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Journal of Power Sources 79 (1999) 143–168

JOURNAL OF POWER SOURCES

A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development

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Received 28 September 1998; accepted 23 December 1998

Abstract

All fuel cells currently being developed for near term use in electric vehicles require hydrogen as a fuel. Hydrogen can be stored directly or produced onboard the vehicle by reforming methanol, or hydrocarbon fuels derived from crude oil (e.g., gasoline, diesel, or middle distillates). The vehicle design is simpler with direct hydrogen storage, but requires developing a more complex refueling infrastructure. In this paper, we present modeling results comparing three leading options for fuel storage onboard fuel cell vehicles: (a) compressed gas hydrogen storage, (b) onboard steam reforming of methanol, (c) onboard partial oxidation (POX) of hydrocarbon fuels derived from crude oil. We have developed a fuel cell vehicle model, including detailed models of onboard fuel processors. This allows us to compare the vehicle performance, fuel economy, weight, and cost for various vehicle parameters, fuel storage choices and driving cycles. The infrastructure requirements are also compared for gaseous hydrogen, methanol and gasoline, including the added costs of fuel production, storage, distribution and refueling stations. The delivered fuel cost, total lifecycle cost of transportation, and capital cost of infrastructure development are estimated for each alternative. Considering both vehicle and infrastructure issues, possible fuel strategies leading to the commercialization of fuel cell vehicles are discussed. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Fuel cell vehicles; Alternative fuel infrastructure

1. Introduction

All fuel cells currently being developed for near term use in electric vehicles require hydrogen as a fuel. Hydrogen can be stored directly or produced onboard the vehicle by reforming methanol or hydrocarbon fuels derived from crude oil (e.g., gasoline, diesel, or middle distillates). The vehicle design is simpler with direct hydrogen storage, but requires developing a more complex refueling infrastructure.

While many in the fuel cell vehicle community would agree that widespread public use of hydrogen in fuel cell cars is the ultimate aim, there is an ongoing debate about the most direct path to this goal. Much of this debate centers around which fuel to use and when in the commercialization process to use it.

In this paper, we compare three leading options for fuel storage onboard fuel cell vehicles (see Fig. 1):

- compressed gas hydrogen storage,
- onboard steam reforming of methanol,
- onboard partial oxidation (POX) of gasoline

with respect to vehicle performance, fuel economy and cost, infrastructure requirements, and lifecycle cost of transportation.

To examine vehicle design trade-offs, we have developed a computer simulation model of a fuel cell vehicle [32–34], including detailed models of onboard fuel processors [16]. This allows us to calculate vehicle performance, fuel economy and cost for alternative fueled fuel cell vehicles. The effect of using various fuels is then compared for vehicles offering identical performance characteristics. We have concentrated on modeling a PNGV type mid-size automobile, with reduced weight, rolling resistance and aerodynamic drag. In most cases, the vehicles are hybrids (e.g., a peak power device such as a battery is used to assist the fuel cell in meeting peak demands, such as high speed passing). The simulation model is described below and results are presented for a variety of cases.

Capital costs for hydrogen and methanol refueling infrastructure development are estimated for various near term fuel supply options. The overall infrastructure capital costs per car (including both onboard fuel processors and

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PII: S0378-7753(99)00057-9

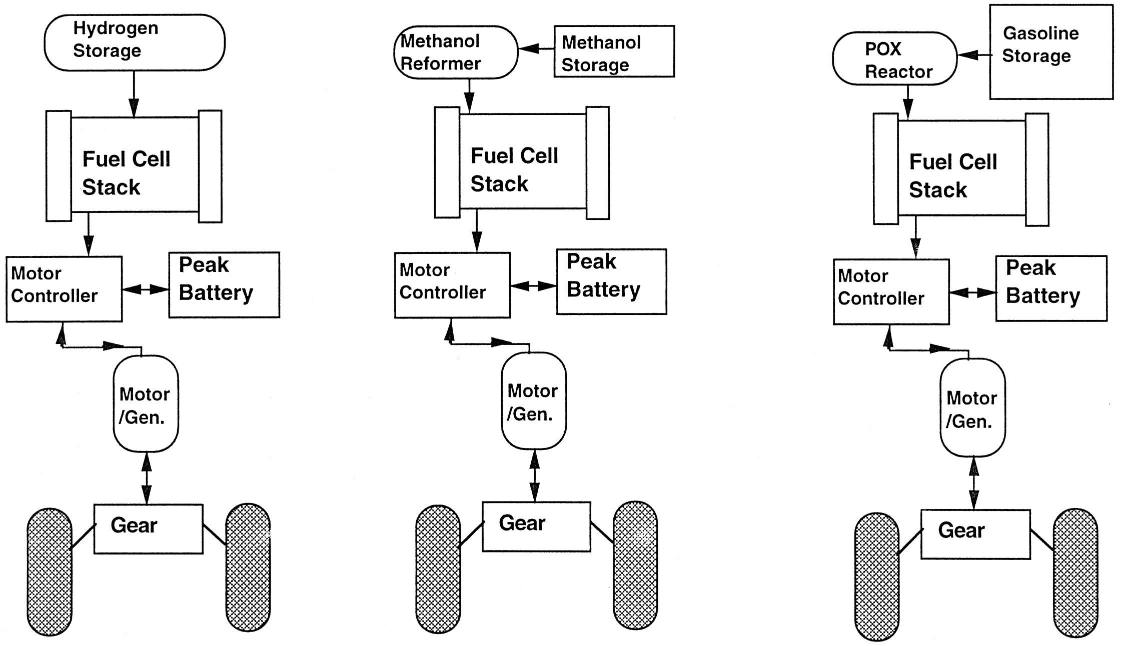


Fig. 1. Possible fuel cell vehicle configurations.

off-board fuel infrastructure) are compared. The cost of delivered fuel to the consumer and the lifecycle cost of transportation are calculated.

Finally, the implications of fuel choice for fuel cell vehicles are summarized, and possible fuel strategies for the development of fuel cell vehicles are discussed.

2. Comparison of alternative designs for fuel cell vehicles

2.1. Model of fuel cell vehicles

We have developed a computer model for proton exchange membrane fuel cell vehicles [32–34]. This program allows us to estimate the performance, fuel economy and cost of alternative fuel cell vehicle designs.

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), and
- 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/s at 65 mph.

These criteria are consistent with the goals set by the Partnership for a New Generation of Vehicles (PNGV). Vehicles meeting these criteria readily satisfy the power demands of the FUDS and FHDS driving schedules, which typically require only 10–20% of the peak power.

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' Eq. (1) is solved to find the total power P_D needed from the vehicle's electrical power system (fuel cell plus peak power device).

$$P_D = P_{aux} + \left(mav + mgC_R v + 0.5 \rho C_D A_F v^3 \right) / \eta \qquad (1)$$

where: P_D = total electrical power demanded of vehicle's power system (W); P_{aux} = power needed for accessories such as lights and wipers (W); 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 = coefficient of rolling resistance; ρ = density of air (kg/m^3); C_D = aerodynamic drag coefficient; A_F = vehicle frontal area (m^2); η = 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

Table 1
Conversion factors and economic assumptions

1 GJ (gigajoule) = 10^9 J = 0.95 million Btu
1 EJ (exajoule) = 10^{18} J = 0.95 quadrillion (10^{15}) Btu
1 million standard cubic feet (scf) = 26,850 normal cubic meters (m_N^3) = 343 GJ (HHV)
1 million scf/day = 2.66 tons/day = 3.97 MW H_2 (based on the HHV of hydrogen)
1 scf H_2 = 343 kJ (HHV) = 325 Btu (HHV); 1 lb H_2 = 64.4 MJ (HHV) = 61.4 kBtu (HHV) = 187.8 scf
1 m_N^3 = 12.8 MJ (HHV); 1 kg H_2 = 141.9 MJ (HHV) = 414 scf
1 gal gasoline = 130.8 MJ (HHV) = 115,400 Btu/gal (LHV)
Gasoline heating value = 45.9 MJ/kg (HHV) = 43.0 MJ/kg (LHV)
US$1/gal gasoline = US$7.67/GJ (HHV)
1 gal methanol = 64,600 Btu/gal (HHV) = 56,560 Btu/gal (LHV)
Methanol heating value = 22.7 MJ/kg (HHV) = 19.9 MJ/kg (LHV)
US$1/gal methanol = US$15.4/GJ (HHV)

All costs are given in constant US$1993.
Capital recovery factor for hydrogen production systems, distribution systems and refueling stations = 15%.

charge, by recharging from the fuel cell during driving). Knowing the fuel cell current–voltage characteristic and 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. (Assuming that 1 gal of gasoline contains 0.1308 GJ (gigajoule) of energy on a higher heating value basis—see Table 1).

2.1.1. Fuel storage capacity and range

The vehicle range is allowed to vary, but all fuel storage systems are assumed to weigh 50 kg, fully loaded with fuel. We assume that 7.5% hydrogen by weight can be stored in a compressed gas tank at 5000 psia. For gasoline and methanol, 13 gal of fuel are stored in a 12-kg tank.

2.1.2. Model of the fuel cell system

The fuel cell is modeled based on current–voltage curves for existing PEM fuel cells [33]. For hydrogen-air fuel cells operated at 3 atm, with cathode stoichiometry of 2, the voltage–current relation is given by [32]:

$$V = 0.787 - 0.0533 \log i - 0.148 i + V_{\text{comp/exp}} - V_{\text{reformate}} \tag{2}$$

where: V = voltage output in volts (V); i = current density is in ampere per square centimeter (A/cm^2).

$V_{\text{comp/exp}}$ = voltage correction for power consumed/generated by net air compression/expansion, $= -0.08$ for hydrogen; $= +0.067$ for methanol reforming; $= 0$ for gasoline POX.

$V_{\text{reformate}}$ = voltage penalty due to H_2 dilution when operating on reformate = 0 (hydrogen); $= 0.06\ i$ for methanol reformate; $= 0.128\ i$ for gasoline POX.

This expression is valid for $0 < i < 1.5\ A/cm^2$.

Both the power produced by the fuel cell and the power required for cathode air compression are proportional to the flow of hydrogen through the fuel cell (or the current drawn from it.) Thus in order to properly account for the net auxiliary power (compression–expansion) we apply a constant voltage drop of $V_{\text{comp/exp}}$ to the polarization curve, as shown in Eq. (2). (Our assumption that the power required for air compression is proportional to the hydrogen flow rate is a simplification, based on the assumption that the compressor and expander efficiencies are constant with flow rates. At very low flow rates, the air compressor efficiency would be expected to decrease.)

The output of PEM fuel cells varies with the concentration of hydrogen in the anode feed gas. For compressed gas hydrogen storage, the feed gas to the fuel cell anode is pure hydrogen. For the case of methanol steam reforming, the hydrogen content is about 75% by volume and for gasoline POX about 35%. The voltage and power output of the fuel cell on different anode feed gases is shown in Fig. 2. The peak power output is highest on pure hydrogen. The higher the hydrogen content, the better the fuel cell performance, and the greater its power density.

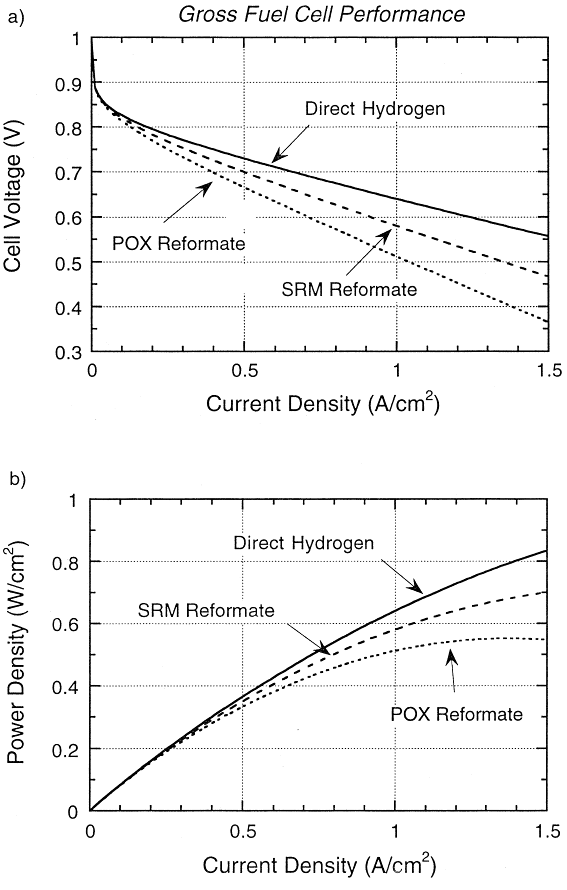


Fig. 2. Fuel cell model polarization and power curve for pure hydrogen and reformates.

