An Assessment of Fuels for Fuel Cell Vehicles in Brazil: Potential Resources and Costs

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Appendix A: Ogden, Steinbugler, and Kreutz, "A Comparison of Hydrogen, Methanol, and Gasoline Fuels as Fuels for Fuel Cell Vehicles: Implications for Vehicle Design and Infrastructure Development," draft manuscript, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, September 1998.

Appendix B: Williams, Larson, Katofsky, and Chen, *Methanol and Hydrogen from Biomass for Transportation, with Comparisons to Methanol and Hydrogen from Natural Gas and Coal*, PU/CEES Report No. 292, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, July 1995.

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EXECUTIVE SUMMARY

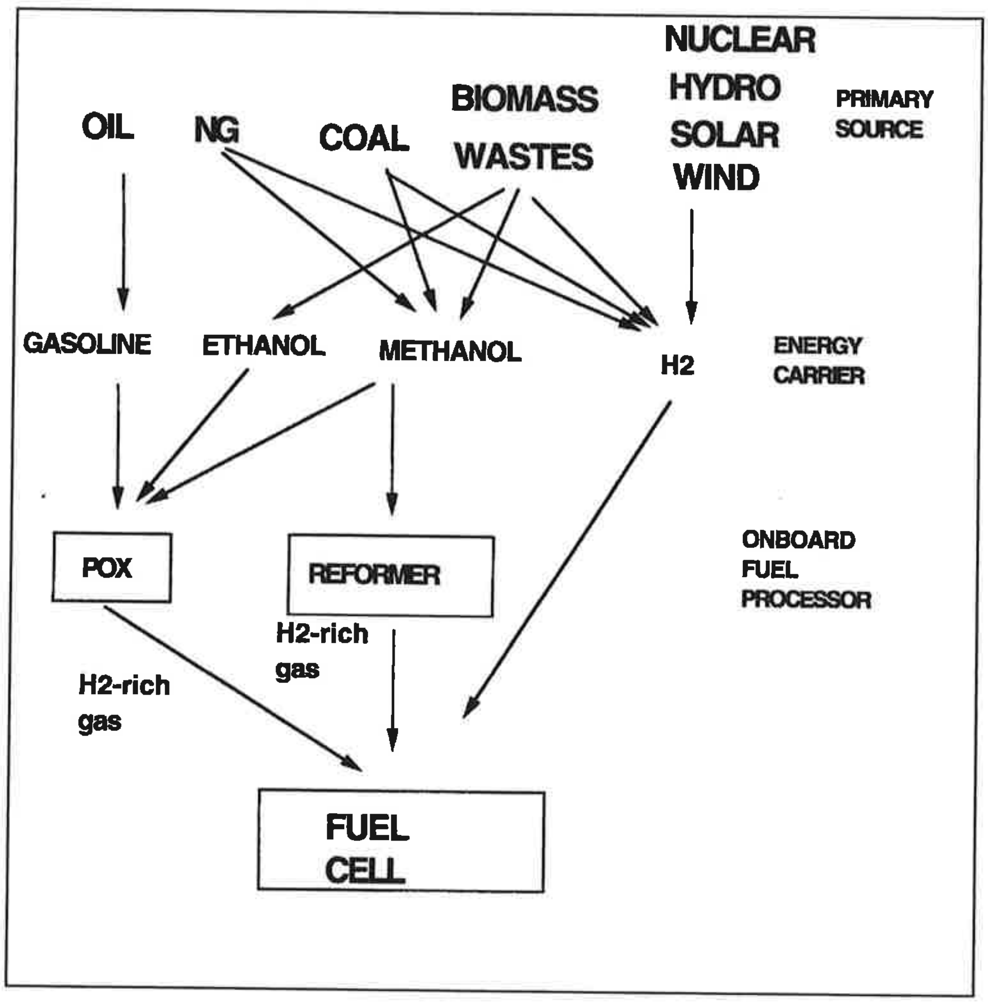
ES1. Introduction

This report has been prepared as an input to the development of a proposal to the Global Environment Facility for a project to demonstrate fuel cell bus technology in the city of São Paulo, Brazil. This report assesses the potential magnitude and costs of alternative sources of hydrogen and hydrogen carriers (methanol and ethanol) for use as fuels in fuel cell vehicles in Brazil in the near, medium, and long term. Fossil and renewable primary sources for these fuels are included in the analysis, which draws on data collection and analytical work in Brazil and at Princeton University.

ES2. Fuel Cell Vehicles and Their Demands for Fuels

A variety of fuels derived from a variety of primary energy sources can be used in fuel cell vehicles (Figure ES1). The most easily used on a vehicle is hydrogen (H_2), while others (gasoline, ethanol and methanol) require onboard transformation by chemical reaction (called reforming) into the H_2-rich gas required by the fuel cell.

Figure ES1: Fuels for fuel cell vehicles.



The largest potential market for fuel cell vehicles (FCVs) is passenger cars, and commercial development is proceeding rapidly in this area (Table ES1). However, fuel cells are likely to be widely introduced first in buses. Buses are particularly attractive as an entry market for fuel cell vehicles, because 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 and fuel storage limitations are less severe.

Commercialization of fuel cell buses is also being pursued aggressively. A fleet of three commercial prototype buses has had several months of operation by the Chicago Transit Authority as of August 1998, and a similar fleet will soon start operating in Vancouver, British Columbia. Commercial offering of fuel cell buses from at least two or three companies is expected before 2002.

Table ES1: 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 3 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, na experimental PEM fuel cell van with hydrogen storage
1995	Ballard Power Systems demonstrates improved hydrogen fueled PEM fuel cell bus
1995	Mazda demonstrates H2 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 H2 PEM fuel cell buses in Vancouver, BC
1997	Ballard and Daimler Benz form $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 onobard methanol reformer
1997	Ford joins Daimler-Benz and Ballard in $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	Shell International Petroleum and Ballard/Daimler Benz (DBB) form alliance to develop hydrocarbon reformer technology for fuel cell vehicles.
1998	Nissan announces plans to sell methanol fuel cell cars with Ballard fuel cells starting 2003-2005.

This report includes a review of the projected fuel consumption of fuel cell automobiles and fuel cell buses, based on available published information. These fuel-use levels are then used as a basis for estimating the relative magnitude of alternative primary energy resources from which fuel cell vehicle fuels for Brazil might be derived, and assessing the required infrastructure development.

For automobiles, several vehicle fuel options are considered, including use of compressed hydrogen gas stored onboard a vehicle, methanol converted to H_2-rich gas via onboard steam reforming, ethanol converted to H_2-rich gas via onboard partial oxidation reforming, and gasoline converted to H_2-rich gas via onboard partial oxidation reforming. Simulations of these fuel/vehicle configurations over standard driving schedules (assuming a Ford Taurus type vehicle) by researchers at Princeton Univeristy provide a basis for a consistent performance comparison. The direct hydrogen fuel cell car has the highest fuel economy, about 2.2 liters of gasoline-equivalent per 100 km. FCVs with onboard fuel processors (reformers) have about a 50% greater fuel consumption than this because of conversion losses in the reformer, added weight of the fuel processor system, and lower performance of fuel cells on the reformate gas produced by the fuel processor as compared to pure hydrogen.

For buses, 12-meter (40-foot), wheelchair-equipped and air-conditioned hydrogen/PEM fuel cell buses (suitable for use in New York City) are expected to achieve fuel consumption levels of 1.1 to 1.6 Nm^3 hydrogen per kilometer, depending on duty cycle. The average of this range, 1.35 Nm^3/km, corresponds to 2.31 km/liter diesel equivalent. For comparison, the average fuel economy for comparable diesel engine buses in New York City today is 1.35 km/liter diesel. Fuel consumption estimates for fuel cell buses using methanol or other H_2 carriers have not been made. Hydrogen has been the preferred fuel in PEM fuel cell bus demonstrations thus far and thus may be the most likely fuel for any near-term demonstration in Brazil.

ES3. H_2 and H_2-Carriers: Resources and Fuel Production Technologies

Primary energy sources examined in this report for production of H_2, methanol and ethanol include natural gas, electricity (hydro, wind, and solar-PV), biomass (including sugarcane and municipal solid waste), and coal. An assessment of the present-day hydrogen production in Brazil (for industrial uses) is also presented. Estimates are made of the magnitude of each resource in terms of potential production of H_2 or H_2-carrier and compared against different levels of demands for fuel cell vehicle fuels that might be seen in Brazil in the near to long term. Table ES2 compares estimates of potential primary energy resources, estimates of the hydrogen, methanol, or ethanol production possible from these resources, and estimates of the maximum number of fuel cell cars or buses that each primary energy resource would be able to fuel. For comparison with these latter estimates, there are an estimated 16 million passenger cars operating in Brazil today (about 4 million of these in the greater São Paulo region), and there are some 161,000 buses (25,000 urban transit buses in the São Paulo area alone).

Figures ES2a through ES2e display the size of the various hydrogen, methanol, and ethanol resources in Brazil relative to different levels of demand for these fuels by fuel cell vehicles. A variety of resources that are accessible in the near term appear more than sufficient to satisfy any conceivable near-term demands of fuel cell vehicle fleets, including resources for hydrogen production (Figure ES2a), resources for methanol production (Figure ES2b), and resources for ethanol production (Figure ES2c). For meeting long-term fuel demands of millions of cars and tens of thousands of buses, ethanol (Figure ES2c), hydrogen from natural gas or from biomass (Figure ES2d), and methanol from natural gas or from biomass (Figure ES2e) are the most abundant resources. Global warming concerns increase the attractiveness of biomass as a source of hydrogen, methanol, and ethanol.

ES4. Cost of Delivered Fuel Cell Vehicle Fuels

Costs are estimated for H_2 and H_2-carriers made from different primary sources and delivered to fuel cell vehicles. Estimates are made for both centralized production of the fuels, with pipeline or truck delivery to refueling stations, as well as for on-site production of fuels at the refueling station. On-site production is likely to be the preferred option in the near term until fuel demands grow large enough to justify building large-scale centralized production plants. The cost estimates presented here represent projections for costs once the fuel production and delivery systems are commercially-mature and widely-implemented. Cost estimates are given in 1997 US$ per unit of energy ($ per GJ). (On a higher heating value basis, the energy cost of $0.34/liter gasoline is equivalent to $10/GJ). Primary energy prices assumed in the fuel cost calculations reflect current conditions in either the São Paulo city area or in Brazil more generally, as appropriate.

Table ES2: Primary resources for hydrogen, methanol, and ethanol production in Brazil, with associated maximum number of fuel cell vehicles that could be fueled therefrom.

