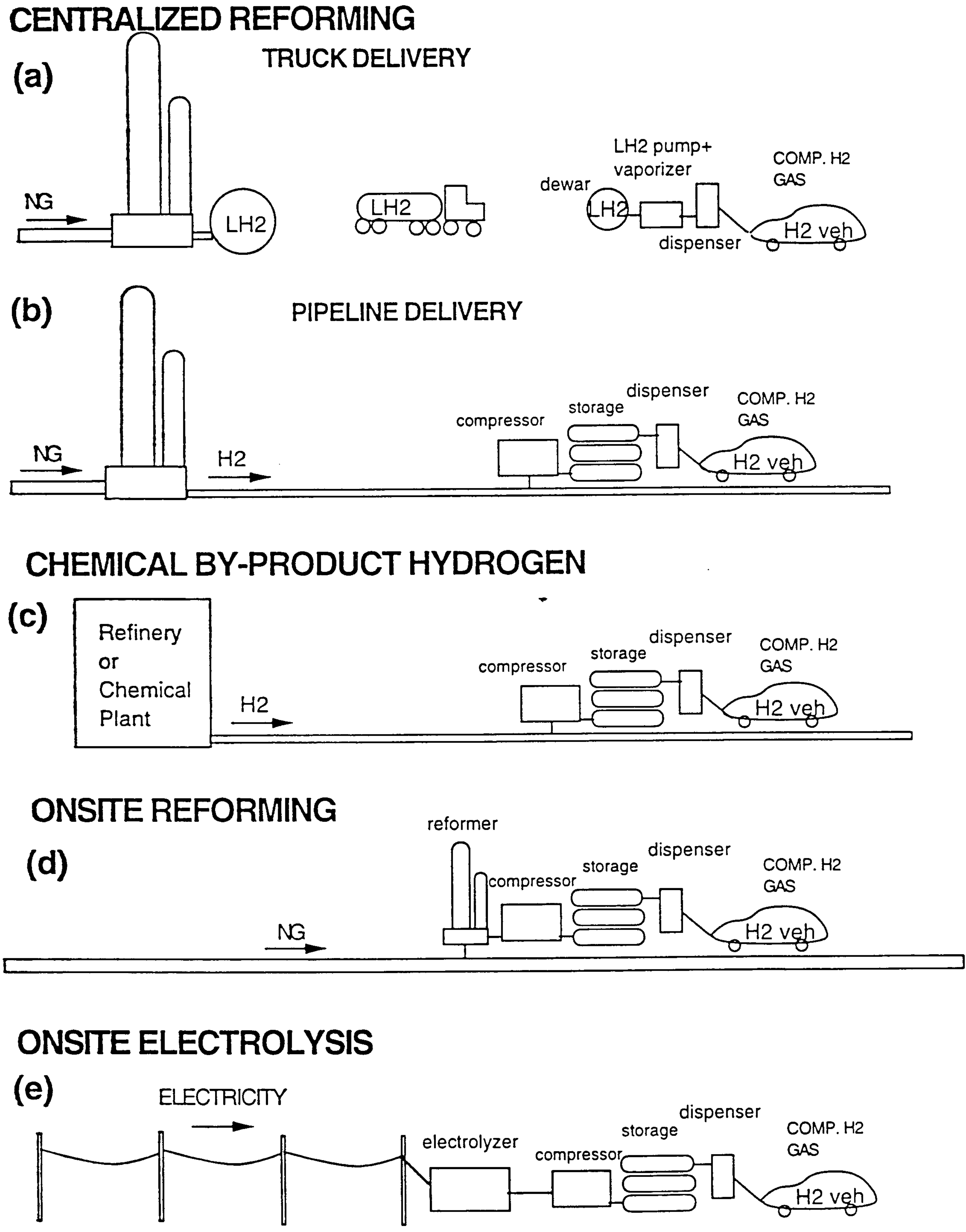


Figure 