2.1.3. Model of peak power battery

We have modeled our peak power battery as a thin film, spiral wound, lead–acid technology, based on data from the Bolder Battery [13,15,29]. The battery system specific weight is assumed to be 1.0 kg/kW. To ensure a long lifetime, the battery is kept near its initial state of charge of 50% by recharging from the fuel cell during driving. The battery charge and discharge rates depend on the battery power demand, the state of charge and on the battery resistance. The charging current is limited to 30 A for a string of 12 A.h cells in series.

It is assumed that energy is recaptured via regenerative braking, up to the battery's maximum charge rate. When the battery state of charge exceeds its nominal value of 50%, the program demands more power from the battery and less from the fuel cell, in order to bring the battery state of charge back down to the nominal 50% level.

2.1.4. Models of onboard fuel processors

Onboard fuel processors convert a liquid fuel (methanol or gasoline) to a hydrogen-containing gas for use in the fuel cell.

Heat integrated methanol steam reformer and gasoline POX systems have been modeled using ASPEN-plus software [14,16]. Configurations for a methanol steam reformer/fuel cell system and a gasoline POX/fuel cell system are shown in Figs. 3 and 4.

For the methanol steam reformer, the fuel cell anode exhaust gas is used as fuel in the catalytic reformer burner. The energy is recovered as heat input to the steam reforming reaction.

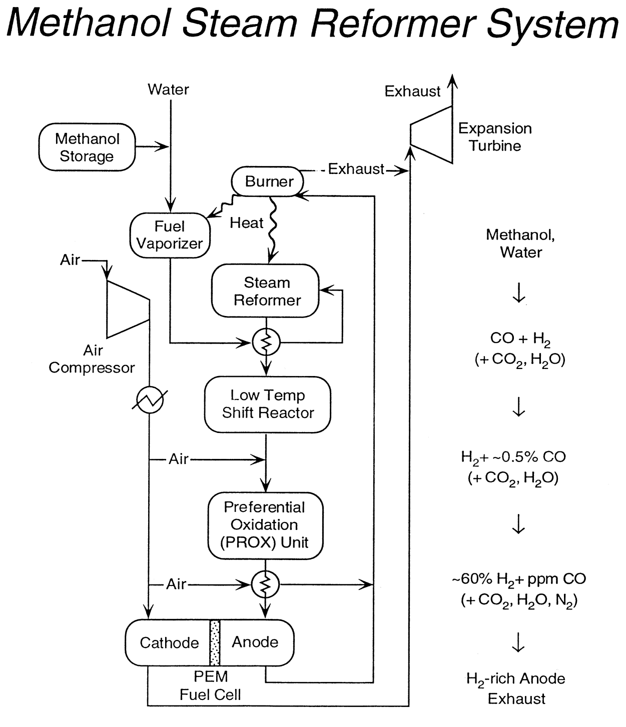


Fig. 3. Onboard methanol steam reformer/PEM fuel cell system.

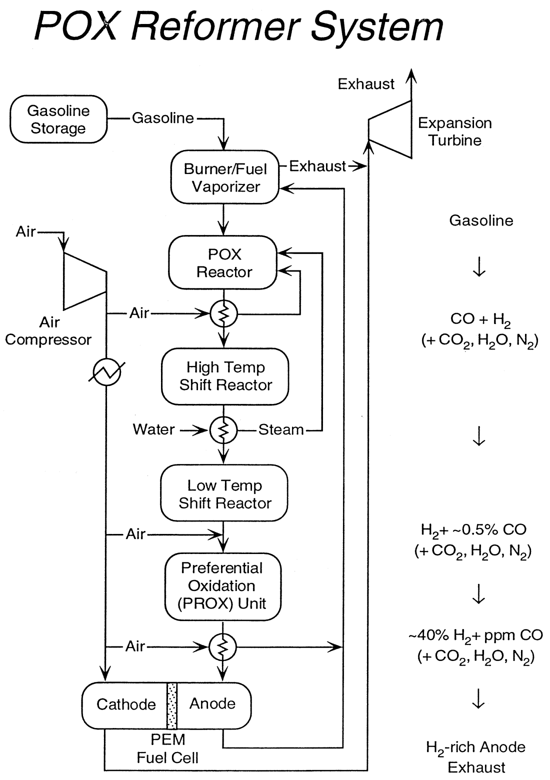


Fig. 4. Onboard gasoline POX/PEM fuel cell system.

The critical feedback loop, in which the anode exhaust is burned to partially satisfy the heat requirements for the steam reforming reaction, complicates a clear definition of the steam reformer efficiency independent of the fuel cell. As a gauge of system efficiency we employ the product of the steam reformer efficiency (HHV of hydrogen produced/HHV of methanol feed) times the hydrogen utilization in the fuel cell. This yields a system fuel reformer efficiency corresponding to the (HHV of the hydrogen consumed in the fuel cell)/(HHV of the methanol feed) = 62%. However, the expander work significantly exceeds that required for air compression, accounted for by a $V_{\text{comp/exp}} = 0.067$ or on average an 8% increase in the DC output of the system.

In contrast to methanol steam reforming, which requires heat input, POX is an exothermic reaction. A well heat integrated POX reformer has no need for the energy contained in the anode exhaust. Some of the energy in the anode exhaust gas can be recovered for uses other than the POX reaction. For example, anode exhaust can be burned, providing enough energy to both vaporize the incoming gasoline and also to provide expander work to offset the required air compressor work (in fact, the expander work which could be recovered after gasoline vaporization exceeds power demands for compression, but the excess power produced (< 1 kWe) is not sufficient to warrant a separate generator). The conversion efficiency for the POX reactor is well defined (HHV H_2 out/HHV gasoline in) and has been measured as the near-equilibrium value of 86.7% [20].

For comparison with the steam reformer efficiency note that the product of the POX efficiency times the 80% hydrogen utilization in the fuel cell gives a POX system efficiency = (HHV H_2 consumed/HHV gasoline in) of 69.4%.

Plotting the power demand P_D from Eq. (1), we see that the demands on the power system change rapidly over a typical driving cycle. This is shown in Fig. 5, where the power required by the FUDS is plotted vs. time (when P_D is negative, the vehicle is braking).

In a hydrogen fuel cell vehicle, the fuel cell should be able to follow the rapidly changing demands of the driving schedule. However, onboard fuel processors can have a longer characteristic response time as much as tens of seconds. It may be difficult for the fuel processor/fuel cell system to follow the rapidly changing demands.

For POX reactors this may not be much of an issue, as the response time is expected to be quite fast. For steam reformers, it may be longer, on the order of several seconds or more. To model the effect of response time, we assumed that the fuel processor tries to follow the demands of the driving cycle, reaching the desired level in a characteristic response time. Meanwhile, the peak power battery supplies the power needed by the drive cycle, until the fuel processor can ‘catch up’. The peak power battery is recharged from the fuel cell while driving (whenever the power demand falls below the maximum fuel cell output power) or from regenerative braking.

The drive cycle power demand and the output of the fuel cell system are plotted in Fig. 6 for fuel processor cases with 1- and 5-s response times. The fuel cell output matches the power demand well for the 1-s case, but lags the power demand significantly for the 5-s case. The battery state of charge is also shown for each case. For the 5-s response time, the battery is used more often and the battery state of charge has larger excursions away from its target value. The amount of energy routed through the

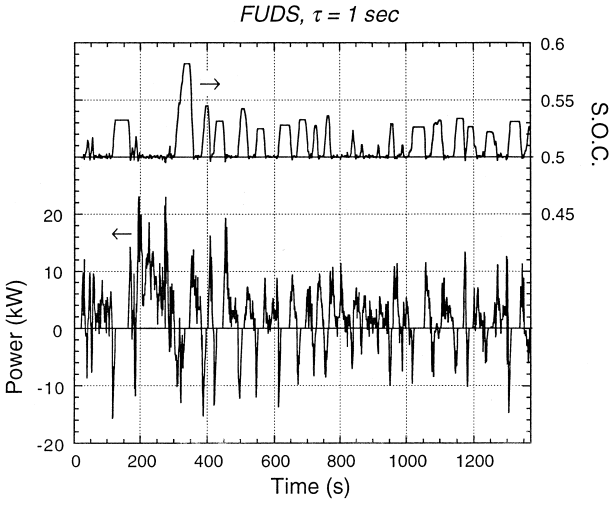


Fig. 5. Power demanded under the FUDS and FHDS driving cycles vs. time.

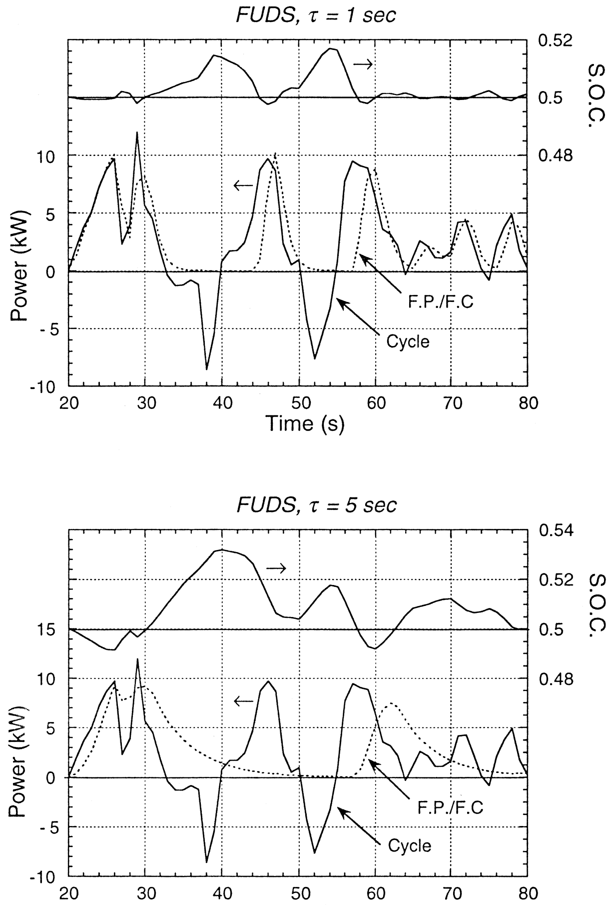


Fig. 6. Response of the fuel processor/fuel cell system and peaking battery state of charge as a function of time for the FUDS cycle, assuming fuel processor response times of 1 and 5 s.

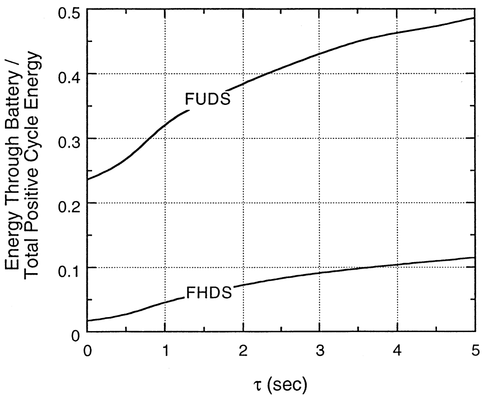


Fig. 7. Fraction of the energy routed through the peaking battery as a function of fuel processor response time.

Table 2
Parameters used in fuel cell vehicle modeling

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 H_2 consumed in fuel cell/HHV MeOH in.)	62%
$V_{\mathrm{comp/exp}}$	0.067 V
Hydrogen utilization[g]	80%
Voltage penalty for reformate operation[h]	0.06 × current (A/cm^2)
Weight of system	32 kg + 1.1 kg/kW
Response time	5 s
Reformate composition	70% H_2, 24% CO_2, 6% N_2
Gasoline POX	
Efficiency (HHV H_2 consumed/HHV gasoline in)[j]	69.4%
Hydrogen utilization[g]	80%
Voltage penalty for reformate operation[h]	0.128 × current (A/cm^2)
Weight of system[i]	32 kg + 1.1 kg/kW
Response time	1 s
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[k]	30 A
Nominal state of charge[k]	50%
Energy stored[k]	15 W h/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% H_2 by weight
Methanol, gasoline	12 kg tank, 13 gal capacity total weight 50 kg
Driving schedules	FUDS, FHDS
Regenerative braking recovered up to battery capabilities	

[a] Based on PNGV targets (source: CALSTART website: http://www.calstart.org/about/pngv/pngv_ta.html).
[b] From Ref. [39].
[c] From Ref. [30].
[d] From Ref. [35].
[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] From Ref. [3].
[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] From Ref. [40].
[j] From Ref. [20].
[k] From Ref. [15].
[l] From Ref. [5].