Resources	Estimated Potential Size of Resource	Fuel Production Potential	Maximum Number of Fuel Cell Vehicles that Could be Fueled
Existing eight industrial hydrogen production sites plus refineries	250,000 Nm^3/d H_2	H_2: 1.17 million GJ/yr	Cars: 83,000 Buses: 870
Brazilian natural gas resources in year 2000 (Petrobras)	53 x 10^6 Nm^3/d gas	H_2: 623 million GJ/yr	Cars: 44.2 million Buses: 460,000
		Meth: 549 million GJ/yr	Cars: 27.0 million Buses: 254,000
Natural gas pipeline from Bolivia to SP (at capacity in year 2000)	20 million m^3/d gas	H_2: 235 million GJ/yr	Cars: 16.7 million Buses: 174,000
		Meth: 207 million GJ/yr	Cars: 10.2 million Buses: 96,000
Off-peak hydropower	1000 to 2000 MW_e	H_2: 25-50 million GJ/yr	Cars: 1.8 - 3.6 million Buses: 19,000 - 37,000
Current Brazilian fuel ethanol production		Eth: 321 million GJ/yr	Cars: 15.9 million Buses: 148,000
Excess bagasse in SP state (2% of total bagasse produced)	6.8 million GJ/yr	H_2: 5.0 million GJ/yr	Cars: 350,000 Buses: 3,700
		Meth: 4.1 million GJ/yr	Cars: 203,000 Buses: 1900
Sugarcane tops and leaves in Sao Paulo state (half of total generated)	169 million GJ/yr	H_2: 124 million GJ/yr	Cars: 8.8 million Buses: 92,000
		Meth: 102 million GJ/yr	Cars: 5 million Buses: 47,000
Biomass tree plantations (potential in NE Brazil)	12,600 million GJ/yr	H_2: 9,200 million GJ/yr	Cars: 650 million Buses: 6.8 million
		Meth: 7,600 million GJ/yr	Cars: 380 million Buses: 3.5 million
MSW in Sao Paulo city	25 million GJ/yr	H_2: 15 million GJ/yr	Cars: 1.1 million Buses: 17,000
		Meth: 12 million GJ/yr	Cars: 570,000 Buses: 8,700
World methanol production capacity	560 million GJ/yr (28 million tonnes)		Cars: 28 million Buses: 260,000
Excess methanol prod. capacity (7% of total)	39.2 million GJ/yr		Cars: 2 million Buses: 18,000
New methanol facility (10,000 tonne per day)	74.6 million GJ/yr		Cars: 3.7 million Buses: 35,000
LNG imports	10 million m^3/day gas (Equivalent amount to fuel for 2000 MW_e combined cycle power plant fueled by LNG)	H_2: 118 million GJ/yr	Cars: 8.3 million Buses: 87,000
		Meth: 103 million GJ/yr	Cars: 5.1 million Buses: 48,000

Figure ES2(a). Potential near-term supplies of hydrogen for fuel cell vehicle from alternative sources in Brazil compared against different potential fuel demand levels.

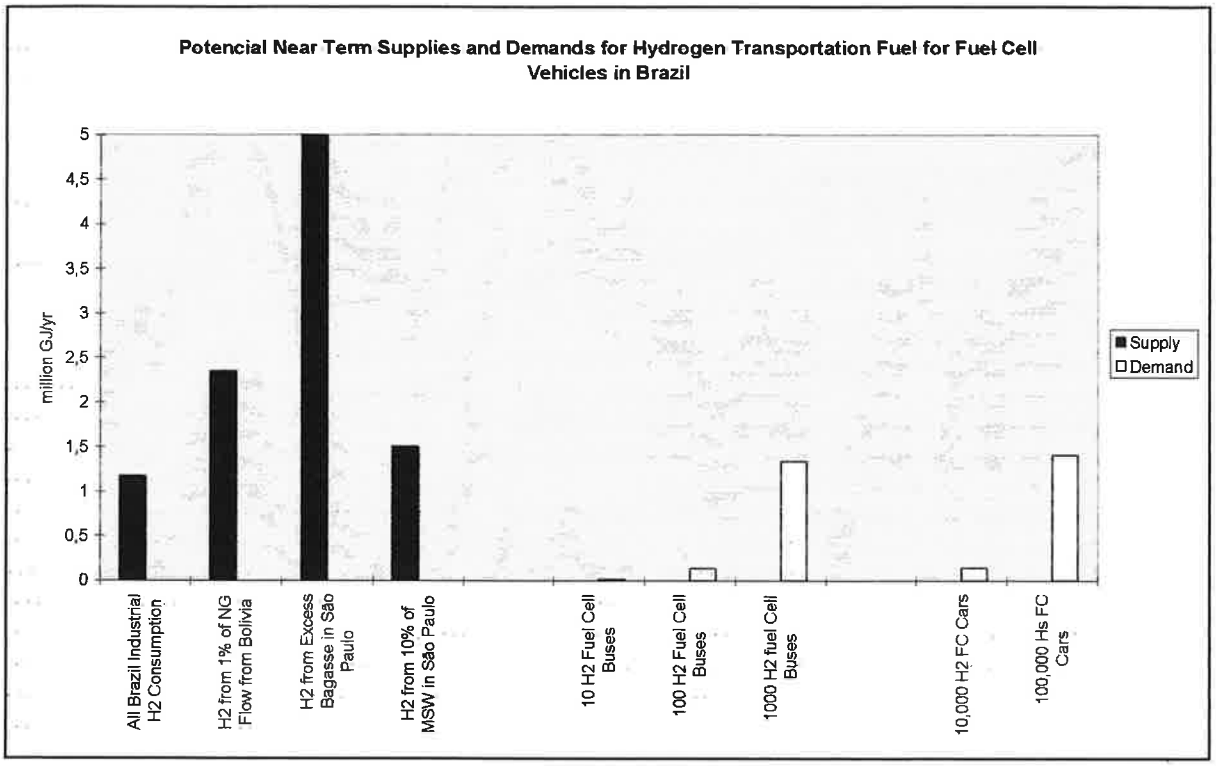


Figure ES2(b). Potential near-term supplies of methanol for fuel cell vehicle from alternative sources in Brazil compared against different potential fuel demand levels.

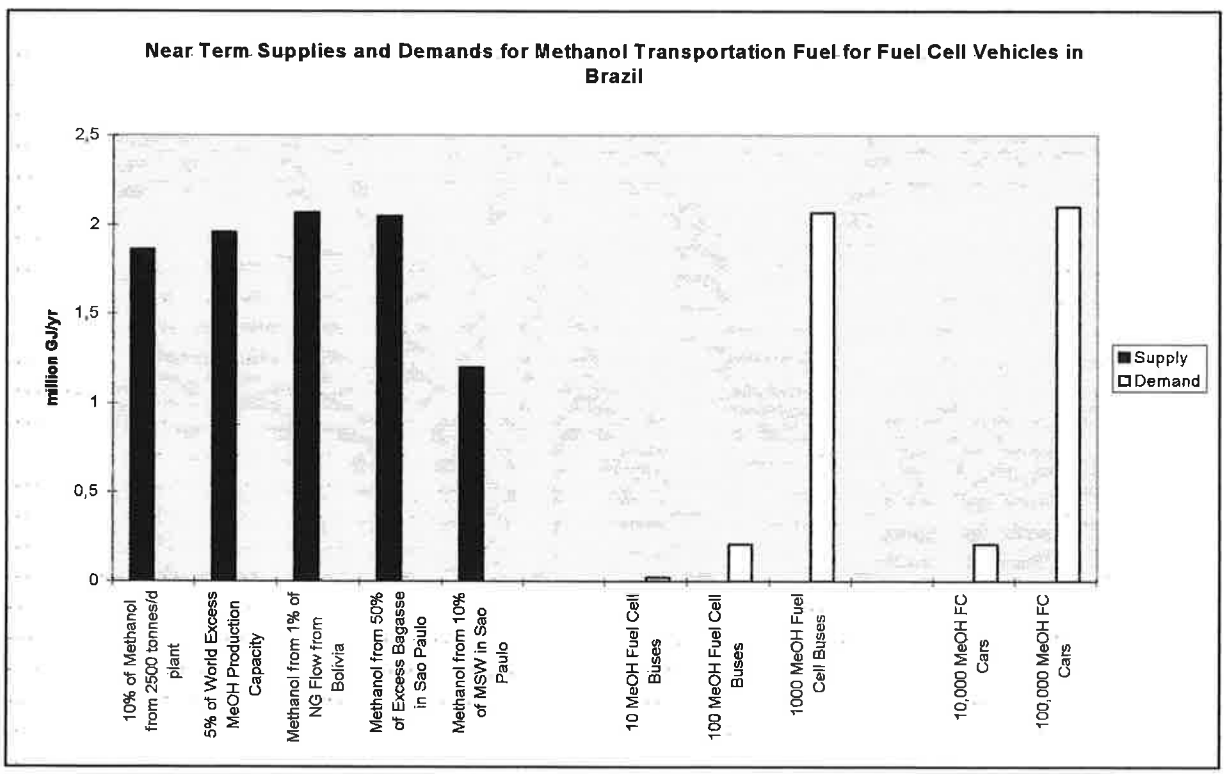


Figure ES2(c). Potential supplies of ethanol for fuel cell vehicles in Brazil compared against different potential fuel demand levels.

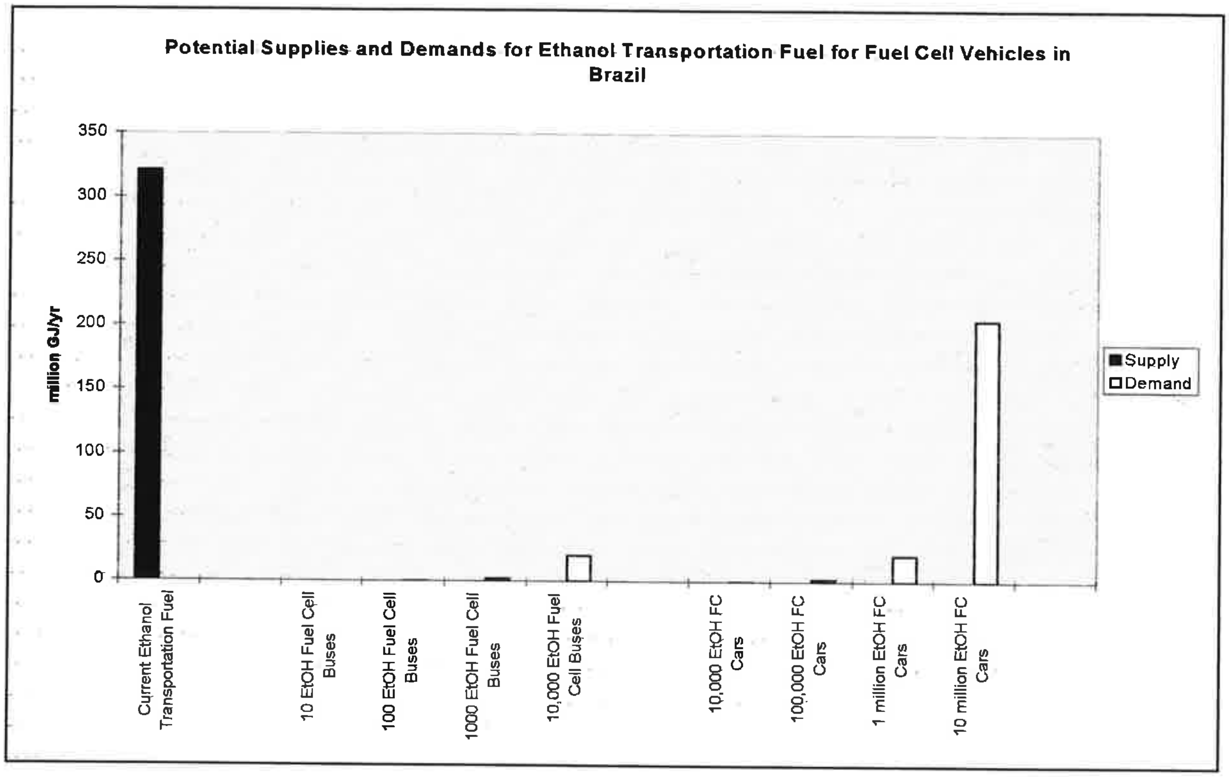


Figure ES2(d). Potential supplies of ethanol for fuel cell vehicles in Brazil compared against different potential fuel demand levels.