5. Long Term H2 Supply Options

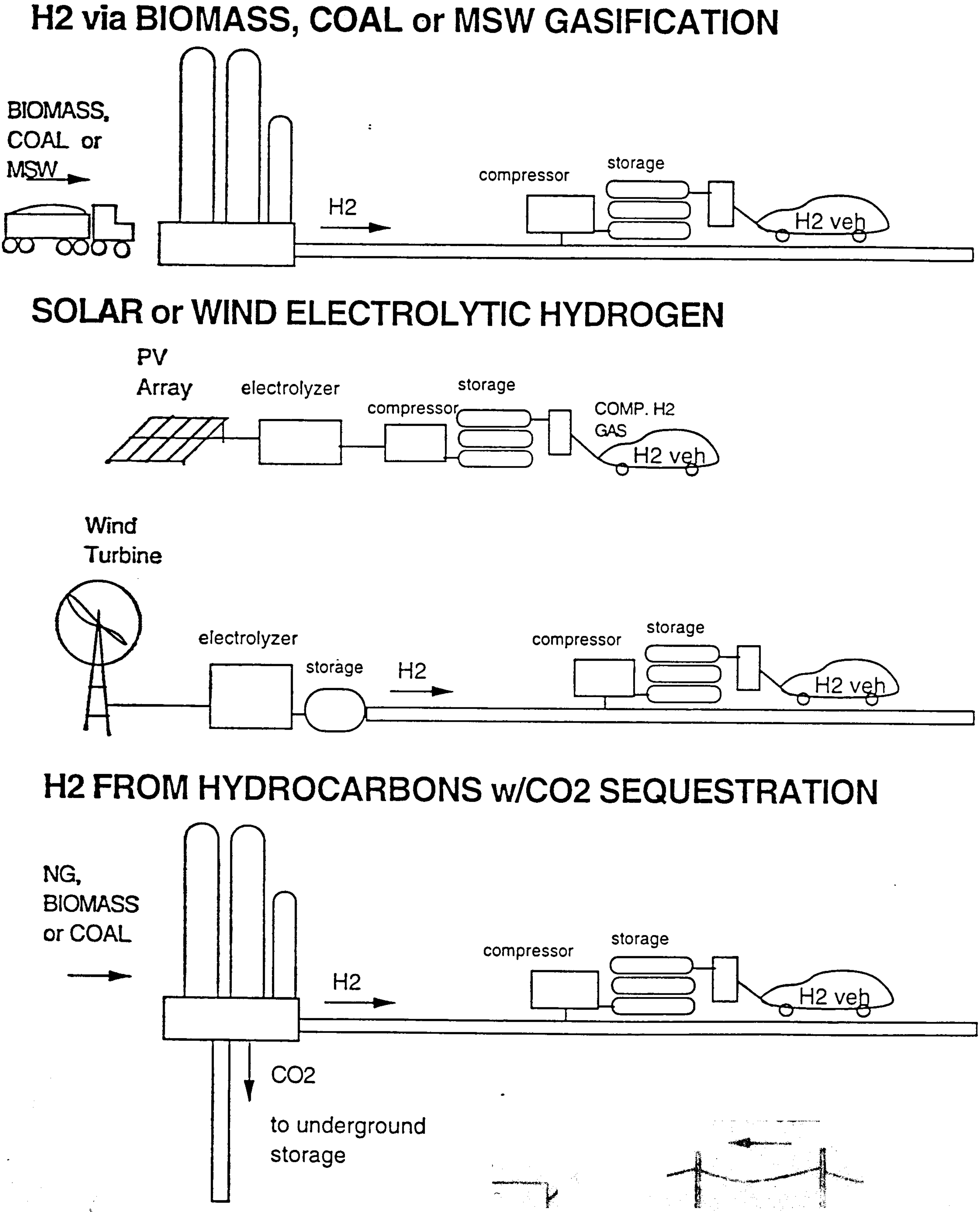