Table 3
Model results: comparison of alternative fuel cell vehicle designs

Fuel storage/H_2 generation system	Vehicle mass (kg)	Peak power (kW) (FC/battery)	FUDS (mpeg)	FHDS (mpeg)	Combined (55% FUDS and 45% FHDS)	
					mpeg	Range (miles)
Direct H_2	1170	77.5 (34.4/43.1)	100	115	106	425
Methanol steam reformer	1287	83.7 (37.0/46.7)	62	79	69	460
Gasoline POX	1395	89.4 (39.4/50.0)	65	80	71	940

For the assumptions in Table 2.

battery is shown in Fig. 7 as a function of fuel processor response time for the FUDS and FHDS cycles. The longer the response time, the more the battery must be used. For a 5-s response time 40–50% of the energy reaching the wheels on the FUDS cycle has been routed through the battery.

The effect of fuel processor response time might be compensated to some extent by the presence of a ‘surge tank’ holding a reserve of reformed fuel. Fuel from the surge tank could be available to the fuel cell while the reformer was changing its output, allowing the fuel cell to meet a transient demand more rapidly than the response time of the reformer alone would dictate. The fuel cell itself plus associated piping holds some hydrogen, so that there is some inherent ‘surge capacity’ in the system. We have not considered the effect of surge capacity in our model.

2.2. Model results: vehicle performance, fuel economy and cost for alternative fuel cell vehicle designs

We now apply the model to compare alternative designs for fuel cell vehicles. Table 2 summarizes the assumptions used in our calculations. 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 have identical performance characteristics.

2.2.1. Vehicle weight

The vehicle mass 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 Fig. 8. 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.

2.2.2. 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 peak power output is needed because the vehicle is lighter. In Fig. 9, we have plotted a histogram showing the power demands of the FUDS and FHDS cycles (fraction of the time a certain power is demanded vs. power). The power required by the FUDS and FHDS cycles is considerably less than the fuel cell power, when the fuel cell is sized for sustained hill climbing. However, for fuel cell vehicles that include fuel processors, the long fuel processor response time means that the battery is used even during the FUDS cycle. In a hydrogen fuel cell car (where the fuel cell system response time is assumed to be essentially instantaneous), the peak power device is used to accept regenerative braking during the FUDS cycle.

2.2.3. Fuel economy

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

$$\text{mpg (combined)} = 1/(0.55/\text{mpg FUDS} + 0.45/\text{mpg FHDS}).$$

For mid-size, PNGV type automobiles, we find a fuel economy equivalent to 106 mpg gasoline for the hydrogen

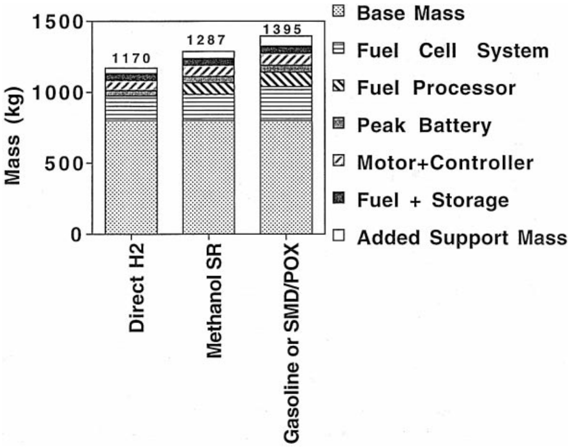


Fig. 8. Contributions to vehicle weight.

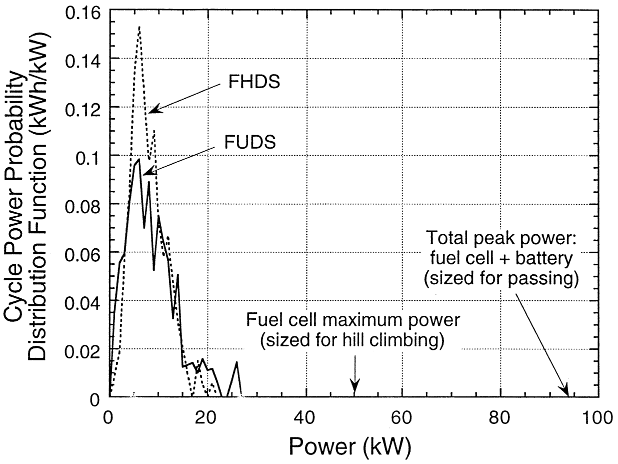


Fig. 9. Histogram of power demands for the FUDS and FHDS driving cycles. The fuel cell power and total peak power are indicated.

fuel cell vehicle. The fuel economies of the methanol and gasoline fuel cell vehicles are 69 mpeg and 71 mpg, about two-thirds that of the hydrogen fuel cell vehicle. The loss of efficiency is due to several effects, as shown in Fig. 10. First is the 15–25% energy loss in converting methanol or gasoline 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 the methanol steam reformer, the 5-s 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.

2.2.4. Range

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

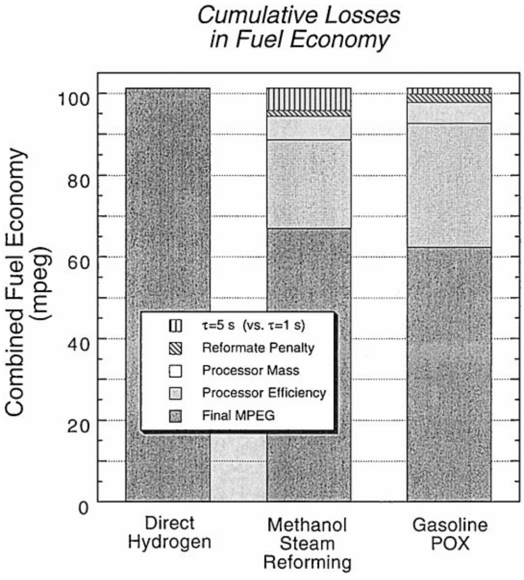


Fig. 10. Fuel economy penalties from onboard fuel processing.

2.2.5. Fuel storage volume

Methanol and gasoline fuel cell vehicles each store 13 gal of fuel, similar to today's gasoline vehicles. The fuel storage volume required for 5000 psi compressed hydrogen gas is about 150 l assuming an advanced composite material pressure cylinder. Although this volume is several times larger that today's automotive gasoline tanks, studies by Ford Motor and Directed Technologies indicate that this volume could be packaged in a mid-sized automobile without sacrificing passenger space [35].

2.2.6. Vehicle cost

Table 4 summarizes our cost assumptions for fuel cell vehicle drive train and fuel storage components in high volume mass production. These are 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 our vehicle simulations for hydrogen, methanol and gasoline fuel cell vehicles

Table 4
Cost estimates for mass produced fuel cell vehicle components

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

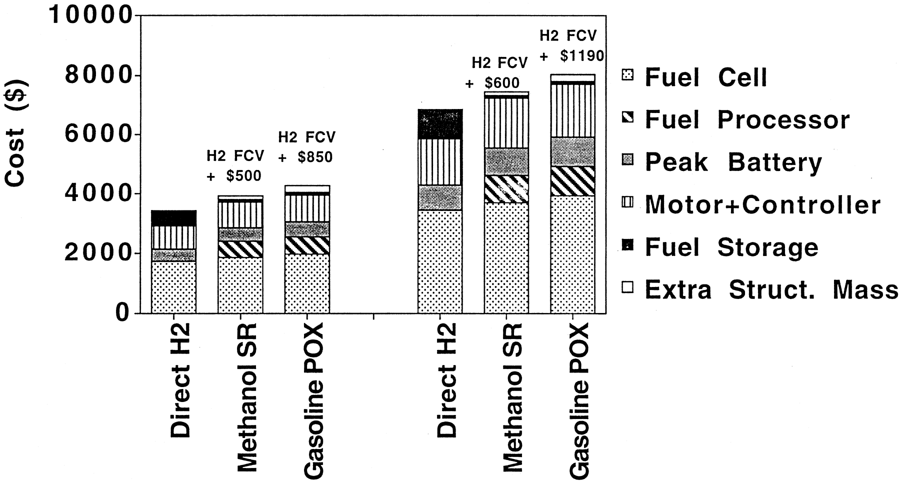
[a] Based on a range of estimates found in the literature. For example, GM/Allison projects a fuel cell 'electrochemical engine' cost of US$3899 for a 60-kW system including the fuel cell, fuel processor (methanol reformer), heat and water management. This is about US$65/kW (at the rated power of 60 kW) or US$46/kW peak. About 45% of the cost per peak kilowatt (US$21/kW) is for the fuel cell stack, 28% (US$13/kW) for the methanol reformer and the rest for auxiliaries. This cost assumes large scale mass production [1].
Mark Delucchi of Institute of Transportation Studies at UC Davis estimates a retail cost of US$2954 for a mass produced 25 kW hydrogen/air PEM fuel cell system or about US$120/kW (the manufacturing cost is US$59/kW, with a materials costs for the fuel cell stack plus auxiliaries estimated to be US$41/kW, and the labor cost US$18/kW) [21].
A study by Directed Technologies for the USDOE estimated a cost in mass production of US$2712 for a hydrogen/air fuel cell plus auxiliaries with net output of 85 kW power (about US$32/kW) [41]. More recently, DTI has estimated fuel cell stack manufacturing costs of US$19–27/kW using conventional manufacturing techniques, assuming production of 500,000 units/year [42].
Chrysler estimates that with current fuel cell manufacturing technology, mass produced costs would be US$200/kW [43].

[b] From Ref. [19].

[c] From Ref. [35].

[d] Derived from estimates in Ref. [12].

[e] Based on PNGV goals.



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 or Methanol Tank = $100
Extra Structural Mass = $1/kg

Fig. 11. Capital cost of components in alternative fuel cell automobiles.

(Table 3), we estimate the total capital cost of drive train and fuel storage components for each case (Fig. 11). The total cost ranges from about US$3600 to over US$7000, depending on the assumptions.

We see that the first cost of fuel cell vehicles with onboard methanol steam reformers would be higher than that for hydrogen fuel cell vehicles by about US$500–600/car. We estimate gasoline POX fuel cell cars would cost US$850–1200/car more than hydrogen fuel cell vehicles.

The fuel processor cost per unit of power output is assumed to be the same for steam methanol reformers and for gasoline POX systems (in the range of US$15–25/kW). The higher cost for the gasoline fuel cell vehicle is primarily due to the fuel cell's lower performance on POX reformate (which contains perhaps 35% hydrogen) as compared to methanol reformate (which contains 75% hydrogen). The lower performance necessitates a larger capacity, cost, and weight for vehicle drive train components (fuel cell, fuel processor, motors and controllers, peak power devices) in order to achieve the same performance.

For comparison the manufacturing cost of corresponding parts for a gasoline internal combustion engine vehicle (e.g., the engine, transmission, electrical system, fuel and tank, and emission control systems) might be about US$39/kW [34]. For a gasoline IC engine car with a 94-kW engine (the estimated power for an aluminum intensive Ford Sable), this would be about US$3666/car. To achieve a first cost similar to that of today's gasoline ICEVs, fuel cell vehicle components must meet stringent cost goals.

2.2.7. 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 or gasoline fuel cell vehicles. Moreover, the tailpipe emissions will be strictly zero under all operating conditions.

3. Refueling infrastructure requirements for fuel cell vehicles

Refueling infrastructure requirements depend on the level of demand. This in turn depends on the vehicle fuel economy, range, annual mileage, and number of vehicles in the fleet. Table 5 describes the assumed characteristics of fuel cell automobiles fueled with hydrogen, methanol and gasoline, based on our simulations. Annual mileage is based on the average in the US [6]. The annual energy use is lowest for hydrogen fuel cell vehicles, as they have the highest fuel economy. Although methanol and gasoline fuel cell cars are projected to have about the same fuel economy (about two-thirds that of the hydrogen fuel cell vehicle), roughly twice as many gal of methanol would be needed per year, because of methanol's lower volumetric energy density.