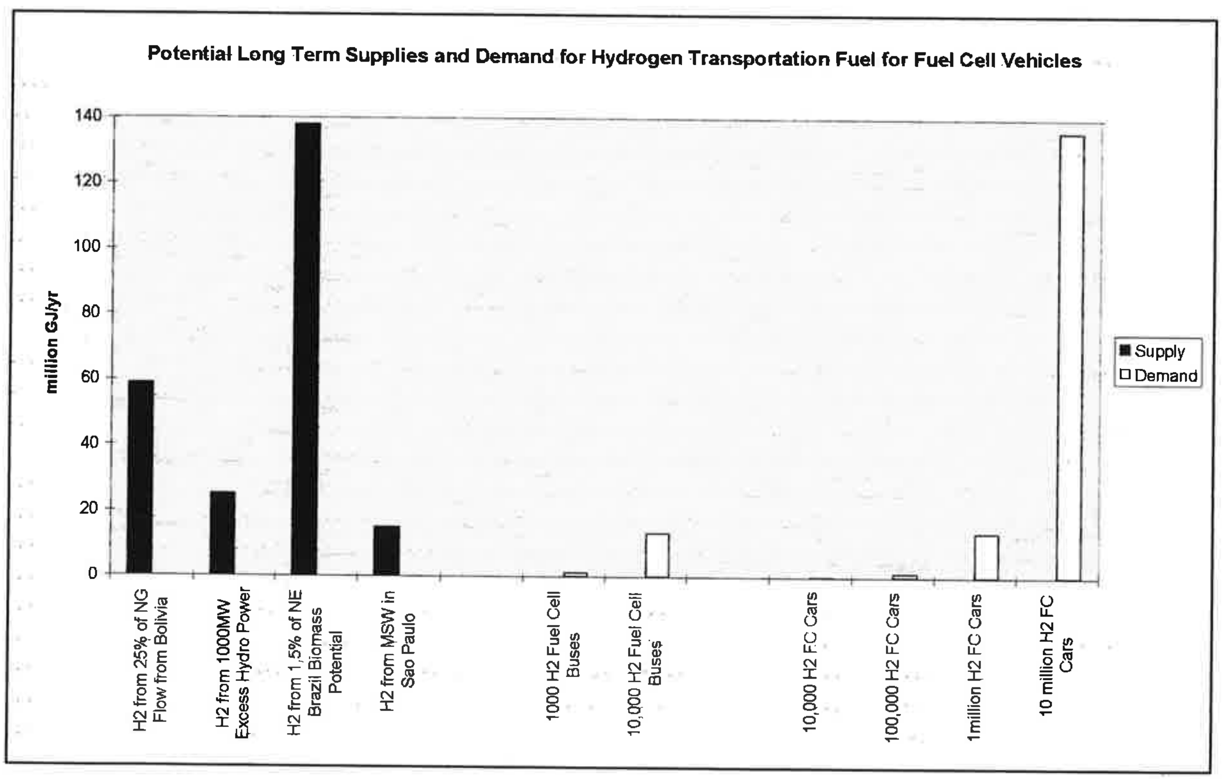
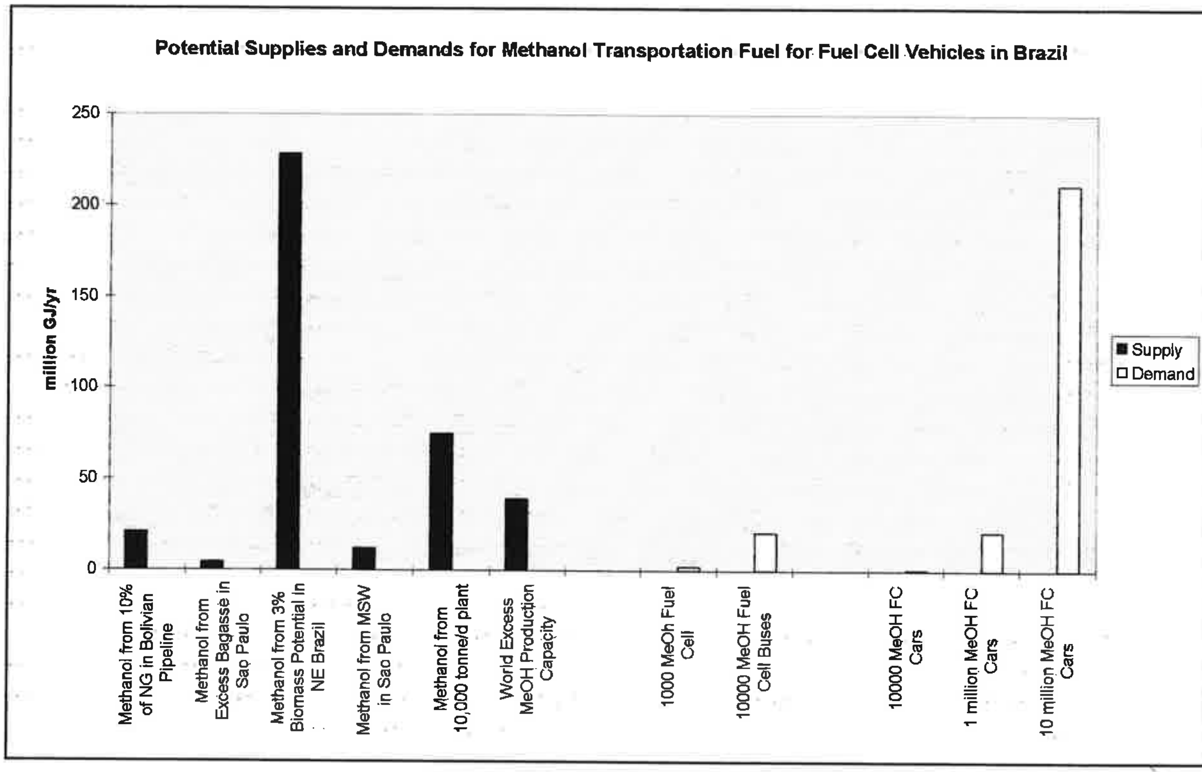


Figure ES2(e). Potential long-term supplies of methanol for fuel cell vehicle from alternative sources in Brazil compared against different potential fuel demand levels



Estimated total fuel costs to consumers, including fuel production, fuel delivery to refueling station, and refueling station costs, are summarized in Figure ES3. Hydrogen costs are shown for on-site production at refueling stations and for centralized production with pipeline delivery to refueling stations. Methanol costs assume centralized production with truck delivery. For ethanol and gasoline, both of which are widely distributed in Brazil today, current fully-taxed prices at Brazilian refueling stations are shown ($15.4/GJ for gasoline and $17.3/GJ for ethanol). The tax adds about $3.3/GJ to the price of ethanol and $6.5/GJ to the price of gasoline. (Taxes are not included in the hydrogen and methanol costs shown in Fig ES3.)

Several options are shown for on-site H_2 production:

- Electrolytic hydrogen from off-peak power using a typical off-peak electricity rate in São Paulo (3 cents/kWh on average).
- Electrolytic hydrogen from power available continuously at 1 cent/kWh.
- Hydrogen produced from natural gas in advanced small scale steam reformers using a gas price currently available in São Paulo for compressed natural gas vehicles, $2.8/GJ.
- Hydrogen produced from natural gas in advanced small scale steam reformers using the standard gas price (about $14/GJ) to industrial or commercial customers in São Paulo consuming between 5,000 and 50,000 m^3/day of natural gas.
- Hydrogen produced via PV powered electrolysis, assuming that PV power can be produced at about 7 cents/kWh (assuming future PV cost and performance goals).

Several options are also shown for centralized hydrogen production:

- Hydrogen from steam reforming of natural gas, with gas prices of $2.5/GJ (approximately the special automotive rate available in São Paulo today) and $5/GJ (approximately the standard industrial rate in São Paulo for the largest gas consumers).

- Hydrogen from coal, with coal costing $1.5/GJ.

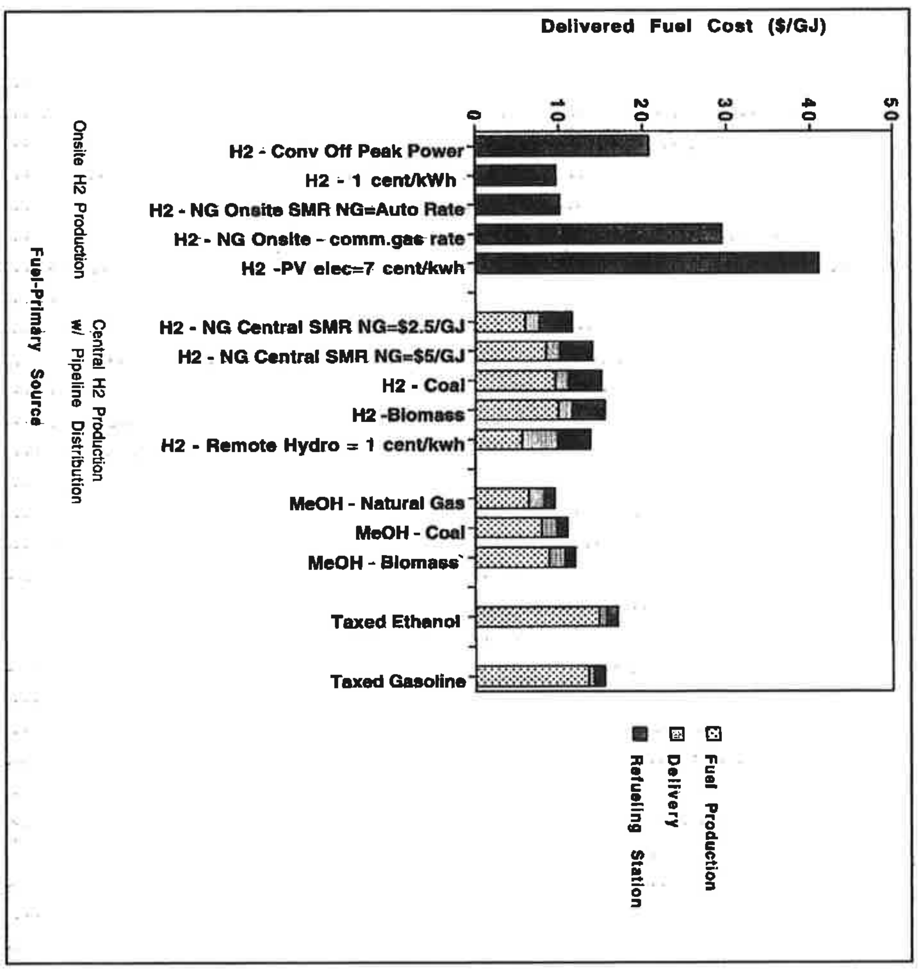
- Hydrogen from biomass, with biomass costing $2.5/GJ, a typical cost for chips of eucalyptus or pine grown on industrial plantations in Brazil today.

- Electrolytic hydrogen from 1 cent/kWh hydropower located 1,000 km from São Paulo. The hydrogen goes to São Paulo via large pipeline (adding about $2.6/GJ), and is then distributed locally via small pipelines to refueling stations.