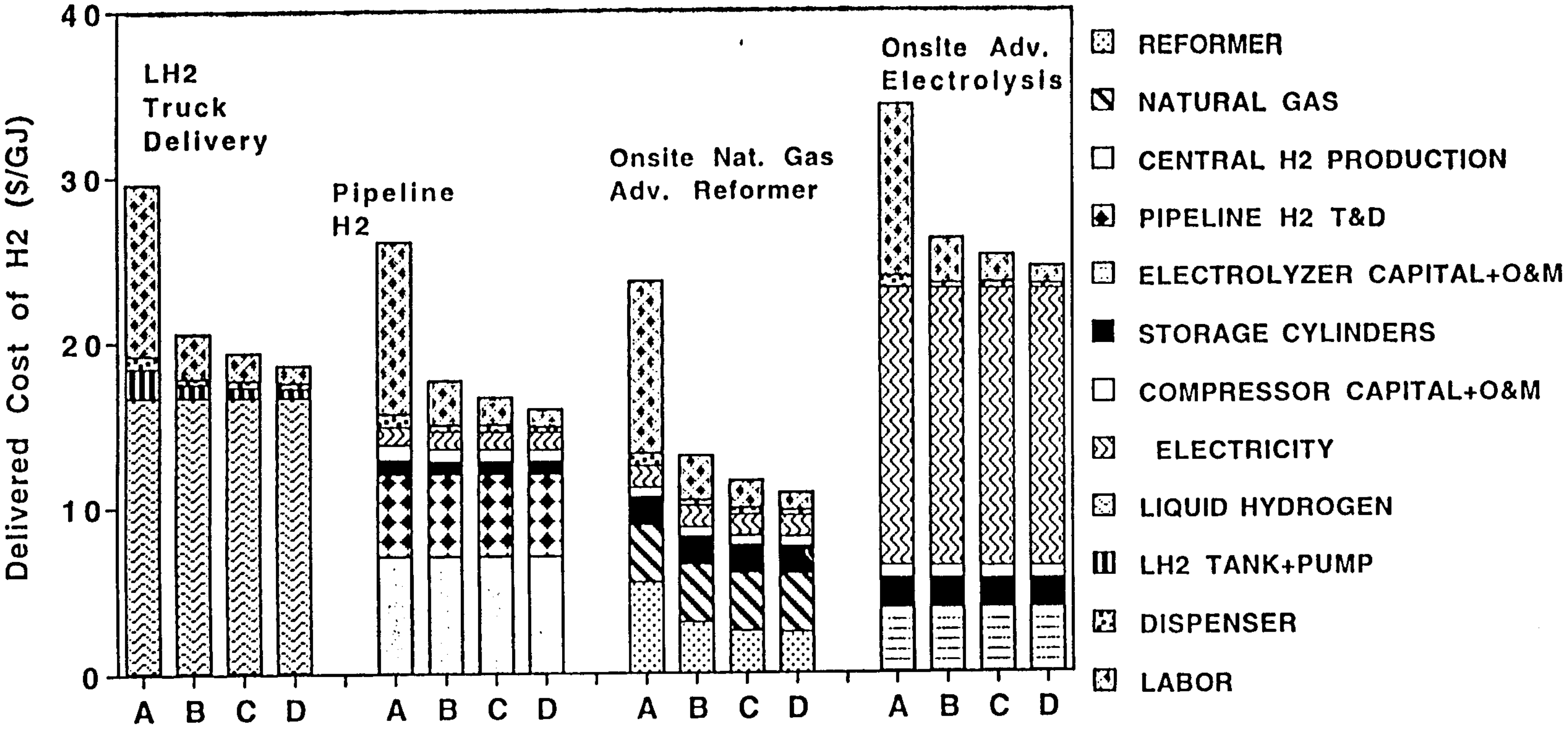