The primary energy requirements for hydrogen, methanol and gasoline fuel cell vehicles are compared in Table 5. Assuming that natural gas is the near term source of both hydrogen and methanol, and that gasoline is produced from crude oil, we see that one unit of natural gas fuels 1.7 times as many hydrogen fuel cell cars as methanol fuel cell cars. This is seen by going through the conversion

Table 5
Assumed characteristics of fuel cell automobiles

	Hydrogen PEMFC car	Methanol PEMFC car	Gasoline PEMFC car
Fuel economy[a,b]	106 mpg gasoline equivalent	69 mpg gasoline equivalent	71 mpg gasoline equivalent
Miles per year[c]	11,000	11,000	11,000
Fuel Storage	H_2 gas @ 5000 psi	methanol	gasoline
Fuel stored onboard[b]	1550 scf H_2 (3.75 kg)	13 gal methanol	13 gal gasoline
Range (miles)[b]	425	460	940
Fuel energy use per year (GJ/year)[a]	13.6	20.9	20.3
Fuel use per year[d]	40,000 scf H_2/year	307 gal methanol/year = 919 kg/year	155 gal gasoline/year = 3.69 barrel (bbl)/year
Primary energy use per vehicle per year[e]	16.1 GJ natural gas feedstock for steam reforming + 2.0 GJ natural gas fuel for generating compression electricity = 18.1 GJ	31.0 GJ natural gas for methanol production + 0.2 GJ of diesel fuel for truck transport of methanol to refueling station = 31.2 GJ	21.8 GJ crude oil for refinery production of gasoline, 0.2 GJ of diesel for truck transport of gasoline to refueling station = 22.0 GJ

[a] The mile per gallon gasoline equivalent efficiency for a fuel cell vehicle is estimated assuming that 1 gal of gasoline contains 125,000 Btu = 0.1308 GJ (HHV), 1 gal of methanol contains 64,600 Btu = 0.068 GJ (HHV) 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] Annual average mileage for passenger cars in the US [6].
[d] The specific weight of methanol is assumed to be 791 kg/m^3. 42 gal gasoline = 1 bbl.
[e] Assumes conversion efficiencies NG → hydrogen = 84.4%; NG → methanol = 67.4%; crude oil → gasoline = 95%. Energy delivery requirements: hydrogen = primary energy for compression electricity = 15% of hydrogen energy; methanol, gasoline = primary energy for truck delivery = 1% of total energy in fuel. Fuel economies are shown above.

steps from primary energy to energy at the wheels of the car. The conversion efficiency of natural gas to hydrogen is about 84%, as compared to 67% for methanol [36]. The conversion efficiency of crude oil in the refinery to gasoline is assumed to be about 95%. The energy cost of delivering methanol or gasoline is relatively low, perhaps 1% of the total energy is required for truck transport of methanol or gasoline from the production to the refueling site. Hydrogen delivery involves compression of the hydrogen at the refueling site. Assuming that electricity for compression is made from natural gas at 45% efficiency, and that electricity is transmitted from the power plant to the compressor at 90% efficiency, hydrogen compression increases the primary energy requirement about 15%. Comparing hydrogen and methanol, we find that for 100 units of primary energy input, about 66 units of methanol, 76 units of hydrogen and 94 units of gasoline energy are delivered to vehicles. The fuel economy is 106 mpg equivalent for a hydrogen fuel cell vehicle, 71 mpg for the gasoline fuel cell vehicle and 69 mpg equivalent for a methanol fuel cell vehicle. So for an equal input of primary energy input, we can fuel 100 hydrogen vehicles, 82 gasoline vehicles, and 57 methanol vehicles.

3.1. Developing a refueling infrastructure for hydrogen vehicles

The relative simplicity of vehicle design for the hydrogen fuel cell vehicle must be weighed against the added complexity and cost of developing a hydrogen refueling infrastructure. Indeed, hydrogen infrastructure is often seen as a ‘show-stopper’ for hydrogen fuel cell vehicles. The perceived issue is not technical feasibility, but cost. Large quantities of hydrogen are produced and delivered routinely for chemical applications today [11], and the technologies to produce, store and transport hydrogen are mature, well established and commercially available.

In previous studies, we have assessed the technical feasibility and economics of developing a hydrogen vehicle refueling infrastructure [22,25,26,28]. A number of near term possibilities for producing and delivering gaseous hydrogen transportation fuel were considered which employ commercial technologies for hydrogen production, storage and distribution. These include (see Fig. 12): (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 small scale 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), and (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 wind, solar or nuclear power (Fig. 13). Sequestration of byproduct CO_2 (for example, in deep aquifers or depleted gas

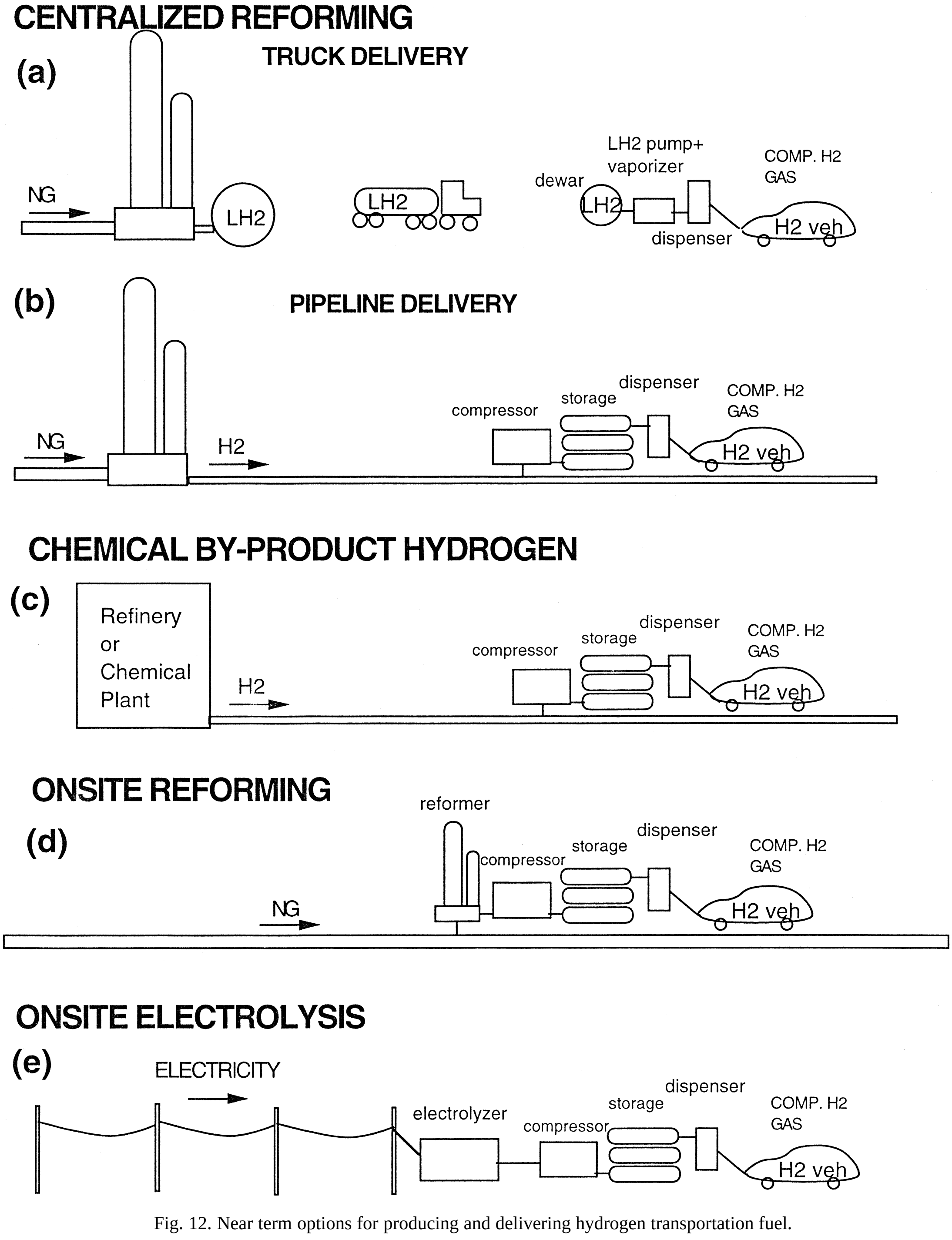


Fig. 12. Near term options for producing and delivering hydrogen transportation fuel.

wells) might be done to reduce greenhouse emissions from hydrogen derived from hydrocarbons [37].

3.2. Economics of hydrogen production and delivery

3.2.1. Delivered cost of hydrogen transportation fuel

The levelized cost of compressed gas hydrogen transportation fuel, delivered to the vehicle at 5000 psi, is estimated in Fig. 14, for various near term supply options. Delivered fuel costs are given in dollars per gigajoule (US$/GJ; on a higher heating value basis, the energy cost of US$1/gal gasoline is equivalent to US$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 (US$2.8/GJ), and the cost of off-peak power is relatively high (3 cents/kW h). A capital charge rate of 15% is assumed.

The cost contributions of various factors are shown for each technology over a range of refueling station sizes from 0.1 to 2.0 million scf/day. For reference a station