Methanol costs are shown assuming centralized production at large facilities in Brazil. Assumed feedstock costs are $2.5/GJ for natural gas, $1.5/GJ for coal, and $2.5/GJ for biomass.

Figure ES3 shows delivered hydrogen costs varying from about $10/GJ for the lowest cost onsite production options (with low primary energy prices) to over $40/GJ for solar-PV hydrogen.

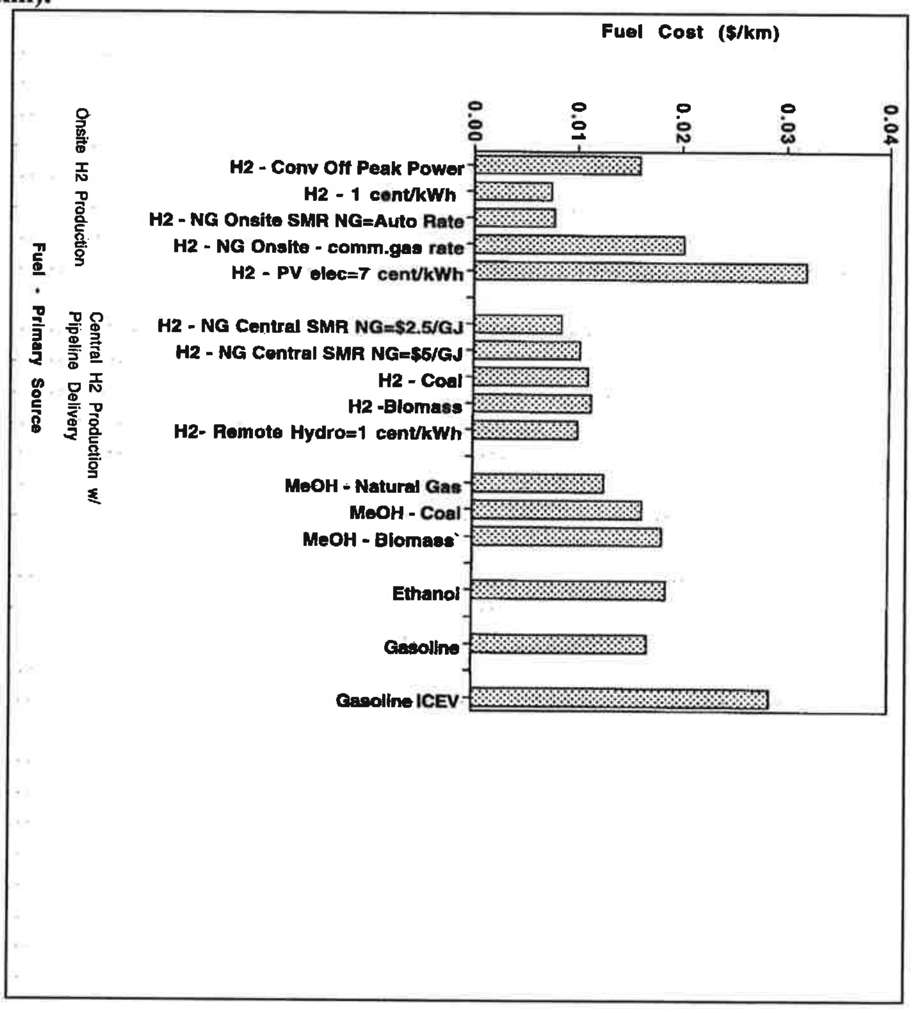
Figure ES3: Delivered cost of fuel cell vehicle fuels from various primary sources ($/GJ).



With energy prices typical of today's rates for industrial customers, centralized hydrogen or methanol production (from any of the feedstocks considered) would appear to offer the lowest fuel costs ($10-$15/GJ)—comparable to gasoline and ethanol costs today. However, large hydrogen or methanol demands (several hundred thousand fuel cell cars) would be required to justify construction of such facilities. Initially when demand is relatively low, on-site hydrogen production or methanol imports might be preferred. This approach has the advantage that it is possible to build one refueling station at a time, as demand dictates, and no additional infrastructure building is required. For the on-site production of hydrogen, costs would generally be considerably higher than for centralized production ($20-$40/GJ for onsite production, as compared to $10-$15/GJ for centralized production), unless the lowest electricity or natural gas rates are available, in which cases hydrogen (at $10/GJ) would be less costly than gasoline or ethanol today and perhaps even less costly than the centralized options shown.

The relative cost rankings of fuels change when the cost per vehicle-kilometer for fuel cell vehicles is considered, due to different efficiencies for hydrogen, methanol, and ethanol fuel cell vehicles. Figure ES4 shows comparative fuel cost per vehicle-km for Ford Taurus type fuel cell vehicles. This figure also shows for reference the estimated cost per v-km for a gasoline internal combustion engine vehicle (with an assumed fuel economy of 5.6 liters/100 km). All the fuel cell car options except for PV hydrogen (at PV electricity costs of 7 cent/kwh) have a lower fuel cost per v-km than the reference gasoline-IC engine vehicle.

Figure ES4: Fuel cost per vehicle-km for fuel cell automobiles for various fuels and primary energy sources ($/v-km).



ES5. Total Lifecycle Costs of Transportation with Fuel Cell Vehicles

Delivered cost of fuel is one important indicator of the prospective economics of fuel cell vehicles, but a better indication of overall economics is given by the total lifecycle cost, including vehicle capital costs, non-fuel operating/maintenance costs, and fuel costs. Total lifecycle cost comparisons are made for alternative fuel cell automobiles and alternative fuel cell bus technologies. Capital costs included in these estimates assume commercially-mature technology and large-scale mass production.

Total lifecycle costs per vehicle-km for fuel cell automobiles are shown in Figure ES5 for the same set of fuel sources shown in Figure ES3 and ES4. Of the three cost components shown for each fuel option, vehicle capital costs account for the largest share, while fuel costs are by far the smallest share. Capital costs for the hydrogen fuel cell cars are slightly lower than for ethanol, methanol, or gasoline fuel cell cars primarily because the liquid-fuel vehicles require on-board fuel processing systems. Surprisingly, the range in total lifecycle cost per v-km for all of the fuel cell vehicles is rather small over the full range of fuel sources shown. Even more surprising is that the total cost per v-km for the conventional gasoline-IC engine vehicle is higher than all but the cost for the PV-H_2 fuel cell vehicle.

Figure ES6 shows total lifecycle cost ($/bus-km) for a hydrogen fuel cell bus over a range of delivered hydrogen fuel prices. Capital costs used in this calculation assume the bus would be designed for use in New York City (wheelchair-equipped, air-conditioned, meeting current safety regulations, etc). Also shown is the total lifecycle cost for comparable diesel buses for diesel fuel prices of $0.3 to $0.4 per liter ($9.5/GJ to $13.9/GJ). For reference, diesel prices are about $0.3/liter in São Paulo and in the U.S.A today, and the projected price of diesel fuel to the transport sector in the U.S.A. in 2015 ranges from $0.3 to $0.4 per liter. In the range of $10-15/GJ for delivered hydrogen fuel, the total cost per bus-km for the fuel cell bus is comparable to that for the diesel bus, with diesel prices of $0.3-$0.4/liter.

Figure ES5: Total lifecycle cost of transportation with fuel cell automobiles with various fuels and primary energy sources ($/v-km).

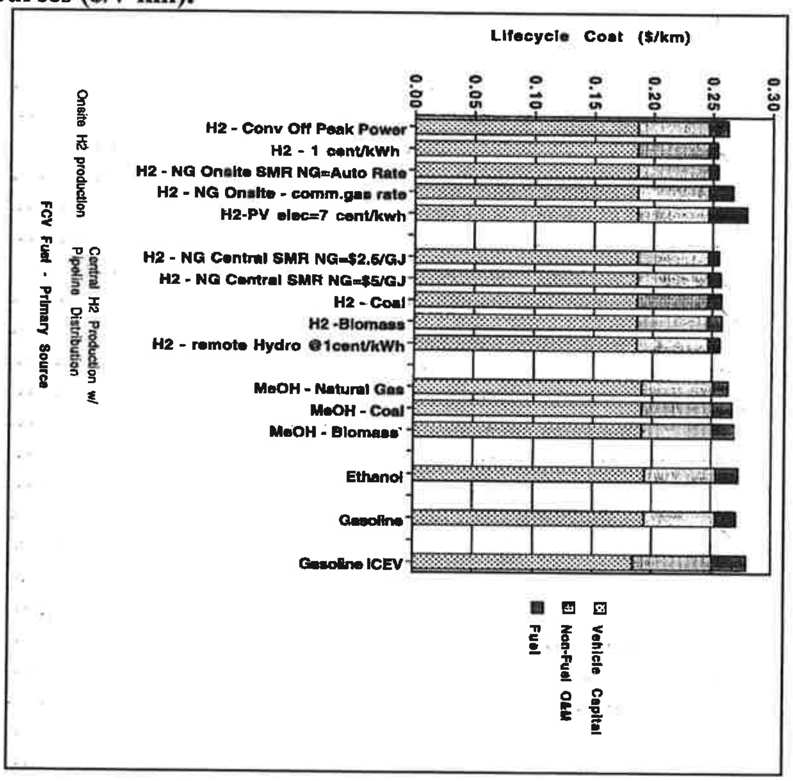
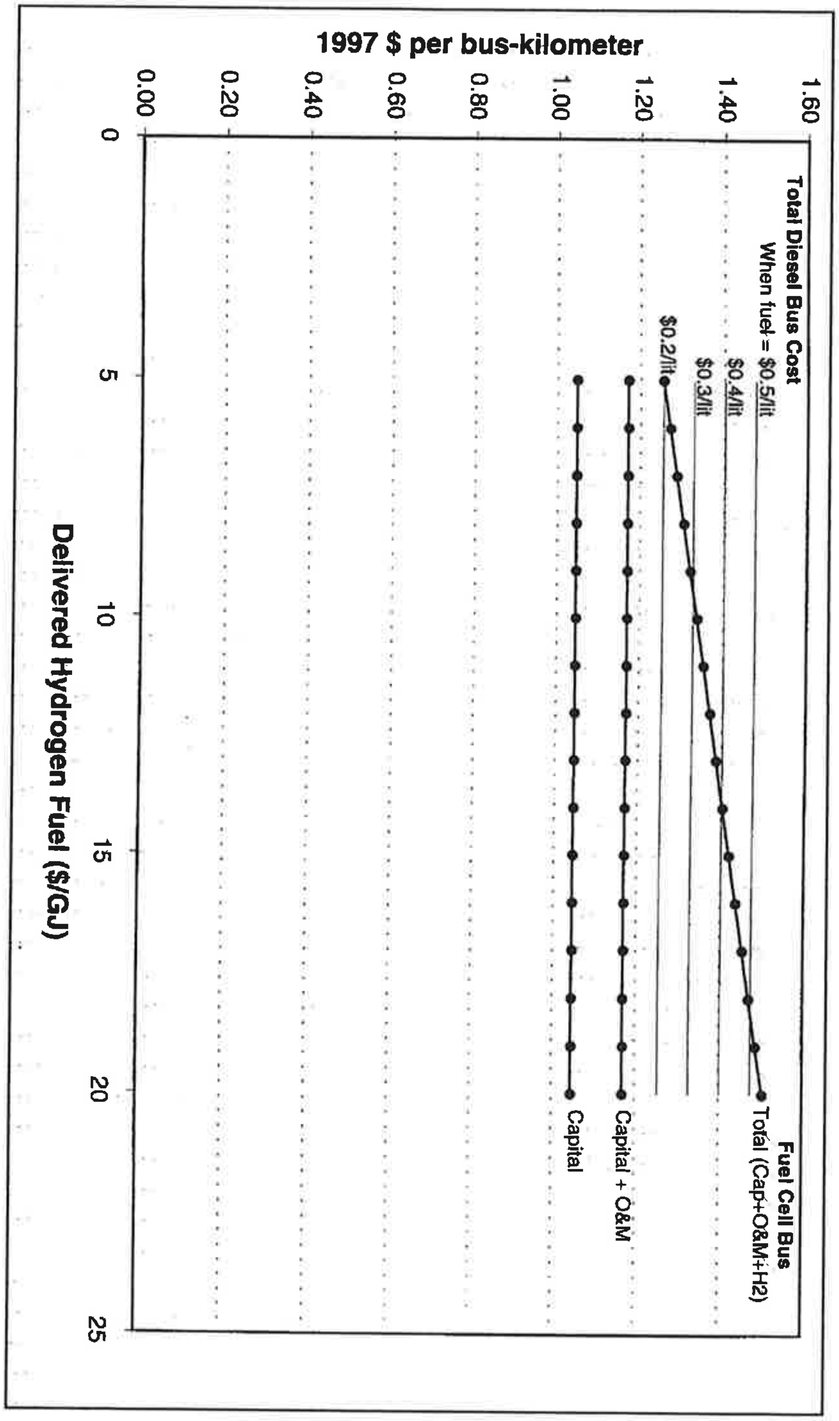