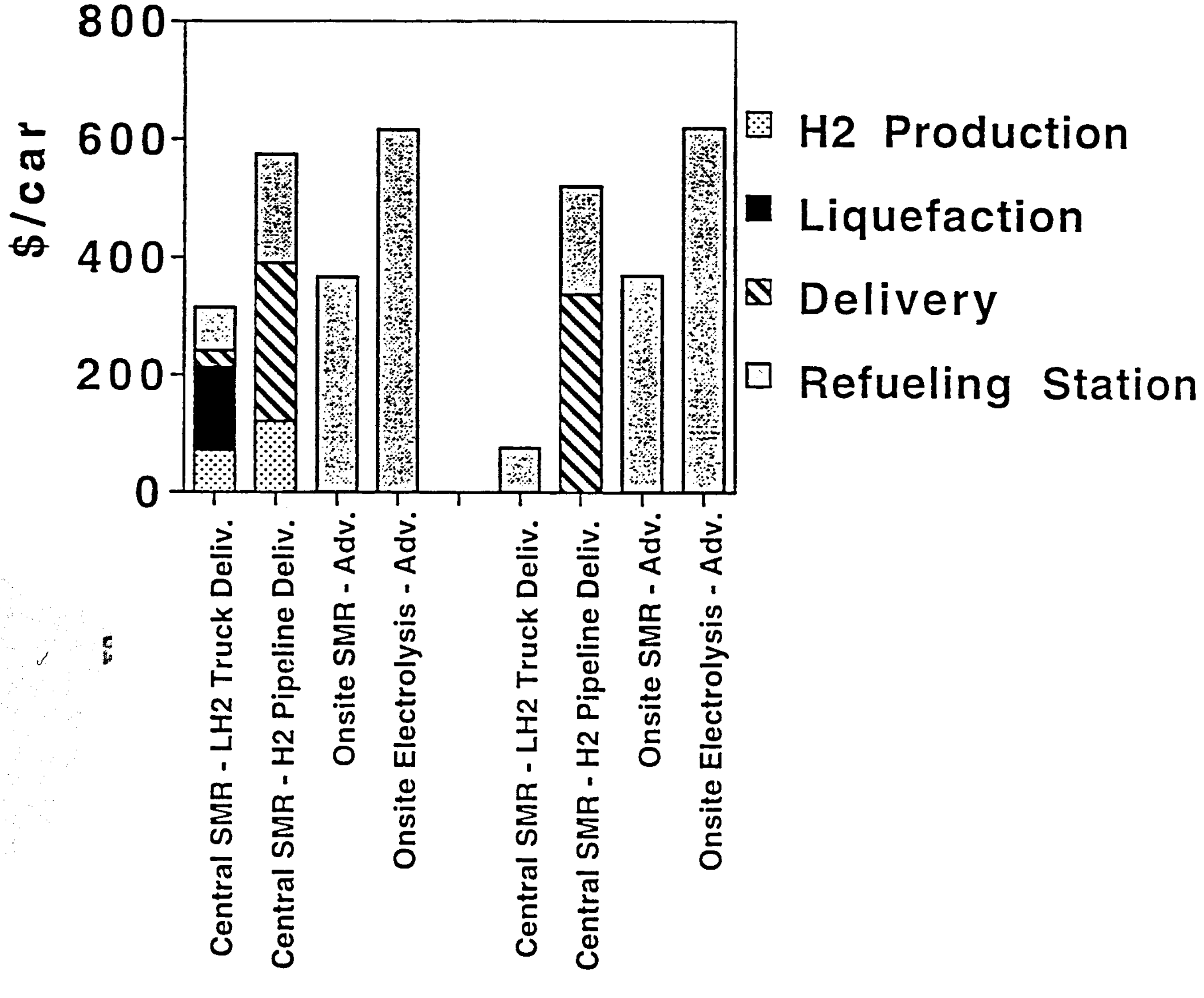