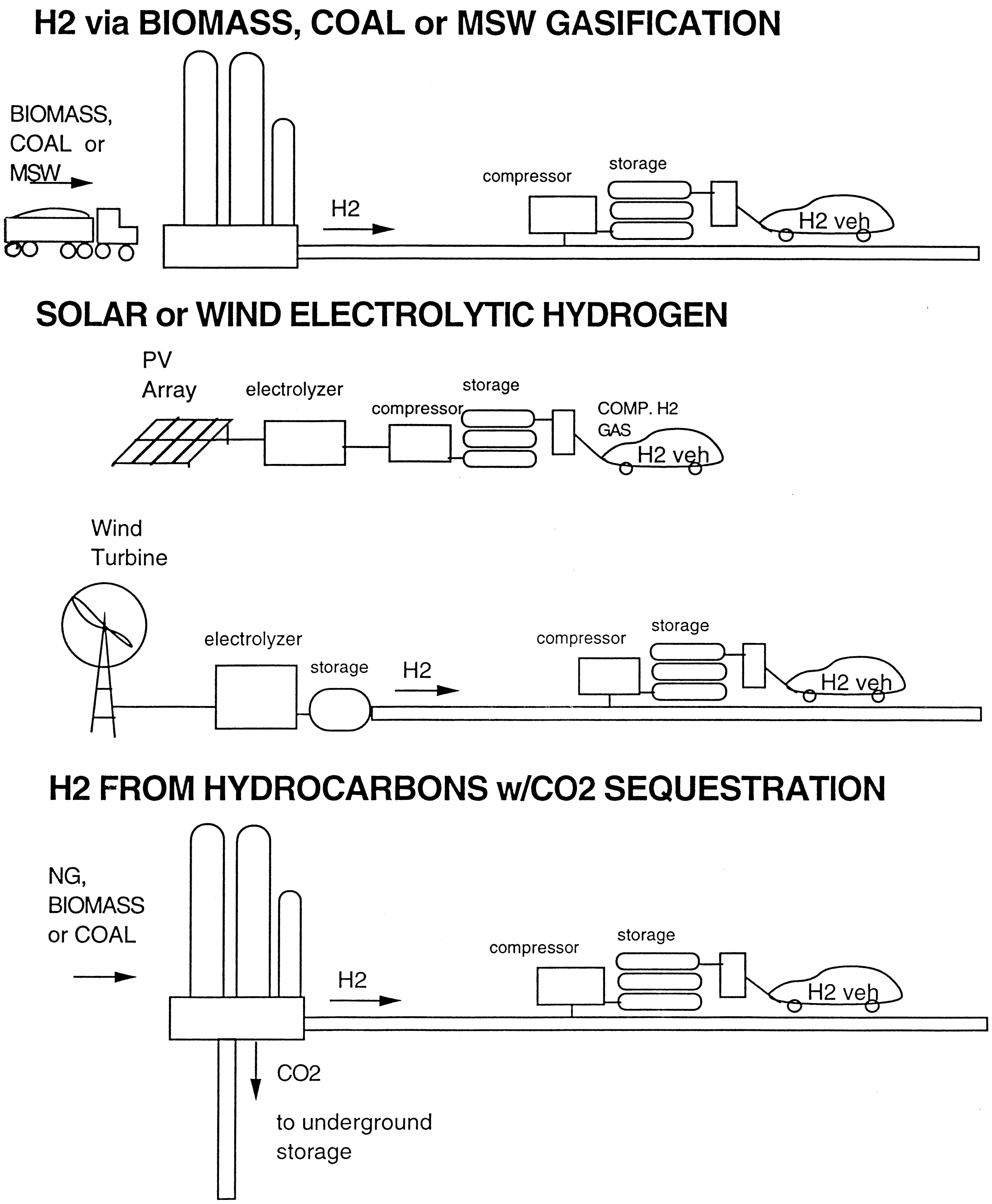
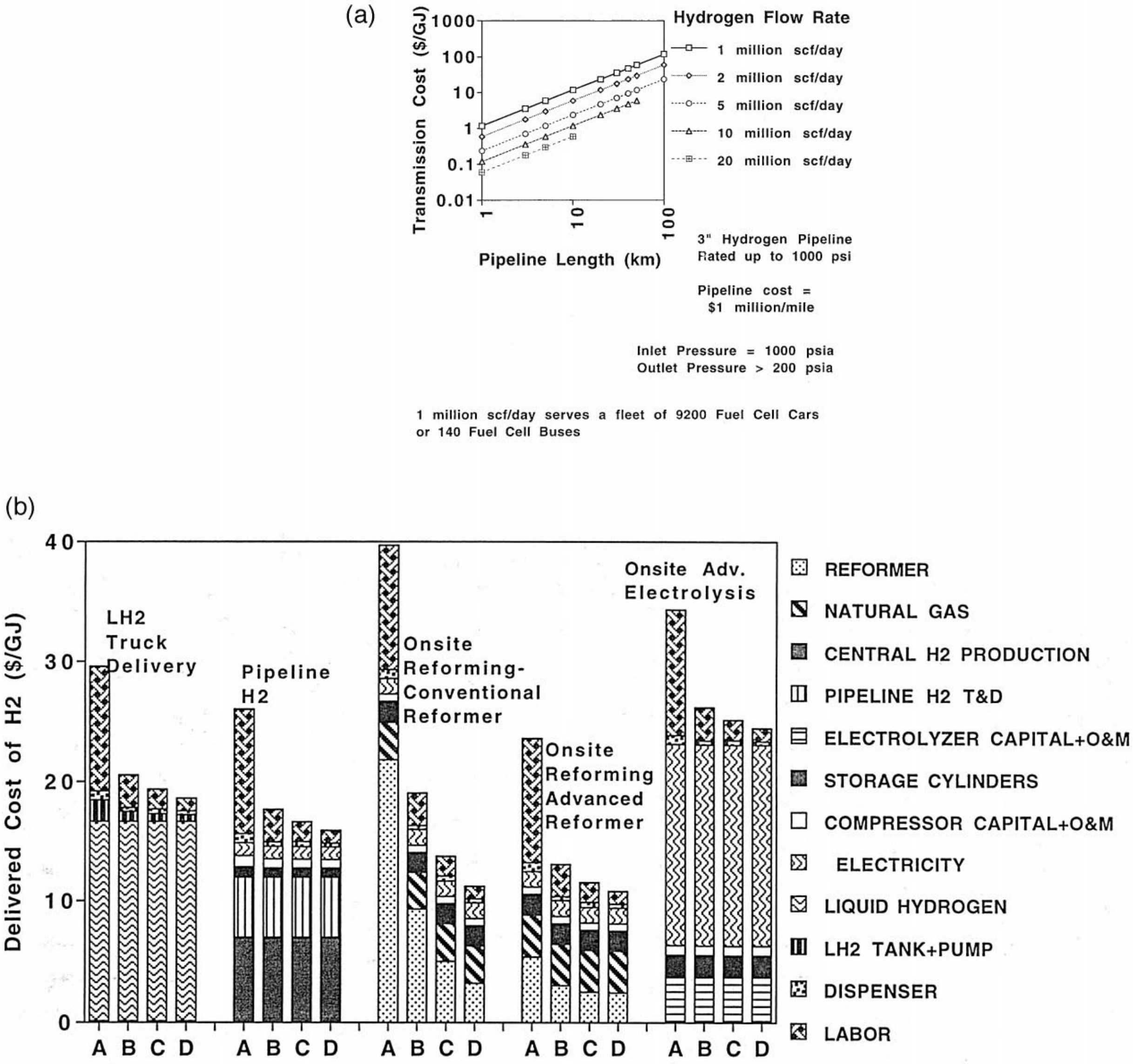


Fig. 13. Long term options for producing hydrogen transportation fuel.

dispensing 1 million scf/day could fuel 650 hydrogen fuel cell cars/day (or a total fleet of 9220 cars) or 80 fuel cell buses/day (or a fleet of 140 fuel cell buses) as shown in Table 6. Although all the supply options are roughly cost competitive, several points are readily apparent.

- The delivered cost of hydrogen transportation fuel is in the range of US$12–40/GJ (or US$1.6–5.2/gal gasoline equivalent), substantially higher than for today's untaxed gasoline, and varies markedly with both the conversion technology and the production scale.
- For our assumptions, at every scale of production, onsite production of hydrogen via small scale steam reforming of natural gas is the lowest cost option (assuming advanced reformer technology is used), and has the advantage that no hydrogen distribution system is required. Delivered hydrogen costs are shown for onsite reforming of natural gas based on: (1) conventional small steam reformer systems and (2) advanced low cost reformers, which have recently been introduced for stationary hydrogen production [8,10]. As discussed in a recent report [24], 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. Advanced reformers differ from conventional



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
Fleet of H2 FCV cars fueled	920	3400	9200	18400
H2 FCV buses/day	8	28	77	154
Fleet of H2 FCV Buses fueled	14	51	140	280

Fig. 14. Delivered cost of hydrogen transportation fuel. (a) Cost of pipeline delivery of hydrogen.

technologies in several important respects: (1) the reformer operates at lower temperature and pressure so that lower cost materials can be used, and (2) the system is more compact and has a standardized design, saving on engineering costs. With advanced reformers, onsite reforming is competitive with liquid hydrogen truck delivery and pipeline delivery over the whole range of station sizes considered.

- Truck delivered liquid hydrogen gives a delivered hydrogen cost of US$20–30/GJ, depending on the station size. Although the delivered hydrogen transportation fuel cost is higher than for advanced steam methane reforming,

Table 6
Fuel cell vehicles and hydrogen use

Hydrogen use	Hydrogen FCVs refueled/day	Total fleet fueled
1 million scf H_2/day	654 FCV cars/day	total fleet of 9223 FCV cars
	77 FC buses/day	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 H_2/day) = annual mileage (miles)/365 days/year/equivalent fuel economy (miles/gal gasoline equivalent energy) × gasoline HHV (GJ/gal)/H_2 HHV (GJ/scf).

For a passenger car: annual mileage = 11,000 miles; equivalent fuel economy = 106 mpg gasoline equivalent (HHV basis); gasoline HHV = 0.1308 GJ/gal; hydrogen HHV = 343 kJ/scf.

Hydrogen use per day (scf/day) for an average passenger car = 11,000 miles/year/(365 day/year × 106 mpg) × (0.1308 GJ/gal/0.000343 GJ/scf H_2) = 108 scf/day.

So, 1 million scf/day could fuel about a total fleet of about 1 million scf/day/ (108 scf/day/car) = 9223 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 (miles)/range (miles).

Cars refueled per day = # refuelings per year/365 days/year × total fleet of vehicles served = annual mileage (miles)/range (miles)/365 days/year × total fleet of vehicles served.

For a passenger car, the number of cars fueled per day at a station dispensing 1 million scf H_2/day would be: # cars refueled per day = 11,000 miles/425 miles/365 day/year × 9223 cars = 654 cars/day.

Similarly for PEMFC buses, where annual mileage = 50,000 miles.

Range = 250 miles.

Fuel economy = 7.3 mpg equivalent, 1 million scf H_2/day could fuel a fleet of 140 buses, or about 77 buses/day.

the liquid hydrogen alternative would be also attractive for early demonstration projects, as the capital requirements for the refueling station would be relatively small [23,24], and no pipeline infrastructure development would be required.

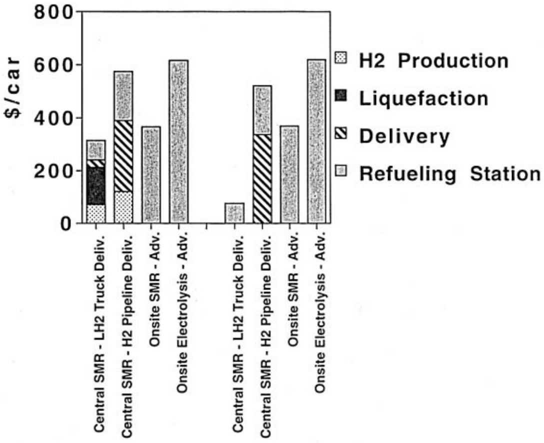
- Under certain conditions, a local gas pipeline bringing centrally produced hydrogen to users could offer low delivered costs. Our example assumes that it costs US$7/GJ to produce hydrogen ‘centrally’ (e.g., at large scale at a central location) and US$5/GJ to distribute it by local pipeline (centrally produced hydrogen ranges in cost from US$3/GJ for refinery excess to US$5–9/GJ for large scale steam reforming to US$8–10/GJ for hydrogen from biomass, coal or MSW). The cost of pipeline distribution depends on the geographic location and size of the demand. In highly developed areas such as the urban US, installed pipeline capital costs for a small (3–6 in.) diameter pipeline are typically US$1,000,000/mile. In flat, rural areas, pipeline costs can be much lower, perhaps US$250,000/mile. In developing countries, lower labor costs may bring down the total installed cost for small scale pipelines (in the US 15–20% of the total installed cost is for pipeline labor, and another 15–20% for engineering services for a pipeline through flat terrain costing US$500,000/mile [44]). Fig. 14a shows how the cost of pipeline delivery depends on the hydrogen flow rate and the pipeline distance. If the cost of hydrogen production is low, higher pipeline costs could be tolerated. Still, for pipeline hydrogen to be competitive with truck delivery or onsite reforming, pipeline costs can be no more than a few dollars per gigajoule (US$/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 more expensive than other options, largely because of the relatively high cost of off-peak power (3 cents/kW h) assumed in the study. If the cost of off-peak power were reduced from 3 cents/kW h to 1–1.5 cents/kW h, hydrogen costs would become more competitive with other options. For example, for off-peak power at 1 cent/kW h, electrolysis competes with onsite steam reforming. Off-peak power is available at 1 cent/kW h in some locations such as Brazil [45], which have excess off-peak hydropower. The amount of very low cost off-peak power available in Brazil (1000–2000 MW) might fuel 1 to 2 million hydrogen fuel cell automobiles.

These conclusions are appropriate for our assumptions. For other assumptions of energy prices, the delivered hydrogen costs will vary. 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 under all conditions.

3.2.2. 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 Fig. 15 and Tables 7 and 8, 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 or to produce it onsite. 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 H_2/day to 650 cars/day (alternatively, this level of infrastructure development could serve two 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.



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

Fig. 15. Capital cost of hydrogen infrastructure.

- 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 dispenses 1 million scf H_2/day to 650 cars/day. (For reference, there are projected to be 7.8 million cars in Los Angeles in 2010. So, this case would be equivalent to a fleet in Los Angeles where about 18% of the cars were hydrogen fuel cell vehicles.) 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 US$1.4–11.4 million or US$80–620/car (the US$80/car is for liquid hydrogen truck delivery including station costs only, no new production capacity or delivery trucks are included). The range of infrastructure capital costs for a system serving 1.41 million fuel cell cars, is about US$440–870 million or US$310–620/car. For the case of advanced onsite steam reforming, the capital cost is about US$516 million, or US$370/car.

For centralized production with pipeline delivery through a highly developed urban area such as Los Angeles, the capital cost of the hydrogen pipeline is assumed to be US$1 million/mile and accounts for almost half the total infrastructure capital cost. In the US, labor costs contribute some 15–20% to the total installed small pipeline cost and engineering another 15–20%. In a location with lower labor costs, the total pipeline cost might be reduced somewhat. If the location was not as developed (so that construction of the pipeline could avoid extensive road crossings, etc.) the capital cost could be reduced as well.