Figure ES6: Total lifecycle cost comparison for comparable-duty fuel cell and diesel buses.



ES6. Conclusions

The fuels that can satisfy a future fuel cell transportation system in Brazil will depend to a large extent on the vehicle designs that are developed. At present, the focus of vehicle developers is on hydrogen vehicles and on liquid-hydrocarbon vehicles. The latter require fuel processing systems to convert the liquid fuel to the hydrogen-rich gas required by the fuel cell. Potentially interesting fuel cell fuels in

Brazil examined in this report include hydrogen, methanol, and ethanol. Brazil has an abundance of options for providing these fuels in the near and long term.

In the near term, small quantities of hydrogen can probably be purchased in the commercial market, which today provides some 7.5 million m^3/day to industrial users. Perhaps 250,000 Nm^3/day might be available in this fashion—enough to fuel a fleet of about 80,000 fuel cell cars or 1200 fuel cell buses.

Alternatively, hydrogen might be produced at refueling stations, from either steam reforming of natural gas or by electrolysis, both of which are commercially available technology options today. Natural gas is already available in the São Paulo area, and the city has a distribution network. Furthermore, gas supplies will increase very soon through increase in domestic production and importation through pipelines. If the gas price presently available in São Paulo for compressed natural gas (CNG) vehicles is available at hydrogen production/refueling stations, this could be an economically attractive fuel supply option. Electrolytic hydrogen production at refueling stations is an option that is especially attractive if the available electricity tariff for interruptible supply contracts (about $0.01/kWh) can be secured. At conventional off-peak rates for electricity (about $0.03/kWh), electrolytic hydrogen would be considerably more expensive than hydrogen from natural gas at the CNG vehicle rate, though less costly than hydrogen from gas at prevailing industrial rates.

Ethanol is readily available in Brazil today and could be used in fuel cell vehicles designed for this fuel. On a cost per unit energy basis, ethanol would be some 50% more costly than on-site production of hydrogen at refueling stations, assuming the lower natural gas or electricity prices discussed in the previous paragraph.

Little methanol is made in Brazil, but it can be easily imported in the near term. Brazil imported about one million m^3/year of methanol in the recent past during periods of ethanol shortages. The cost of methanol in the near term would follow world-market price trends.

In the longer term, once the demand for fuel cell vehicles grows substantially, there would be some additional options for fuel supply.

Projected natural gas resources are such that gas-derived hydrogen could fuel a very substantial fraction of a Brazilian fuel cell vehicle transportation system. Decentralized production of hydrogen from gas would continue to be an option. Once demand reaches a high enough level, centralized production of hydrogen with pipeline distribution to refueling stations will also be an option that will be economically attractive relative to decentralized production, if the CNG vehicle rate for natural gas is not available. As with any option for centralized hydrogen production, the commitment to building a hydrogen pipeline infrastructure requires a large demand level to be in place first.

The amount of hydroelectricity that is likely to be available at sufficiently low cost ($0.01/kWh) to make electrolytic hydrogen competitive with natural gas or other long term options is likely to be inadequate to make a major contribution to fuel supply in a future fuel cell transportation system in Brazil. Still, one to two million cars could probably be fueled from off-peak power electrolysis at competitive costs. If gas at the CNG vehicle rate is not available, the electrolysis option will be attractive even for more typical off-peak electricity rates ($0.03/kWh), which would expand the potential contributions from hydroelectricity to fuel supply.

Solar-PV electrolysis is another option, but cost projections for this indicate that it will be a more expensive option than any of the others considered in this report.

Other long-term options for fuels' production in Brazil that are examined in this report are centralized methanol or hydrogen production from natural gas, coal, or biomass. Gas prices must be $5-$6/GJ before hydrogen or methanol from coal or biomass will become competitive. Any centralized methanol production is likely to have difficulty competing for some time with the cost of imported methanol, which will typically be made at large facilities from very-low-cost remote gas sources. But biomass, including byproducts of sugarcane processing and dedicated energy plantations, is potentially Brazil's largest primary energy resource for fuels production. Municipal solid waste is another resource that can be converted to methanol or hydrogen. It would not be able to provide a large share of total fuel supply, but it might be an attractive option from the standpoint of reducing landfill requirements around São Paulo.

Ethanol derived from sugarcane is also a potentially significant fuel resource. Current levels of ethanol production are sufficient to fuel all automobiles in Brazil today, if these were all fuel cell vehicles.

While there is a fairly large range in the cost per unit of energy among hydrogen, methanol, and ethanol from different sources, the estimated total cost per km for transportation (including vehicle capital cost, operating and maintenance cost, and fuel cost) does not vary substantially among all of the options examined in this report. Furthermore, the total cost per km is slightly lower in almost all cases than the cost for a comparable vehicle with an internal combustion engine fueled by gasoline at gasoline prices prevailing in Brazil today. This suggests that decisions about which fuels and fuel sources should be adopted in Brazil will be made largely on the basis of factors other than total lifecycle cost per km. Important considerations are likely to be vehicle performance (especially performance of on-board reformers for liquid fuels), vehicle first cost, fuel-supply infrastructure capital investment requirements, and environmental considerations, including greenhouse gas emissions.

An Assessment of Fuels for Fuel Cell Vehicles in Brazil: Potential Resources and Costs

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1 Introduction

This report has been prepared as an input to the development of a proposal to the Global Environment Facility for a project to demonstrate fuel cell bus technology in the city of São Paulo, Brazil. The purpose of this report is to assess the potential magnitude and costs of alternative sources of hydrogen and hydrogen carriers (methanol and ethanol) for use as fuels in fuel cell vehicles in Brazil in the near, medium, and long term. Fossil and renewable primary sources for these fuels are included in the analysis here, which draws on data collection and analytical work in Brazil and at Princeton University.

2 Fuel Cell Vehicles and Their Demands for Fuel

A variety of fuels derived from a variety of primary energy sources can be used in fuel cell vehicles (Figure 1). The most easily used on a vehicle is H_2, while the others (gasoline, ethanol and methanol) require onboard fuel transformation by chemical reaction (called reforming) into the H_2-rich gas required by the fuel cell. Fuel cell vehicle designs are typically "hybrids," wherein a peak power battery is used to provide short bursts of power for high speed passing, and to accept energy recovered via regenerative braking. Figure 2 shows possible fuel cell vehicle configurations with either gaseous H_2 fuel or liquid methanol or gasoline as fuel.

2.1 Fuel Cell Vehicle Development

2.1.1 Fuel Cell Automobiles

Progress toward a commercial fuel cell automobile is proceeding at a rapid and accelerating pace (see Table 1). At present eight major automobile manufacturers have announced plans to commercialize PEM (proton exchange membrane) fuel cell cars in the 2004-2005 timeframe. These include Chrysler, GM, Ford, Daimler-Benz, Mazda, Toyota, Honda, and Nissan. 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 in the U.S.A., 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 $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 $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. On Aug. 17, 1998, the Shell International Petroleum Company and the Ballard/Daimler-Benz joint venture announced an alliance to pursue development of on-vehicle reformer technology to enable liquid hydrocarbon fuels to be used with fuel cell engines. And, in early September Nissan announced plans to begin selling fuel cell cars in the 2003-2005 time frame.

2.1.2 Fuel Cell Buses

The largest potential market for fuel cell vehicles (FCVs) is passenger cars, but the FCV is likely to be widely introduced first in buses. Buses are particularly attractive as an entry market for fuel cell vehicles, as they are centrally garaged, refueled and maintained. Furthermore, fuel cells are likely to be economically competitive first in bus markets, where cost goals are not as stringent as for automobiles and fuel storage limitations are less severe.

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. Several commercially-oriented demonstration projects of PEM fuel cell buses are well underway in the US, Canada and Europe, and rapid advances are being made. Ballard Power Systems, Inc. of Vancouver, Canada, introduced a prototype PEM fuel cell bus in 1993, followed by a second generation unit in 1995. A fleet of three commercial prototype buses has had several months of operation by the Chicago Transit Authority as of August 1998, and a similar fleet will soon start operation in Vancouver, British Columbia. Commercial offering of buses from at least two or three companies is expected before 2002.

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 reforming of methanol, ethanol, or gasoline.

- Fuel processor technology for converting methanol and other hydrocarbon fuels to hydrogen is still being developed for use with PEM fuel cells, while hydrogen PEM fuel cell buses are already 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 10 PEMFC buses could be refueled daily using a small scale reformer producing 2000 m^3 H_2/day. Rapid developments in small scale reformer technology are making this an increasingly attractive supply option (Halvorson, Victor and Farris 1997).]

Methanol is also being considered for PEM fuel cell bus applications. Ballard plans to demonstrate a PEM fuel cell bus with onboard methanol reforming, 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. A relatively small amount of attention has been given to date to the use of ethanol as a fuel for fuel cell vehicles. It has also been proposed that other liquid fuels, including gasoline and synthetic middle distillates (made from natural gas) be used for fuel cell vehicles.

2.2 Vehicle Fuel Demands

To put potential fuel cell vehicle fuel resources into perspective, it is important to understand the likely fuel consumption by cell fuel vehicles. Fuel economy estimates for autos and buses are discussed next.

2.2.1 Projected Performance Characteristics of Fuel Cell Automobiles

Several vehicle fuel options are considered in subsequent analysis in this report, including use of compressed hydrogen gas stored onboard a vehicle, methanol converted to H_2-rich gas via onboard steam reforming, ethanol converted to H_2-rich gas via onboard partial oxidation reforming, and gasoline converted to H_2-rich gas via onboard partial oxidation reforming. The performance of these alternative fuel cell vehicle configurations has been simulated by researchers at Princeton University (see Appendix A). These simulations provide a basis for a consistent comparison of the performance of alternative FCVs fueled with hydrogen, methanol, gasoline and ethanol. Table 2 shows the projected vehicle weight and fuel economy for alternative mid-size (Ford Taurus type) fuel cell cars. The assumptions underlying these projections are summarized in Table 3. For details see Appendix A.