Figure 6. Delivered Cost of Hydrogen Transportation Fuel ($/GJ) vs. Station Size



STATION CAPACITY	A	B	C	D
million scf H2/day	0.1	0.366	1.0	2.0
H2 FCV cars/day	65	240	650	1300
H2 FCV buses/day	8	28	77	154

Figure 7. Capital Cost of H2 Refueling Infrastructure ($/car)



For a refueling system serving a fleet of 1.41 million H2 FCVs. Centralized options have new H2 production capacity

For a refueling system serving a fleet of 18,400 H2 FCV cars. Centralized options use existing H2 production capacity

Figure 8. Capital Cost of Methanol Fuel Cell Vehicle Refueling Infrastructure ($/car)

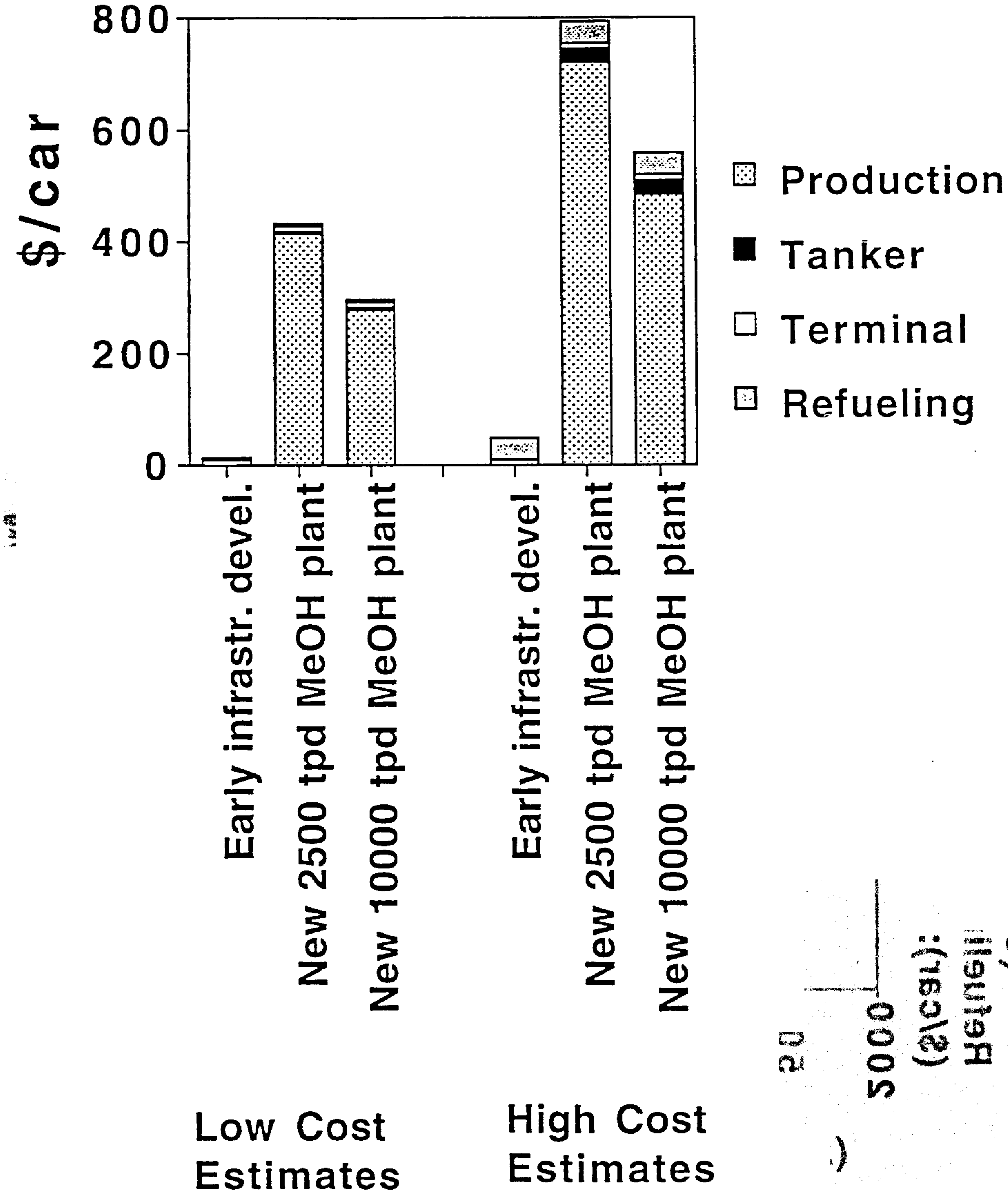
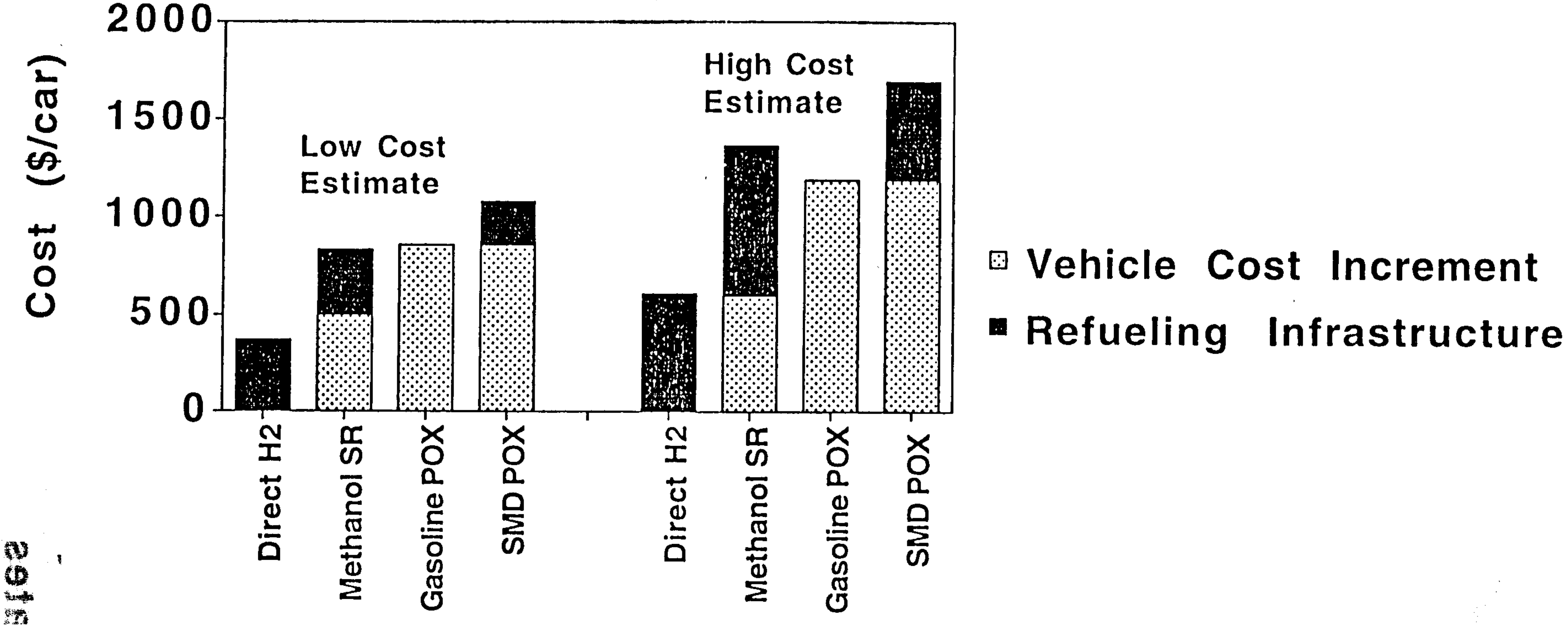