It is important to keep in mind the results of Fig. 14 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.

3.3. 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 tons/year (Table 9). About 23 million metric tons were actually produced in 1995, yielding a capacity factor of about 83%.

A significant methanol distribution already system exists. Of total world production, roughly half or 12 million metric tons were shipped to remote users, 70% by sea and 30% by rail, tank wagon or barge [31]. 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 (Fig. 16). 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 (this compares to about 136 million cars in the US, and 480 million worldwide [2]). 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 US$6000–52,500 for a station dispensing 1100 gal of methanol/day [7]. Such a station might serve a total fleet of 1300 methanol fuel cell cars. The capital cost per car would be a modest US$6–40/car (see Tables 10 and 11).

Table 7
Capital cost for developing new hydrogen delivery and refueling station infrastructure serving a total fleet of 18,400 FCV cars, delivering 2 million scf H_2/day (assuming that existing production capacity is used)

	Centralized production via steam reforming of natural gas with LH_2 delivery	Centralized production via steam reforming of natural gas with 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 = US$6.2 million (at US$1 million/mile)			
Two refueling stations each serving 654 cars/day	US$1.4 million (US$0.7 million/station)	US$3.4 million (US$1.7 million/station)	US$10.8 million (US$5.4 million/station)	US$6.8 million (US$3.4 million/station)	US$11.4 million (US$5.7 million/station)
Total	US$1.4 million	US$9.6 million	US$10.8 million	US$6.8 million	US$11.4 million
Infrastructure cost per car	US$76	US$522	US$587	US$370	US$620

Adapted from Ref. [24].

Table 8
Capital cost for developing new hydrogen production, delivery and refueling station infrastructure serving a total fleet of 1.41 million fuel cell cars, delivering 153 million scf H_2/day

	Centralized production via steam reforming of natural gas with LH_2 delivery	Centralized production via steam reforming of natural gas with 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	US$100 million for reformer + US$200 million for liquefier + LH_2 storage	US$170 million for reformer + H_2 compressor			
Hydrogen distribution	80 LH_2 trucks each with a 3-ton capacity, each making two local deliveries/day = US$40 million	600 km pipeline = US$380 million (at US$1 million/mile)			
153 1 million scf H_2/day refueling stations each serving 654 cars/day	US$104 million (US$0.7 million/station)	US$260 million (US$1.7 million/station)	US$830 million (US$5.4 million/station)	US$516 million (US$3.4 million/station)	US$870 million (US$5.7 million/station)
Total	US$440 million	US$810 million	US$830 million	US$516 million	US$870 million
Infrastructure cost per car	US$312	US$574	US$587	US$370	US$620

Adapted from Ref. [24].

Table 9
Methanol production capacity 1995[a]

Region	1000 metric tons/year	EJ/year (LHV)	Methanol FCV cars fueled (millions)[b]
North America	9550	0.19	10.4
Europe	7280	0.14	7.9
South America	3590	0.07	3.9
Far East and Asia	4680	0.09	5.1
Middle East and Africa	3460	0.07	3.8
World	28,260	0.56	30.7

In 1995 total MeOH demand was 23.4 million metric tons or 83% of nameplate production capacity. This suggests that significant numbers of methanol FCVs might be fueled without having to build new MeOH production capacity.

[a] From Ref. [46].

[b] Assuming the annual methanol use for a methanol fuel cell passenger car in Table 5.

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, the cost for this conversion would be modest as well, perhaps US$9/car [7]. This level of infrastructure conversion would be sufficient until the market for automotive methanol exceeded the excess production capacity in the system.

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 US$50 million for an ultra large tank ship carrying 250,000 DWT [9]. However, it would serve a large fleet of fuel cell cars (a fleet about 3–15 million cars could be served by such a tanker, assuming the ship made 10–50 deliveries/year). The capital cost for new tankers would be modest on a per car basis, perhaps US$4–25/car. However, the capital costs for new production capacity would be significant (Tables 10 and 11). For a new 2500 tons/day plant, serving 1.0 million methanol fuel cell cars, the capital cost would be about US$415–720/car. At a larger plant size (10,000 tons methanol/day) serving 4.0 million cars, the capital cost would be US$280–485/car [17,18].

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 (Fig. 17).

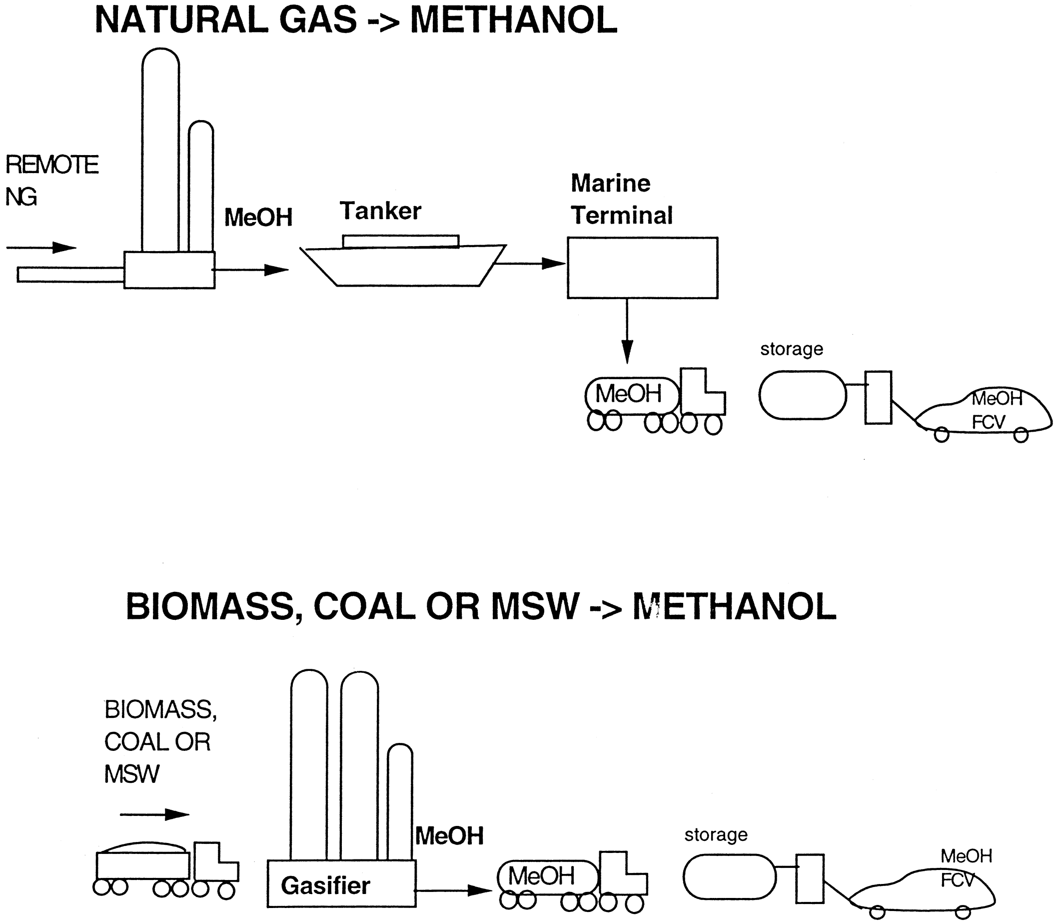


Fig. 16. Options for production of methanol.

Table 10
Projected capital cost of methanol refueling infrastructure development

Item	Cost
Convert gasoline refueling station to methanol	US$45,000/station (for a station dispensing 1100 gal MeOH/day)[a]
Methanol delivery truck	no cost (use existing gasoline trucks)[a] US$140,000 (per new 8500 gal MeOH truck)[a]
Marine terminal bulk storage tank for methanol (for a terminal with 1.3 million bbl storage = 20 days storage)	US$2.50/bbl MeOH (convert gasoline storage)[a] US$15/bbl MeOH (build new MeOH storage)[a]
Other terminal equipment	US$1/bbl MeOH[a]
Methanol overseas shipping costs	capital cost for new 250,000 dead weight ton (DWT) tanker = US$50 million[d] trans cost = 3–5 cents/gal[b,c]
Methanol production plant (from NG)	US$880–1540 million[c] (10,000 metric tons/day) US$330–570 million[c] (2500 metric tons/day)

[a] From Ref. [7]. This assumes that the storage capacity holds 20 days worth of fuel.
[b] From Ref. [18].
[c] From Ref. [17].
[d] From Ref. [9].

At low market penetrations of methanol fuel cell vehicles, infrastructure capital costs will be small (probably less than US$50/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 US$330–770/car, depending on the assumptions (see Tables 10 and 11).

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 you compare only distribution and refueling station costs, a methanol infrastructure is much less costly to implement than a hydrogen infrastructure, as shown in earlier studies of methanol and hydrogen infrastructure [7].

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 capital costs per unit of produced energy are less for hydrogen and 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 [36]. The cost of fuel

Table 11
Capital cost of methanol infrastructure per car

Item	Capital cost	# Cars served	Capital cost per car (US$/car)	Capital cost per car (1995 US$/car)
Refueling station conversion (1100 gal/day) (1990 US$)	US$45,000	1309	34	40
Marine terminal conversion (1990 US$)	@ US$18.5/bbl storage capacity; 6500 bbl (minimum)	2.4 cars/bbl of storage capacity; 15,400 cars (minimum)	8	9
Tanker shipping capacity (1986 US$)	US$200/DWT for a new 250,000 DWT ultra large tanker	3–15 million cars (if tanker makes 10–50 deliveries/year)	$3–17	4–25
New production capacity (1988 US$)	US$880–1540 million (10,000 metric tons/day)	4.0 million cars	220–385	280–485
	US$330–570 million (2500 metric tons/day)	1.0 million cars	330–570	415–720

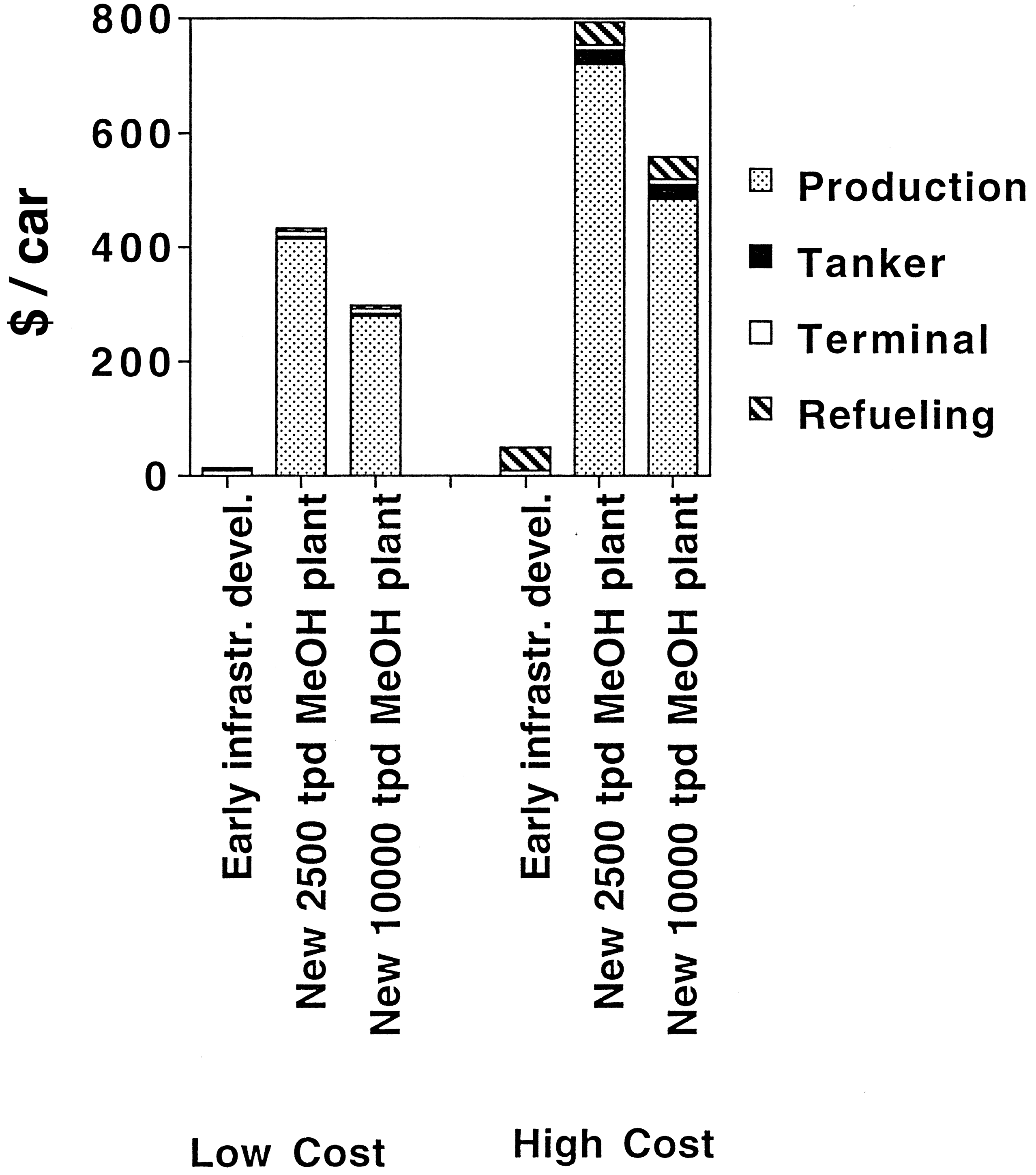


Fig. 17. Capital cost of methanol refueling infrastructure.