The direct hydrogen fuel cell car has the highest fuel economy, about 2.2 liters/100 km (106 miles per gallon of gasoline equivalent, which is the miles-per-GJ fuel economy of the fuel cell vehicle divided by 0.131 GJ/gallon, the higher heating value of gasoline.) Cars with onboard fuel processors (reformers) have about two-thirds the fuel economy of direct hydrogen fuel cell cars. This is due to conversion losses in the reformer, added weight of a fuel processor system, and lower performance of fuel cells on the reformate gas produced by the fuel processor as compared to pure hydrogen. The annual mileage and associated energy use (assuming a standard highway/urban drive cycle for the U.S.A.) for alternative fuel cell vehicle designs is shown in Table 4.

2.2.2 Projected Performance Characteristics of Fuel Cell Buses

Performance simulations of fuel cell buses as detailed as those discussed in the previous section for automobiles have not been carried out, but some performance and cost characteristics of hydrogen fuel cell buses are reported here based on a comparison of urban fuel cell and diesel buses in the context of New York City given by Larson, et al. (1996). While there are many factors that make the situation in São Paulo different from that in New York, the comparative results between fuel cell and conventional diesel buses are likely to be indicative for other urban areas, including São Paulo.

Forty-foot, wheelchair-equipped, air-conditioned hydrogen/PEM fuel cell buses suitable for use in New York City are expected to achieve fuel consumption levels of 1.1 to 1.6 Nm^3 hydrogen per kilometer (Howard, 1995). The average of this range, 1.35 Nm^3/km, corresponds to 2.31 km/liter diesel equivalent. For comparison, the average fuel economy for comparable diesel engine buses in New York City today is 1.35 km/liter diesel (Pellegrin, 1995).

3 H_2 and H_2-Carriers: Resources and Fuel Production Technologies

In this section we discuss the primary resources potentially available in Brazil for production of hydrogen or hydrogen carriers. We also describe the technological processes for converting these resources into hydrogen or hydrogen carriers. In the last part of this section, we make some comparisons of the potential supplies of alternative primary energy sources against the potential fuel demands of fuel cell vehicle transportation systems. We begin with a description of the current hydrogen market in Brazil.

3.1 The Brazilian Hydrogen Market at Present

The Brazilian hydrogen market has been recently evaluated through analysis of the following industrial activities (de Souza and Silva, 1996): ammonia production, methanol production, oil refineries (hydrotreating and hydrocracking), iron and steel production, and chlor-alkali production.

Ammonia is mainly used in the production of nitrogenated fertilizers (approximately 96% of the total) and the volume of H_2 consumption is obtained assuming 100% efficiency of the reaction:

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$

which means that any amount of H_2 gas which is not converted to nitrate is fully recovered and recycled. From the known amount of nitrate fertilizers it is possible to evaluate the amount of H_2 used.
Methanol is produced through the catalytic reaction between CO and H_2. Assuming 100% efficiency for the reaction:

$$CO + 2\,H_2 \rightarrow CH_3OH$$

it is possible to derive the amount of H_2 consumed from the amount of methanol produced.

Chlorine and sodium, in the presence of hydrogen, are produced through electrolysis of fused chlorines or aqueous solutions of alkaline chlorine metals. Assuming an efficiency of 100% for the reaction:

$$NaCl_{(liq)} + H_2O_{(liq)} \rightarrow NaOH_{(liq)} + \tfrac{1}{2}\,H_{2\,(g)} + \tfrac{1}{2}\,Cl_{2\,(g)}$$

it is possible to evaluate H_2 production, from the amount of salt used.

In the steel industry H_2 is used as raw material in the reduction processing of iron ore to sponge iron. Hydrogen is also used in a reducing atmosphere during the thermal treatment of special iron alloys. As a raw material H_2 can be obtained from the stochiometric reaction:

$$Fe_2O_3 + 3\,H_2 \rightarrow 2\,Fe + 3\,H_2O$$

and

$$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2$$

while for the thermal treatment the amount of H_2 is evaluated from the production of an electrolytic plant which operates in an ACESITA steel mill, the only one in Brazil that uses the process.

PETROBRAS is the only user of hydrogen in oil refineries and the amount used in the four refineries which use hydrogen is available. To this value we have to add hydrogen produced in a fertilizer factory in the northeast of Brazil which uses excess nafta from refineries.

Table 5 shows the size of the Brazilian H_2 market in the period 1994 – 1984, and Figure 3 provides a view of the several shares of the market in 1994. To fulfill this demand almost all of the main users produce their own hydrogen. Nevertheless, there is a market for the acquisition of hydrogen from industrial hydrogen producers because there are small consumer industries and the necessity to complement production of some large hydrogen consuming industries.

3.2 Industrial Sources of Hydrogen

At present, the primary suppliers of commercial hydrogen in Brazil are the industrial gas companies Air Products and Chemicals, Inc, Oxigenio do Brasil, White Martins S/A, and AGA.

In Brazil there are eight H_2 industrial plants, five of them in the state of São Paulo. Air Products has three hydrogen plants in Brazil with the following installed capacity:

Mogi-Mirim - SP	420,000 m^3/month
Guaiba - RS	540,000 m^3/month
Camacari - BA	3,000,000 m^3/month

Oxigenio do Brazil is the owner of one H_2 industrial plant which is installed in Minas Gerais with a capacity of 300,000 m^3/month.

White Martins has three H_2 industrial facilities, one of them sited in São Paulo, with the following capacities:

CSN - RJ	1.5 milion m^3/month
Caçapava - SP	350,000 m^3/month
Rio de Janeiro - RJ	350,000 m^3/month

AGA has one H_2 industrial plant in Jundiai, São Paulo with a capacity of 300,000 m^3/month.

The total present consumption of commercial H_2 in Brazil is approx. 7,500,000 m^3/month, of which 35% is used in the food industry, 55% in the chemical and petrochemical industry, and 10% in the metallurgical sector (thermal treatment of iron alloys) (Air Products, 1998). Transported H_2 satisfies 45% of the present market demand and is essentially addressed to the food and metalurgical industries (Air Products, 1998).

Presently, the market price for pure H_2 in gaseous form (the only available delivered H_2 form) is approximately US$1/$m^3$ ($80/GJ) and for extra pure H_2, US$20/$m^3$ ($1600/GJ) On top of these prices it is necessary to add taxes (ICMS 18% + IPI 15%) (Air Products, 1998). Prices can be reduced for large size contracts. [Considering that a demonstration fleet of 5 buses consumes 100 to 200 kg per day (1100 to 2200 m^3 per day), representing approximately 10% of the production of the smallest Air Product plant, significant cost reductions for such scale of a demonstration seem unlikely.]

In addition, a number of oil refineries are located in the vicinity of the city of São Paulo. Some oil refineries produce large amounts of gaseous hydrogen (1 - 4 million m^3/day) using most or all of it onsite. Historically, in the USA some excess hydrogen has been available, and some refineries have sold 10% of hydrogen "over the fence" to other refineries or chemical users, delivering the hydrogen by truck (Figure 4a) or by small scale pipeline (Figure 4c). To meet requirements for better gasoline, significantly more hydrogen is required by U.S. refineries. As a result, several U.S. refineries have recently built extra reformer capacity or are buying hydrogen in the commercial market. Thus, in the U.S., it may be possible to purchase a few hundred thousand m^3/day from refineries, especially those with newly expanded reformer capacity. This could be economically attractive, as the cost (at the plant site) would be quite low. If the reformer capital cost is considered to be a "sunk" cost, gaseous hydrogen might be inexpensive. The delivered cost to the user would depend on how long a pipeline was required, as well as the cost of the refueling station. In Brazil, the situation is less favorable, since only one refinery sited in the state of São Paulo (REVAP in São José) produces and uses hydrogen. Even so, it is not easy to use this H_2 since further clean up is usually required for most commercial applications.

It is worthwhile to comment that Air Products has an advertisement on the internet with an article (Guy, 1995) where it claims that buying H_2 can be a better economical solution for oil refineries which used to make their own H_2. A series of reasons are listed comparing the "Make Case" and the "Buy Case," which go through operational risks, better supply reliability, lack of capital for initial investment, and conclude that from the economical aspect the following advantages are worth noting: capital savings of 5 to 10%; energy savings of 3 to 5%; operating cost reductions of 0 to 10%. This is a good indication that it is possible to acquire low cost H_2 in the market provided the demand is high enough to justify an efficient transportation mechanism and to allow the full use of a large size H_2 industrial production unit. If low cost industrial hydrogen could be obtained in Brazil, it might make a significant contribution to facilitating the introduction of hydrogen fuel cell vehicles over the next 5-10 years.

Hydrogen costs will be discussed in detail later, but a major conclusion is that once H_2 becomes a common fuel for buses and/or cars it should be possible to acquire it at prices of US$10-$15/GJ. (For comparison, gasoline prices are around US$9/GJ at refueling stations in the U.S.A.).

3.3 Natural Gas for H_2 and Methanol Production

Natural gas is a potentially important source for hydrogen or methanol in Brazil. It is presently the least costly way to produce these fuels, and natural gas will be increasingly available in Brazil in the future.

3.3.1 Natural Gas for H_2 Production

The processing of natural gas begins with reforming, i.e. conversion to CO and H_2, usually by reaction with steam over a catalyst at close to 900°C. The gas product leaving the reformer goes through two shift reactors in series to convert to H_2 as much of CO leaving the reformer as possible via the water-gas shift reaction (Figure 5, right-hand side only). The gas then enters a pressure swing adsorber (PSA), which separates gases by exploiting the ability of specially designed porous materials to selectively adsorb specific molecules at high pressure and desorb them at low pressure. The first PSA bed adsorbs CO_2 and H_2O, and the second adsorbs all remaining components except H_2. Up to 97% of the H_2 fed to a PSA can be recovered as final product with greater than 99.999% purity. The H_2 can then be compressed for storage (e.g., Figure 4d) or pipeline transmission.

Once the population of fuel cell vehicles grows to sufficient size that hydrogen supplied from any existing excess hydrogen production capacity is insufficient, other near term supplies could be developed:

- Industrial gas suppliers indicate that they could build a new, large hydrogen plant based on steam reforming of natural gas in 2-3 years. Typical hydrogen output capacities for large scale reformer plants are 1-3 million Nm^3/day. A 2 million Nm^3/day steam reformer plant (similar in size to the recently built Air Products plant) could serve a fleet of about 600,000 fuel cell cars. Hydrogen from such a plant could be liquefied for truck delivery or delivered via a small scale pipeline system (Figure 4a, 4b).

- It is also possible to produce hydrogen onsite at the refueling station via small scale steam reforming of natural gas (Figure 4d). Recent improvements in small scale reformer technology are making this option increasingly attractive (Halvorson et al, 1997; Ogden et al, 1996). Partial oxidation of methane at the refueling station is another potentially interesting option.