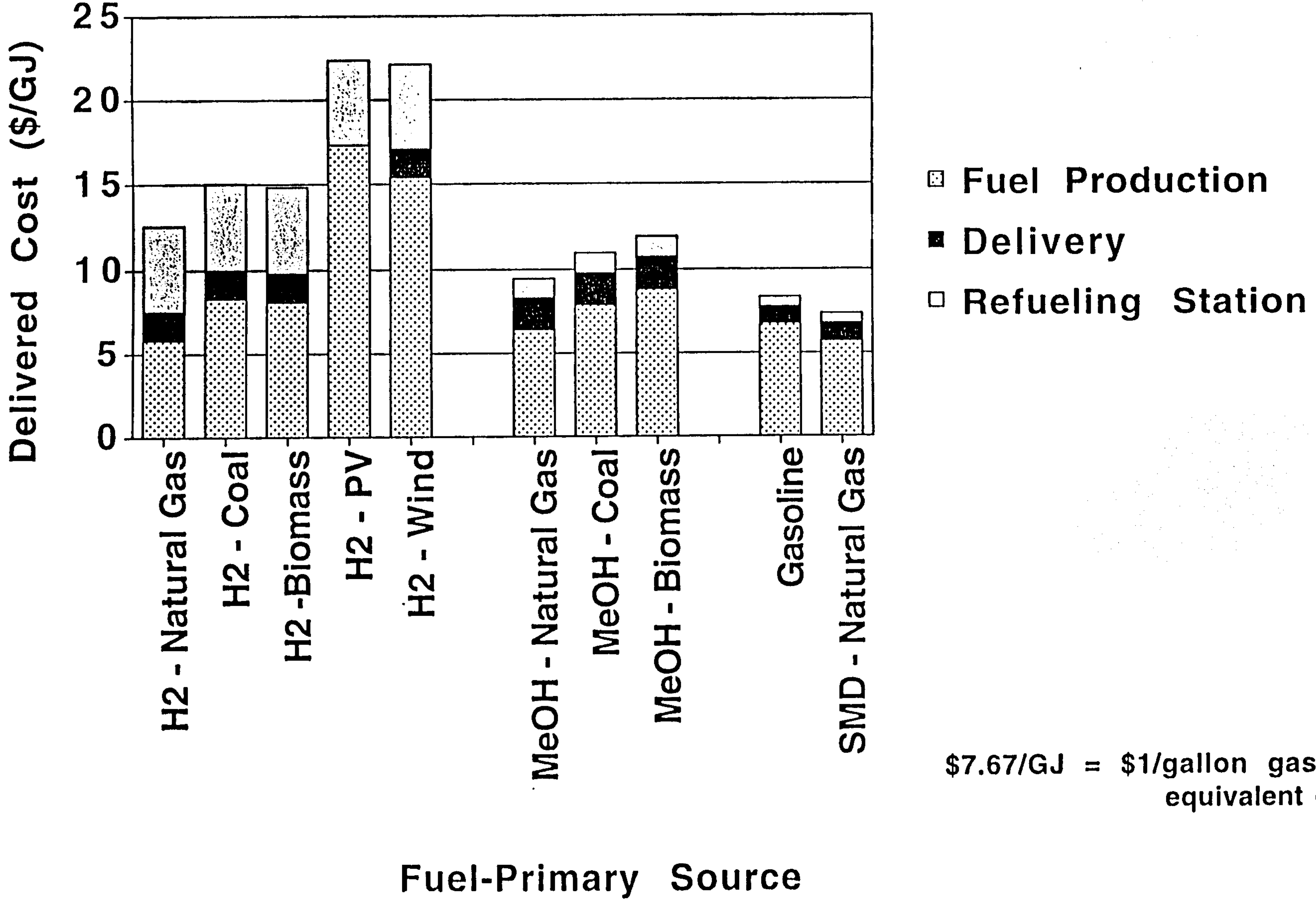
Figure 9. Comparison of Incremental Costs for Vehicles (Compared to H2 Fuel Cell Vehicle) and Refueling Infrastructure (Compared to Gasoline) ($/car): Extensive Methanol Infrastructure Devel.