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 US$1.9/GJ, as compared to US$1.0/GJ for gasoline [21]. The estimated delivered cost of methanol is shown in Fig. 19 for various primary sources.

3.4. 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.

3.5. Total infrastructure costs (on and off the vehicle) for fuel cell vehicles: a comparison of hydrogen, methanol and gasoline

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

Defining 'infrastructure' to mean all the equipment (both on and off the vehicle) required to bring hydrogen to the fuel cell, it is clear that gasoline and methanol fuel cell vehicles also entail extra costs. For gasoline vehicles, these costs are for onboard fuel processing. For methanol, there are extra costs both on and off the vehicle. In the case of hydrogen, the infrastructure development capital cost is paid by the fuel producer (and passed along to the con-

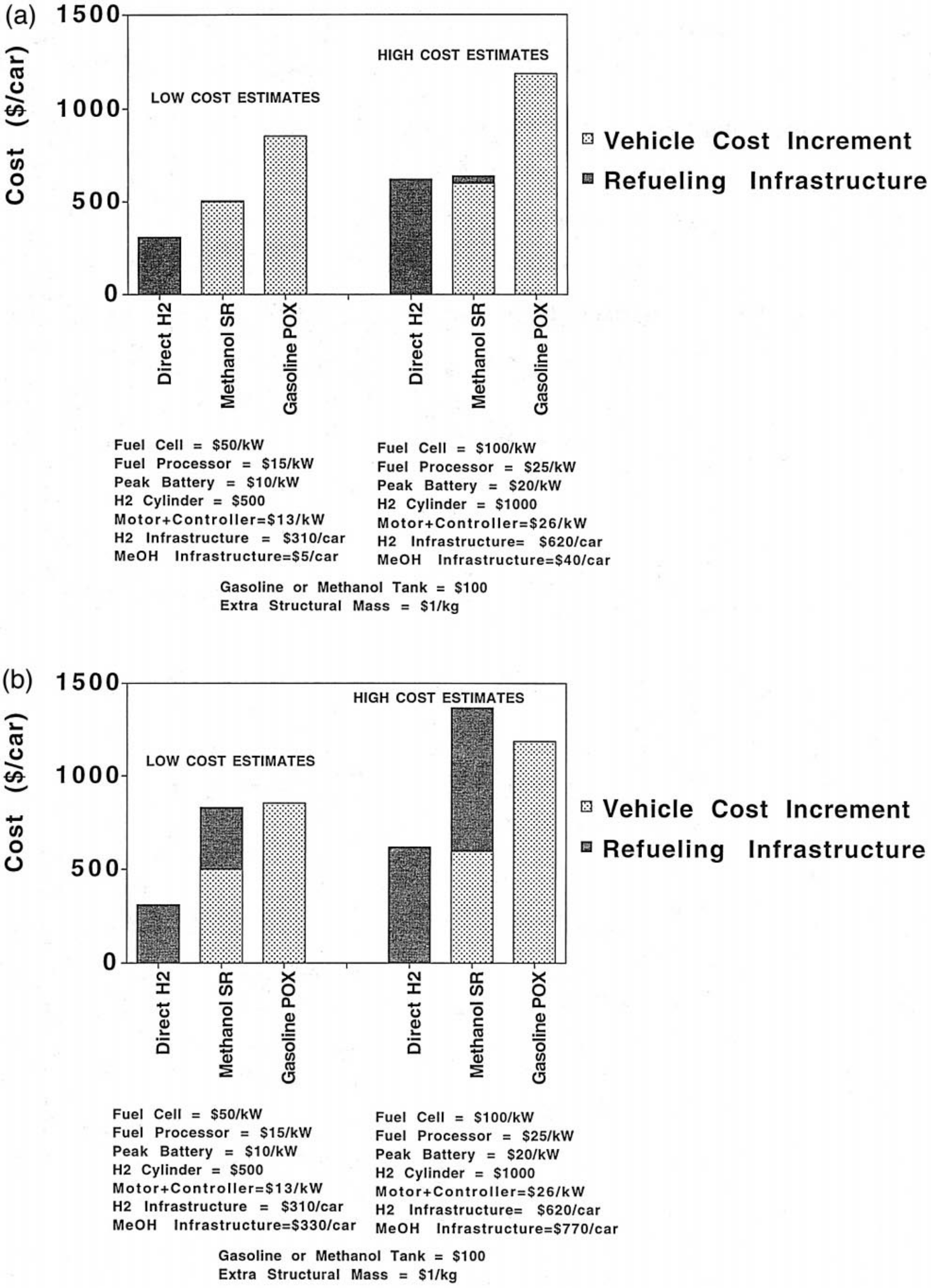
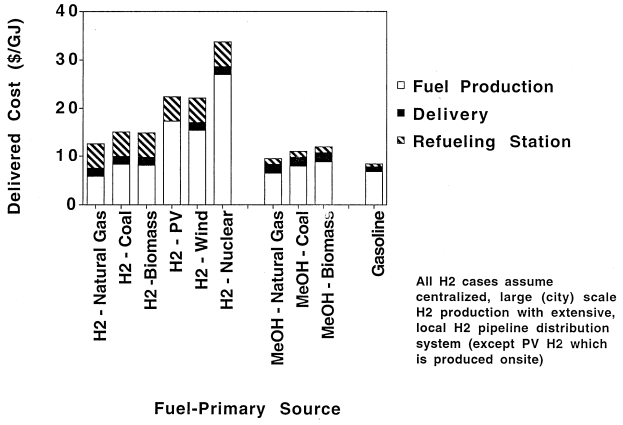


Fig. 18. Comparison of incremental capital costs for alternative fuel cell vehicles (compared to H_2 fuel cell vehicles) and refueling infrastructures (compared to gasoline). a) early methanol infrastructure, b) large scale methanol infrastructure.



All H2 cases assume centralized, large (city) scale H2 production with extensive, local H2 pipeline distribution system (except PV H2 which is produced onsite)

Fig. 19. Comparison of the delivered cost of hydrogen, methanol and gasoline transportation fuels.

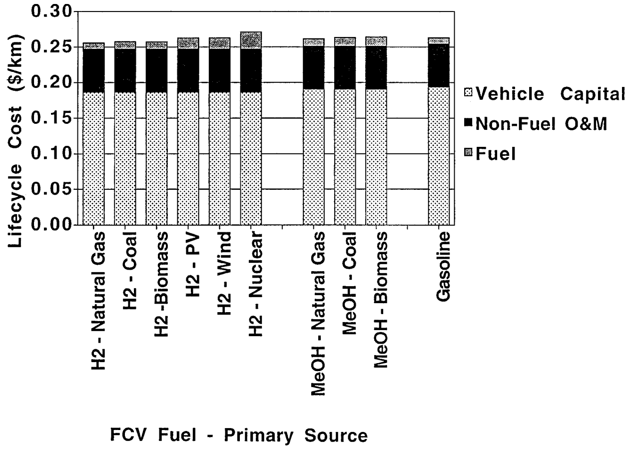


Fig. 21. Comparison of the total lifecycle cost of transportation for alternative fuel cell vehicles run on hydrogen, methanol and gasoline.

sumer as a higher fuel cost). In the case of gasoline fuel cell vehicles, the capital cost is paid by the consumer buying the car. In the case of methanol both the fuel producer and the vehicle owner pay extra capital costs.

In Fig. 18 we combine our estimates of the cost of alternative fuel cell vehicles (Fig. 11) and off-board refueling infrastructure (Figs. 15 and 16). Our estimates show that methanol fuel cell cars are likely to cost US$500–600/car more and gasoline POX fuel cell vehicles US$850–1200/car more than comparable hydrogen fuel cell vehicles. The added cost of off-board refueling infrastructure for hydrogen is in the range of US$310–620/vehicle (for advanced small scale steam reforming it is US$370/vehicle). For methanol the off-board refueling infrastructure costs will be small (less than US$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, total methanol infrastructure capital costs would be US$330–770/car. The is comparable to off-board costs for hydrogen infrastructure. To within the accuracy of our cost projections, it appears that the total capital cost for infrastructure on and off the vehicle would be comparable for methanol and gasoline fuel cell vehicles, and somewhat less for hydrogen when advanced steam reformers are used at the refueling station.

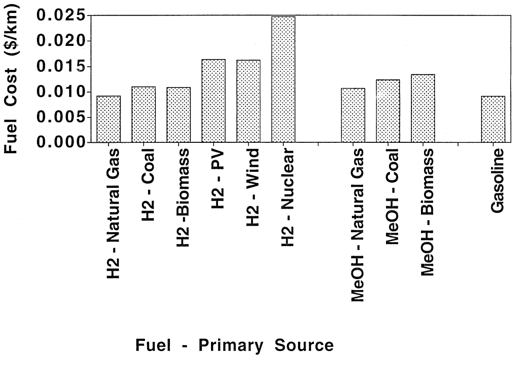


Fig. 20. Comparison of the fuel cost per kilometer for alternative fuel cell vehicles run on hydrogen, methanol and gasoline.

3.6. Lifecycle cost of transportation

In Fig. 19 the delivered cost of fuel (including production, delivery and refueling stations) is compared for hydrogen, methanol and gasoline based on estimates by Williams et al. [36]. A variety of primary sources are considered. We see that the cost per unit of energy for hydrogen is higher than for methanol or gasoline.

The fuel cost per kilometer is shown in Fig. 20. 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 Fig. 21. This includes the vehicle capital cost, non-fuel O&M costs, and fuel costs. The lifecycle cost of transportation for a hydrogen fuel cell vehicle is slightly less than for a gasoline fuel cell vehicle. This is true 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.

These results have led analysts to suggest that there would be an economic pressure to move toward hydrogen as a fuel, even if fuel cell cars were commercialized first using gasoline [38].

4. Fuel strategies for developing fuel cell vehicles

4.1. Fuel cell fleet vehicles

As with any new vehicle technology which uses alternative fuels, the first applications of fuel cell vehicles are occurring in centrally refueled fleet applications. Buses are particularly attractive as an entry market for fuel cell vehicles, as they are centrally garaged, refueled and maintained. Moreover, fuel cells are likely to be economically competitive first in bus markets, where cost goals are not as stringent as for automobiles.

The Georgetown fuel cell bus, which was first demonstrated in 1993, employed a methanol reformer coupled to a phosphoric acid fuel cell. Since that time the emphasis has moved toward PEM fuel cells, because of their potential for lower cost and higher power density.

The first experimental PEM fuel cell vehicle fleets are hydrogen fueled buses (Ballard has begun demonstrating hydrogen fueled PEMFC buses in Vancouver and Chicago, with commercialization planned for 1999). Hydrogen has been the preferred fuel in PEM fuel cell bus demonstrations thus far for several reasons.

- Vehicle systems are simpler with compressed hydrogen gas storage as compared to onboard reformation of methanol or gasoline.
- Fuel processor technology is still being developed for use with PEM fuel cells, and hydrogen PEM fuel cell buses are available.
- Fuel cell fleet demonstrations offer an excellent opportunity to test hydrogen refueling systems. Hydrogen infrastructure demonstrations are an important part of hydrogen fuel cell bus projects. (Demonstrations of small scale methane reformers may be of particular interest. A fleet of about 8 PEMFC buses could be refueled daily using a small scale reformer producing 100,000 scf H_2/day. Rapid developments in small scale reformer technology are making this an increasingly attractive supply option [11].)