Ample natural gas resources will be available in the São Paulo area to produce hydrogen in the near term. Present gas policy is to increase the supply through importation from Bolivia (the gas pipeline will be operational in 1999 and at full capacity—20 million m^3/day—by 2000), through importation from Argentina (several private investors are showing growing interest in building gas pipeline from Argentina to the south of Brazil), through increasing the supply of natural gas produced by Petrobras (from 27 million m^3 in 1997 to 53 million m^3 in 2000 - PETROBRAS, 1998), and even through possible importation of LNG [a 2000 MWe combined cycle electric power plant to be fueled with LNG in Northeast Brazil is under discussion (Gazeta Mercantil, 1998)].

Fueling a fleet of 200,000 fuel cell cars and light trucks plus 330 fuel cell buses would require about 1 million $m^3 H_2$/day. This amount of hydrogen could be produced via steam reforming from about 0.3 million m^3/day of natural gas or about 10% of the total natural gas flow in the COMGAS system in the state of Sao Paulo. [Table 6 (COMGAS, 1998) shows the amount of natural gas which is being presently delivered by the Companhia Municipal de Gas (COMGAS) in the surroundings of São Paulo (Suzano, Capuava, and São Bernardo city gates) as well as for the cities of São Jose and Pindamonhangaba in the state of São Paulo. This averages nearly 4 million m^3/day.]

For the city of São Paulo, where an extensive distribution network exists, handling natural gas in the amount needed to produce 1,000 to 2,000 m^3 of hydrogen per day is not a problem, where the distribution network is available. The delivery of 300 to 600 Nm^3 of natural gas per day (which might be the necessary amount for a demonstration project of 5-10 buses) is feasible through any installed grid in town. For a larger fleet it is also feasible to deliver natural gas in the city of São Paulo if the producing H_2 plants are located near the major supply ring which circles the city. (300,000 Nm^3/day of natural gas, representing about 10% of the total COMGAS present capacity, is sufficient to produce some one million Nm^3 of hydrogen.)

3.3.2 Natural Gas for Methanol Production

Natural gas is the principal feedstock for methanol production worldwide today. Natural gas is converted to methanol by steam reforming over a catalyst at close to 900°C. The resulting CO and H_2 then combine over a catalyst at about 250°C to form MeOH (Figure 5, right side). Conversion of carbon as CO to carbon as MeOH is typically in excess of 98%.

As of 1995 the worldwide methanol nameplate production capacity was about 29 million metric tonnes per year (Table 7). About 23 million metric tonnes were actually produced in 1995, yielding a capacity factor of about 83%. A significant methanol distribution system already exists (see Figure 6 upper part). 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 (Ogden et al, 1998a). 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 is possible to produce methanol via gasification of coal, heavy liquids, biomass or wastes (Figure 6 lower part), as discussed further below. The main uses of methanol today are production of formaldehyde, MTBE and acetic acid.

If the entire 1995 methanol production world capacity were dedicated to producing fuel for methanol fuel cell cars, we estimate that about 28 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 vehicles, 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. 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. To bring methanol to tens of millions of fuel cell cars would involve increases in methanol production capacity and tanker capacity, as well. Adding new production capacity is by far the most expensive step in developing a new methanol refueling infrastructure, as discussed later.

3.4 Electricity as a Source of H_2

Electrolysis is a process where water is dissociated to H_2 and O_2 through the flow of direct electric current through it. To allow the current flow in water, it is mixed with other elements to produce an aqueous solution with pH different from 7. The current flows through the ionic media from one positive electrode (anode) to the other negative electrode (cathode) when a DC voltage is applied to them. The operational set is called an electrolyzer and can be used as a source of H_2 (Figure 4e). Electrolyzers marketed today are classified as unipolar or bipolar. The basic difference between them regards how electricity flows between the several cells of the electrolyser. Unipolar electrolysers have the electrode from one cell connected in parallel with the respective electrode from the other one; bipolar ones are assembled with cells electrically mounted in series, in such a way that the anode of one cell is also the cathode of the neighbor cell. The product commonly used to conduct the electric current is potassium hydroxide (KOH at 25 to 45% by volume).

Table 8a presents typical data for some commercial electrolyzers, and Table 8b shows some estimates for the performance and capital cost of small electrolyzers versus the rated output of the electrolyzers in kW H2 out (at the rated current density on a higher heating value basis). Values are given for proton exchange membrane (PEM) electrolyzers and for alkaline electrolyzers.

PEM electrolyzers offer the potential advantages of low cost at small size, and of pressurized operation at up to 750 psi, which could reduce compressor costs. Early cost estimates (Fein and Edwards 1984) for small scale PEM electrolyzers showed significant scale economies below about 2 MW. However, Thomas and Kuhn (1995) have argued recently that mass-produced small PEM electrolyzers might cost less than \$300/kW H2 out (HHV) even at sizes of only a few kW, even though capital costs for electrolyzers today can range up to \$1000/kW.

Both bipolar and unipolar alkaline electrolyzers are commercially available. At small scales, bipolar electrolyzers would exhibit only modest economies of scale, and unipolar systems would have essentially no scale economy. The plant cost for these systems might be about \$500/kW for unipolar and \$600/kW for bipolar systems. Bipolar systems would allow pressurized operation at up to 450 psi, which could reduce compression costs.

Electricity sources for electrolysis are discussed next.

3.4.1 Hydroelectricity

There is a significant potential for using off-peak power in the interconnected South/Southeast/Centerwest electric grid in Brazil. The most recent evaluation of supply and demand of electricity in Brazil (ELETROBRAS,1997) estimates that electricity demand in all Brazil will increase from the 1997 level of 272 TWh to 425 TWh in 2006, while installed capacity will grow from 59 GW to 91 GW, which is enough to guarantee a power surplus of 13.8 GW in the South/Southeast/Centerwest integrated system (24.4% above the maximun demand) and of 5.6 GW in the North/Northeast integrated system (36.5% above maximun demand). The projected average cost of generation for the proposed system expansion is US\$ 40/MWh.

The projected power surpluses are not always available since part of the generators are under regular maintenance periods, and, since most of the electricity is from hydroplants, there is always a possibility of supply shortage, although this has been small and declining with the years as shown in Figure 7 (ELETROBRAS, 1997). Even so, if the supply system was able to provide reliable service in 1998 when the risk of deficit was the highest (Figure 7), it is possible to anticipate that a fraction of the surplus could be used for almost every year except in case of excessive lack of rainfall. Again observing Figure 7, we see that the risk of supply shortage due to inadequate rainfall will be below 6% in the coming years up to 2006. This means, on average, we can expect 1 year of shortage in 16 years of normal supply. It is compatible with the system capacity to allocate 1000 to 2000 MW for the production of H_2. This could be used to power electrolyzers, providing some 4.4 - 8.8 million m^3 H_2/day (assuming an electrolyzer efficiency of 70%), enough to fuel a fleet of 1 to 2 million fuel cell cars. Electrolyzers producing 0.003-0.05 million Nm^3 H_2/day (the size range needed to serve 8-160 buses/day or 65-1300 cars/day) would be in the 400-8000 kW range.

3.4.2 Electricity from New and Renewable Sources of Energy

Renewable electricity sources such as wind or solar could be used to power electrolyzers. There are few good wind sites in the state of São Paulo, though there are some attractive sites in Northeastern Brazil, where some 20 MW of wind turbines are already installed (ELETROBRAS, 1997).

The state of São Paulo has good solar resources, and solar photovoltaic (PV) electrolytic hydrogen could be produced in areas of the state of São Paulo. The surface area required to produce 4.2 million m^3 H_2/day (enough to fuel a fleet of 1 million fuel cell cars) would be about 40 km^2 (assuming annual average insolation of 16 MJ/m2/day or 180 W/m2 (which is typical of the interior part of the state of São Paulo), PV efficiency of 15% and electrolyzer efficiency of 80). PV hydrogen systems could be centralized or stand-alone (at the refueling site).

In areas with good direct insolation (such as the interior of the state of São Paulo), solar thermal power could be used in thermochemical cycles for producing hydrogen via solar-assisted steam reforming of natural gas or via water decomposition (Williams and Wells, 1997).

3.5 Biomass for Hydrogen and Methanol Production

Hydrogen or methanol can be made from biomass and municipal solid waste via thermochemical processing (Figure 5). Before describing process technologies, we discuss biomass resources in Brazil.

3.5.1 Biomass Resources in Brazil

Biomass resources are many in Brazil.

Due the activity of the pulp and paper and charcoal-steel industries, several million hectares of tree plantations exist, mainly of eucalyptus and pine. Also the expansion of the commercial market of firewood, while partially supplied by natural forests, requires the plantation of forests. Due to favorable climatic conditions rapid-growth wood plantations can be harvested in 3 to 6 years.

The potential for additional plantations in Brazil is large. For example, in the nine states comprising the Northeast region of Brazil (18% of Brazilian land area), it has been estimated that some 50 million hectares (one-third of the total land area of the Northeast) is suitable and potentially available for tree plantations. The total estimated potential biomass energy yield from this area is some 12,600 million GJ/year (Carpentieri *et al.*, 1993). The amount of hydrogen transportation fuel that could be produced from this much biomass is greater than 20 times the amount of energy consumed as ethanol in Brazil today.

Briquettes are another potential source of biomass. Due to some state legislation in the south of Brazil, wood residues can not be burned in open fires (Gomes Filho, 1998). This limitation motivates the briquette market which is becoming a common source of firewood, mainly for pizzerias and restaurants established in large cities, where space limitation precludes storage of conventional firewood. Briquettes are sold in São Paulo at around US$35/tonne (with 20% moisture content), or about $2.2/GJ.

Another very large source of biomass, in the state of São Paulo, are residues of sugarcane, both bagasse and tops/leaves. Even considering the very low efficiency of bagasse burning in the mills to produce steam and electricity, approximately 10% of the total is surplus. Very soon the amount of residue should increase since the traditional harvesting practice, which requires pre-burning of tops and leaves before manual harvesting, will not be allowed, according to existing legislation. A new decree (Orsini, 1998) provides a few more years for changes in the harvest practice. The most probable solution, which is already in practice in approximately 10% of the sugarcane plantations in the state, is green cane harvesting (Macedo, 1998). Tops and leaves, which have an energy content equivalent to all the produced sugarcane bagasse, will be available in the field (Braumbeker et al, 1997). The decision to transport it to some central location depends of the existence of a commercial market. Some evaluations performed by Copersucar (Macedo,1997) claim that transportation cost of such new kind of residue exceeds the present commercial value of surplus sugarcane bagasse, which is being commercialized at US$ 6-8/tonne (with 50% moisture) at the mill gate ($0.8-1.1/GJ).

With a total production of 180 million tonnes of sugarcane, 45 million tonnes of bagasse (50% moisture) is produced in the state. With a heat value (LHV) of 7500kJ/kg, the surplus (4.5 million tonnes per year) has an energy value of 33.8 million GJ/year. A significant fraction of this surplus biomass has a market since it is used by neighboring agro-industries (mainly the orange juice manufacturers). But it is secure to assume that 20% (6.8 million GJ/yr) has no market, and that small increases in demand might be met by better management of the mills' boilers. Regarding tops and leaves, the total energy value is ten times bigger (338 million GJ/year), but some amount of this material will be left in the field for soil protection. Also, there are areas where green cane harvesting probably will be uneconomical since such areas may be unsuitable for mechanical harvesting. Considering that at least half of the material can be collected, as much as 169 million GJ are available at a price above US$8/tonne ($1.1/GJ), but less than US$16/tonne ($2.1/GJ) (Macedo,1997).