Low Cost Estimate	High Cost Estimate
Fuel Cell = $50/kW	Fuel Cell = $100/kW
Fuel Processor = $15/kW	Fuel Processor = $25/kW
Peak Battery = $10/kW	Peak Battery = $20/kW
H2 Cylinder = $500	H2 Cylinder = $1000
Motor+Controller=$13/kW	Motor+Controller=$26/kW
H2 Infrastructure = $370/car	H2 Infrastructure= $610/car
MeOH Infrastructure=$330/car	MeOH Infrastructure=$770/car
SMD Infrastructure = $220/car	SMD Infrastructure = $505/car

Gasoline, SMD or MeOH Tank = $100
Extra Structural Mass = $1/kg

Figure 10. Delivered Cost of Hydrogen, Methanol, Gasoline and Synthetic Middle Distilate Transporation Fuels ($/GJ)



$7.67/GJ = $1/gallon gasoline equivalent energy

Figure 11. Fuel Cost Contribution to Fuel Cell Vehicle Lifecycle Cost ($/km)

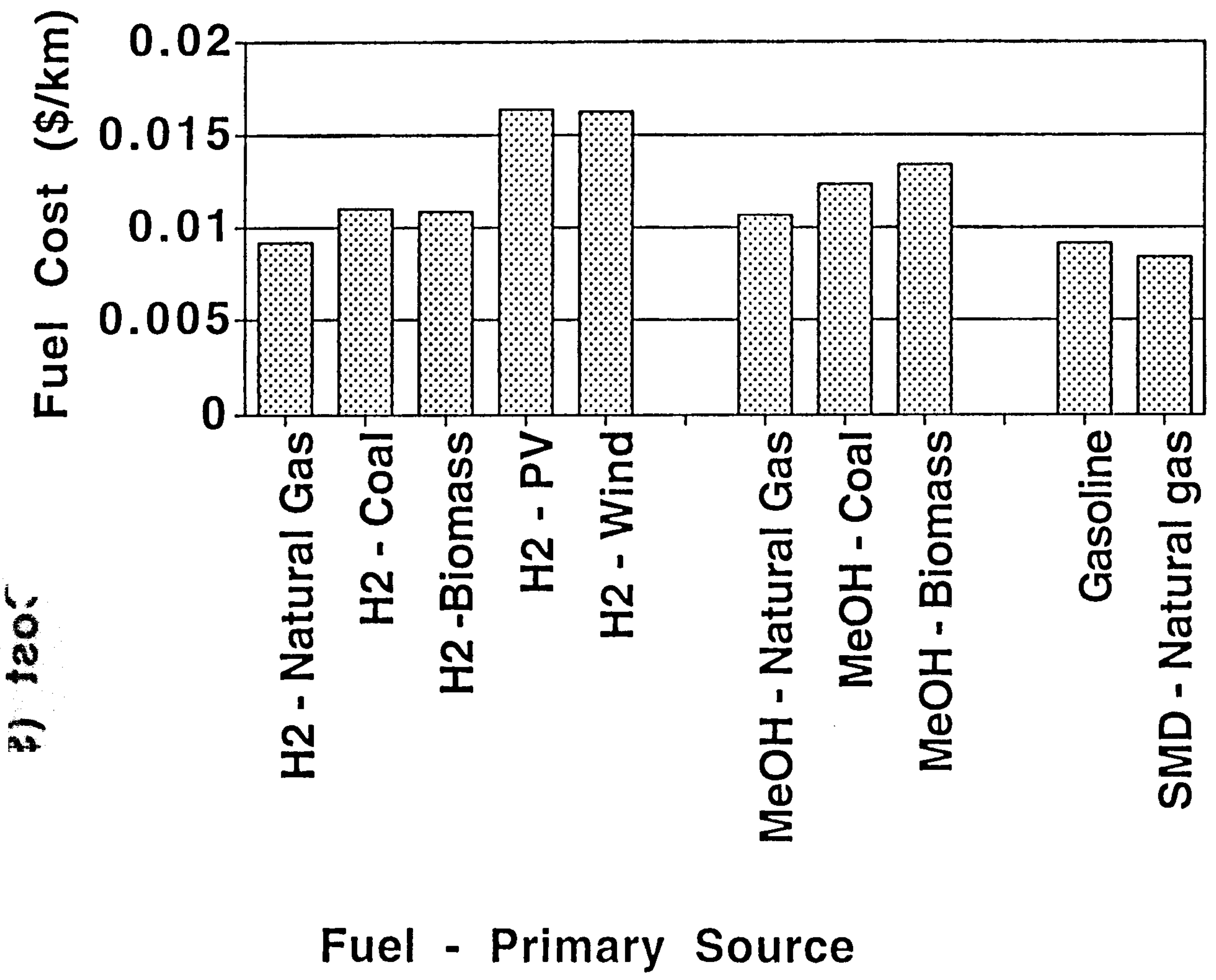


Figure 12. Lifecycle Cost of Transportation for Alternative Fuel Cell Vehicles and Primary Fuel Sources