Methanol is also being considered for PEM fuel cell bus applications. Ballard plans to demonstrate a PEM fuel cell bus with onboard methanol reformation, and the Georgetown bus project has shifted to methanol reformers with PEM fuel cells. With methanol the refueling systems would be less complex, and the vehicles more complex than with hydrogen.

It has also been proposed that liquid fuels such as synthetic middle distillates could be made from natural gas for use in fuel cell vehicles. These could be more easily reformed than diesel or gasoline, and would be compatible with the existing gasoline infrastructure. However, as with methanol, production of synthetic middle distillates would involve significant capital costs for production. as well as onboard costs for reformers similar to those for gasoline POX fuel cell vehicles [27].

4.2. Introduction of fuel cell automobiles

4.2.1. Review of progress in commercialization of fuel cell automobiles

Progress toward a commercial fuel cell automobile has proceeded at a rapid and accelerating pace (see Table 11). At present eight major automobile manufacturer have announced plans to commercialize PEM fuel cell cars in the 2004–2005 timeframe. These include Chrysler, GM, Ford, Daimler–Benz, Mazda, Toyota, Honda, and Nissan (Table 12).

The first impetus toward development of fuel cell vehicles came with California's zero emission vehicle mandate in 1990. The Partnership for a New Generation of Vehicles program, which began in 1993, greatly accelerated research and development work on fuel cell vehicles. In 1993 Ballard Power Systems, demonstrated the first PEM fuel cell bus, run on hydrogen. This was followed in 1995 by the NECAR I, an experimental hydrogen fueled PEM fuel cell van built by Daimler–Benz. Mazda, Toyota and Daimler–Benz demonstrated experimental hydrogen fuel cell vehicles in 1995–1996. In 1997 Ballard and Daimler–Benz announced a US$320 million joint venture to develop PEM fuel cell cars by 2005. Toyota and Daimler–Benz demonstrated PEM fuel cell cars with onboard methanol reformers in 1997, and in December 1997, Ford joined Daimler and Ballard in a US$420 million venture to commercialize a PEM fuel cell car by 2004. In early 1998, GM and Chrysler announced their intent to develop fuel cell cars by 2004. In 1998 Mobil joined Ford to work on fuel issues for fuel cell vehicles. Mazda has also joined the Ford–Daimler–Benz alliance. In 1998 Honda announced its plans to develop a methanol fuel cell vehicle. Nissan announced similar plans in 1998. Shell Oil and Daimler–Benz announced plans to develop an onboard gasoline reformer.

4.2.2. Fuels strategies for fuel cell automobiles

All the auto manufacturers developing fuel cell vehicles are looking at a variety of fuel possibilities. Various manufacturers are emphasizing particular near term fuel options in their demonstration vehicles.

Chrysler and Daimler–Benz with Shell are pursuing onboard reformation of gasoline in POX systems. This would have the advantage of using the existing gasoline infrastructure, but many technical challenges remain in developing onboard gasoline fuel processors.

Daimler–Benz, Toyota, and Honda are emphasizing methanol in their latest experimental vehicles. Ford and Mazda are in a joint project with Daimler–Benz, but Ford has done a significant amount of work on the hydrogen alternative. One of the reasons for Ford's interest in hydrogen is the relative simplicity of the vehicle. GM has worked with methanol reformers, but is reportedly examining all options.

Near term demonstration projects will help elucidate the technical issues for various types of fuel cell vehicles. Assuming that onboard reformers can be successfully developed, there are several evolutionary long term fuels strategies which have been proposed for fuel cell automobiles.

Table 12
Progress in commercialization of fuel cell vehicles

1990—California Air Resources Board announces zero emission vehicle mandate, requiring introduction of zero emission vehicles, and catalyzing interest in electric vehicles, including fuel cell vehicles.

1993—Georgetown Bus demonstrated, with phosphoric acid fuel cell and onboard methanol reformer.

1993—Partnership for a new generation of vehicles announced, a government/industry partnership aimed at producing cars with three times the fuel economy of current vehicles. Big Three US automakers begin studies of options, including fuel cells.

1993—Ballard Power Systems demonstrates first hydrogen fueled PEM fuel cell bus.

1995—Daimler–Benz demonstrates the NECAR I, an experimental PEM fuel cell van with hydrogen storage.

1995—Ballard Power Systems demonstrates improved hydrogen fueled PEM fuel cell bus.

1995—Mazda demonstrates H_2 fueled PEM fuel cell golf cart.

1996—Toyota demonstrates experimental PEM fuel cell car with metal hydride storage.

1996—Daimler–Benz demonstrates the NECAR II, a prototype van with compressed hydrogen gas storage and Ballard fuel cell.

1997—Ballard begins demonstration of H_2 PEM fuel cell buses in Vancouver, BC.

1997—Ballard and Daimler–Benz form US$320 million joint venture to develop PEM fuel cell cars by 2005.

1997—Daimler–Benz demonstrates NECAR III, a prototype small car with PEMFC and onboard reformation of methanol.

1997—Toyota demonstrates PEM fuel cell car with onboard methanol reformer.

1997—Ford joins Daimler–Benz and Ballard in US$420 million venture to commercialize PEM fuel cell car by 2004.

1998—GM announces intent to develop production ready prototype fuel cell car by 2004.

1998—Chrysler announces intent to develop production ready prototype fuel cell car by 2004 with onboard reforming of gasoline.

1998—Mobil and Ford form alliance to develop onboard fuel processors for fuel cell vehicles.

1998—Mazda joins Ballard, Daimler–Benz and Ford alliance to develop fuel cell automobiles.

1998—Honda announces intent to develop methanol fueled fuel cell vehicle.

1998—Nissan announces intent to develop fuel cell vehicle.

4.2.2.1. Scenario 1: gasoline POX fuel cell car → hydrogen fuel cell cars. Introduction of fuel cell cars with onboard gasoline fuel processors would allow the rapid introduction of large numbers of fuel cell automobiles to general consumers without changes in the refueling infrastructure. This might decrease the cost of fuel cells via mass production to levels where they could compete with advanced internal combustion engine vehicles. Once the cost of fuel cells is reduced, it can be argued that there would be economic pressure to move to hydrogen fuel cell vehicles, because of their lower first cost and lifecycle cost [38]. Environmental and energy supply concerns might also dictate a switch from gasoline. In the longer term, a widespread hydrogen refueling infrastructure would be implemented for hydrogen fuel cell cars. This would allow diverse primary sources to be used for fuel production, and enable significant reductions of greenhouse gas emissions. Alternatively, it has been suggested that there could be a switch from gasoline to another liquid fuel produced from hydrocarbon feedstocks [4].

4.2.2.2. Scenario 2: hydrogen moves from centrally refueled fleets to general automotive markets. In this scenario, hydrogen is implemented first in centrally refueled fleet vehicles, and later moves to general automotive markets. The impetus to bring hydrogen into widespread use would be environmental or energy supply concerns. Fig. 18 suggests that this strategy might involve the lowest overall capital outlay, counting both vehicle costs and infrastructure costs. However, this scenario faces a ‘chicken and egg’ problem in reaching beyond niche markets, and getting enough fuel cell cars on the road to bring down costs. (Until large numbers of hydrogen cars are present, it will be difficult to justify a geographically widespread hydrogen fuel distribution system. But general automotive use depends on widespread availability of fuel.) Implementing this strategy would involve a societal decision to move toward a zero emission transportation system.

4.2.2.3. Scenario 3: methanol fuel cell vehicles are introduced for fleet applications, moving to general automotive markets. Eventually a switch to hydrogen may be implemented. In this scenario, methanol fuel cell vehicles are introduced first in centrally refueled fleet applications. The advantages are that methanol is easier to store and handle than hydrogen, and easier to reform than gasoline. The disadvantages are that methanol faces the same ‘chicken and egg’ problem as hydrogen in reaching general automotive markets, and that the methanol vehicle will be more costly than one with hydrogen. Initially, methanol infrastructure costs will be less than those for hydrogen, but once methanol makes significant penetration into automotive markets, costly new production capacity will be needed, so that off-vehicle infrastructure costs alone might be comparable to those for hydrogen. In the near term the most likely source for methanol production is remote natural gas. Ultimately, other feedstocks for making methanol could be used such as biomass, wastes or coal. Eventually, a switch from methanol to hydrogen might occur, because hydrogen vehicles would be lower cost, and the capital costs for developing a new fuel production and delivery infrastructure would probably be lower for hydrogen than for methanol. Moreover, a hydrogen based transportation system would allow lower greenhouse gas emissions than one based on methanol. (Greenhouse gas emissions would be lower, since less primary energy would be used with hydrogen than with methanol. Moreover, sequestration of CO_2 might be done if hydrogen is produced from hydrocarbons.) A disadvantage of this scenario is that the fuel infrastructure would have to be changed twice (once from gasoline to methanol, and then from methanol to hydrogen).

The optimum near to mid term fuel strategy for fuel cell vehicles is uncertain, awaiting the results of demonstrations of alternative fuel cell vehicle types. In the long term, it appears that hydrogen has advantages over gasoline and methanol in terms of vehicle cost, complexity and fuel economy, and environmental and energy supply benefits. The total capital cost of implementing fuel cell vehicles (counting both onboard fuel processors and off-vehicle fuel supply infrastructure) appears to be lowest for hydrogen, as well.

5. Conclusions

Simulation programs of fuel cell vehicles and onboard fuel processors have been developed. For the same performance, we found that hydrogen fuel cell vehicles are simpler in design, lighter weight, more energy efficient and lower cost than those with onboard fuel processors.

Vehicles with onboard steam reforming of methanol or POX of gasoline 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 driving cycle) are projected to be about 106 mpeg for hydrogen fuel cell vehicles, 69 mpeg for fuel cell vehicles with onboard methanol steam reforming, and 71 mpeg for onboard gasoline POX.

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

The capital cost of developing hydrogen refueling infrastructure based on near term technologies would be about US$310–620/car depending on the type of hydrogen supply. Methanol infrastructure capital costs should be low initially (less than US$50/car), but would increase to US$330–770/car once new methanol production capacity was needed. 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 comparable for hydrogen, methanol and gasoline POX fuel cell vehicles. Hydrogen appears to entail the lowest overall capital costs.

The cost and efficiency estimated for various types of fuel cell vehicles depend on our assumptions, which may change as technology progresses. For example, future improvements in onboard fuel processor technology or development of fuel cells with higher performance on reformates could increase the vehicle efficiency for methanol or gasoline vehicles; better methods of hydrogen storage might lead to lower cost for hydrogen vehicles.

Hydrogen is the preferred fuel for fuel cell vehicles, for reasons of vehicle design, cost and efficiency, as well as potential energy supply and environmental benefits (e.g., the possibility for reduced total fuel cycle greenhouse gas emissions plus strictly zero tailpipe emissions). The capital cost of developing hydrogen refueling infrastructure is comparable to or less than the total cost (on and off the vehicle) for methanol or gasoline fuel cell vehicles. The lifecycle cost of transportation is slightly less for hydrogen than for gasoline or methanol fuel cell vehicles. Like compressed natural gas or methanol, hydrogen faces the issue of reaching beyond centrally refueled fleet markets. The choice of fuel for the near term 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.

Acknowledgements

We would like to thank the US Department of Energy Hydrogen R&D Program, the Energy Foundation, the Link Energy Foundation and the American Association of University Women Educational Foundation for their support. For useful conversations, the authors would like to thank Jeff Bentley (Epyx), Paul Farris (IFC), Shimson Gottesfeld (Los Alamos National Laboratory), Brian James (Directed Technologies), Sivan Kartha (Princeton University), Ryan Katofsky (Arthur D. Little), Michael Kerr (Praxair), Ira Kuhn (Directed Technologies), Paul Kydd (BOC), Eric Larson (Princeton University), Christian Lenci (Praxair), Frank Lomax (Directed Technologies), Robert Miller (Air Products and Chemicals), William Mitchell (Epyx), David Moard (Hydrogen Burner Technology), Robert Moore (Air Products and Chemicals), David Nahmias (National Hydrogen Association), Venki Raman (Air Products and Chemicals), Robert Socolow (Princeton University), Sandy Thomas (Directed Technologies) and Robert Williams (Princeton University).

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