Municipal solid waste (MSW) is also a potential resource for hydrogen or methanol production. With a population of 15 million in the São Paulo area and a typical waste generation rate of 1 kg/capita/day an estimated 15,000 tonnes per day of MSW are generated. With an energy content of 4.2 to 5 MJ/kg (Reis, 1996), the total MSW energy resource in the greater São Paulo region is some 25 million GJ/year.

3.5.2 Process Technology for Methanol and Hydrogen Production from Biomass and MSW

The production of liquid MeOH or gaseous H_2 from biomass or MSW has some similarities to the thermochemical processes that are or can be used to convert natural gas (discussed earlier) or coal (discussed later) to these fuels (Figure 5). Biomass is first gasified by heating it to above 700°C in the presence of little or no oxygen into a synthesis gas (syngas) consisting of CO, H_2, CO_2, H_2O(g), and in some cases methane (CH4) and small quantities of other hydrocarbons. The syngas exiting the gasifier is cooled and then quenched with a water spray to remove particulates and other contaminants. Additional cleanup of any sulfur compounds prevents poisoning of downstream catalysts. The syngas then undergoes a series of chemical reactions (discussed in sections on production of hydrogen and methanol from natural gas) that lead to the desired end product.

All equipment for fuels production from coal is commercially available today. Biomass (and MSW) gasifiers, the only system components for fuels production from biomass (and MSW) that are still under development, operate by direct or indirect heating.

Direct heating involves partial oxidation of the feedstock, the basic principle used in coal gasification. Directly-heated gasifiers use air or oxygen to burn some of the feedstock in situ, thereby providing the heat needed to gasify the remaining feedstock. In the production of MeOH or H_2, oxygen is preferred, so as to minimize the gas volumes that must be treated downstream. A disadvantage of O_2 use is increased costs. Because of the sensitivity to scale of capital costs for O_2 plants, there is a cost penalty with O_2 that grows with decreasing production scale.

Indirectly heated gasifiers are not suitable for most coals due to the low reactivities of coal compared to biomass. Indirectly-heated gasifiers obtain the heat needed to drive the gasification reactions from heat-exchange tubes or from an inert heat-carrying material like sand. Indirect heating gives rise to lower reactor temperatures than direct heating, but temperatures are sufficiently high (700-800°C) for effective biomass gasification. The indirect heating makes possible the production of a gas undiluted by N2, without the use of costly O_2.

MSW gasifiers operate on similar basic principles as biomass gasifier, but can be somewhat more complicated (Whiting, 1997) because of the need to minimize contaminant emissions. Alternatively, pre-processing of the MSW into refuse-derived fuel (RDF) enables more "conventional" gasifier designs to be used.

There are a number of projects ongoing worldwide to commercially-demonstrate biomass and MSW gasification technologies (CHESF et al., 1998; Whiting, 1997; Stahl, 1997; Paisley et al., 1997; Reed, 1997; Pitcher and Lundberg, 1997). Tables 9 and 10 summarize the energy balances for hydrogen and methanol production from biomass and from MSW, respectively, for several different gasifier designs. These results are based on detailed process modeling carried out at Princeton University. (See Appendix B and Larson et al., 1996.) The overall energy efficiency of producing hydrogen from biomass is about 60% (higher heating value basis), based on the average of the three process designs included in Table 9. For methanol from biomass, the average efficiency is 56%. For MSW to hydrogen the average efficiency is 59%, and for MSW to methanol the average is 50%.

3.6 Ethanol

Ethanol, which can be made from a variety of plant materials, can be used as a fuel for FCVs by first reforming it into a H_2-rich gas. Ethanol is used commercially today in internal combustion engines, primarily in Brazil and the U.S.A.

In 1997 Brazil produced from sugarcane 14 billion liters of fuel ethanol, which supported 3.7 million cars running on pure hydrated ethanol (96% ethanol + 4% water) and 12 million cars on gasohol, a 22% ethanol-78% gasoline blend (Moreira and Goldemberg, 1998 and DATAGRO, 1998). The US produces about 4 billion liters of ethanol from maize, all used for gasohol applications. In both countries, subsidies support the ethanol industry. However, substantial cost reductions are being made for cane-derived ethanol (Moreira and Goldemberg, 1998), and there are good prospects for making it competitive with petroleum fuels, even at the present world oil price, if electricity is simultaneously cogenerated from the non-sugar biomass residues of cane processing using advanced cogeneration technology (Williams and Larson, 1993). The prospects are poor for making ethanol economically from grain (Wyman et al., 1993).

3.6.1 Sugarcane Resources

The amount of land used to grow sugarcane for ethanol production in Brazil today is some 2.7 million hectares, which represents less than 4% of the total agricultural land in Brazil. More than 50% of all Brazilian ethanol is produced in the state of São Paulo. Considering the future availability of land in Brazil, there is no significant difficulty to, at least, double the production of ethanol from sugarcane in Brazil. In the longer term, if advanced processes for ethanol production from lignocellulosic biomass via enzymatic hydrolsis become commercially viable, as projected by some researchers (Lynd, 1996), the ethanol resource potential would be far greater still.

3.7 Coal

Coal can be converted to methanol or hydrogen using thermochemical processes similar to those described earlier for biomass (Figure 5).

3.7.1 Coal Resources

Brazil has significant coal reserves, but with two major limitations:

1□ Their restricted localization in the south states requires a large extension in the transport systems if they are to be used elsewhere, or in-situ production of H_2 or CH3OH followed by transportation of these products to the point of use.

2□ Most Brazilian coal is of low quality, with high amounts of ash and sulfur. This increases mining and transportation costs, increases volumes to be handled at the conversion facility, with consequent increases in investment costs, as well as increases in operating costs due to high sulfur removal requirements.

While the use of Brazilian coal may be problematic, large quantities of coal resources are available from elsewhere in the world at relatively low cost (well below \$2/GJ delivered to Brazil, excluding any environmental externality costs that might be charged, e.g. a carbon tax) for at least the next several decades.

3.7.2 Technology for Hydrogen and Methanol Production from Coal

As noted above, the processes for producing H_2 or MeOH from coal are similar to those described for producing these fuels from biomass (Figure 5 and see Appendix B). Unlike biomass gasifiers, coal gasifiers are well established commercially. These operate at much higher temperatures (1300°C or higher) than biomass gasifiers, as required to fully gasify coal, which is typically less reactive than biomass. Because of the high temperature, little or no methane is generated by the gasification step, obviating the need for a downstream reforming step. Compared to biomass processing, however, greater sulfur cleanup requirements are typical for many coals. Based on detailed process modeling consistent with the results described earlier for biomass-based methanol and hydrogen production, the overall energy efficiency of converting coal to hydrogen is about 64% (slightly higher than for biomass conversion). Coal to methanol efficiency is about 61%, again slightly higher than for biomass conversion to methanol. See Table 9.

3.8 Comparison of Fuel Production Potential and Potential Fuel Demands of FCVs

As has just been discussed, hydrogen can be produced in centralized plants or at refueling stations using natural gas, electricity, biomass, coal, ethanol, or methanol. (Methane derived from sugarcane stillage is another potential source.) It can also be produced on board vehicles, in which case methanol is the most suitable fuel, but other liquid fuels including ethanol can be used.

By way of summarizing the various primary energy resource estimates in previous parts of Section 3 and the corresponding potential for producing fuel cell vehicle fuels, we have assembled Table 11. This table shows various estimates of potential primary energy sources for producing fuels for fuel cell vehicles in Brazil. Also shown are estimates of the hydrogen, methanol, or ethanol production that would be possible from these resources. Finally, the table also shows an estimate of the maximum number of fuel cell cars or buses that each primary energy resource would be able to fuel. For comparison with these latter estimates, there are an estimated 16 million passenger cars operating in Brazil today (about 4 million of these in the greater São Paulo region), and there are an estimated 161,000 buses operating in Brazil (some 25,000 of these in the Sao Paulo metropolitan region). The following can be noted in scanning the resource estimates in Table 11:

- Pure hydrogen can be purchased in the commercial market, the size of which today is 7.5 million m^3/day. Also, it may be possible to acquire in the state of São Paulo from one particular PETROBRAS refinery around one hundred thousand m^3/day (de Souza and da Silva, 1996).

- Considering that more than 61,000 MW of electric power is installed in the country it should be feasible to use 1,000 to 2,000 MW for H_2 production. Furthermore, for demands below 1,000 MW, a very low tariff is available for intermittent supply. Using intermittent supply in combination with firm electricity it should be possible to purchase around 1,000 MW at quite low cost, while guaranteeing continuous supply through many years.

- Natural gas is already available in the country and in São Paulo. The city of São Paulo has a distribution network able to deliver small quantities of natural gas (1,000 to 10,000 Nm^3 per day) for decentralized H_2 production and large amount (100,000 Nm^3 per day) for centralized H_2 production. Natural gas supply will increase very soon through increase in domestic production and the importation through pipelines and possibly LNG tankers.

- Biomass can be a significant future source for H_2 or methanol. Municipal solid wastes produced in the city of São Paulo could generate some 18 million GJ/year of H_2. Using gasification technologies, surplus sugarcane bagasse and other sugarcane residues in São Paulo state alone can provide some 130 million GJ/year of H_2. Biomass from tree plantations have a future potential of several billion GJ per year.

- Coal is the largest fossil fuel resource in the world. Brazil has modest resources compared with other countries but even so present production is equivalent to 100,000 GJ/year, enough to produce some 60,000 GJ/yr of H_2. The possibility of using imported coal is always open and this represents a very large capacity for H_2 production, though perhaps not the most attractive option because of carbon emissions.

- Ethanol derived from sugarcane is also a potentially significant source of fuel for fuel cell vehicles.

- Little methanol is made in Brazil today, but it can be easily imported for short term use and produced locally from natural gas if a high enough demand exists to justify the investment. Brazil imported approximately 1 million m^3 /year of methanol during a few years when there were ethanol shortages.

Figures 8a-8e graphically display the size of the various hydrogen, methanol, and ethanol resources in Brazil relative to differing levels of demands for these fuels by fuel cell vehicles. A variety of resources that are accessible in the near term appear more than sufficient to satisfy any conceivable near-term demands of fuel cell vehicle fleets, including resources for hydrogen production (Figure 8a), resources for methanol production (Figure 8b), and resources for ethanol production (Figure 8c). For meeting long-term fuel demands of millions of cars and tens of thousands of buses, ethanol (Figure 8c), hydrogen from natural gas or from biomass (Figure 8d), and methanol from natural gas or from biomass (Figure 8e) are the most abundant resources. Global warming concerns increase the attractiveness of biomass as a source of hydrogen, methanol, and ethanol.

4 Cost of Delivered Fuel Cell Vehicle Fuels

Estimated total costs are given here for hydrogen gas, methanol, and ethanol delivered to a vehicle. The estimates represent costs that can be expected once the fuel production and delivery systems are commercially-mature and widely-implemented. Costs are estimated for fuels that might be made available in the near term (by on-site conversion from primary resources at refueling stations), as well as fuels that might be made available in the longer term (e.g., those involving centralized production with pipeline delivery to refueling stations, Figures 4 and 9). Costs for the on-site production systems are based on Ogden *et al.* (1998a,b). Costs for the centralized options are based on detailed production cost estimates by Williams *et al.* (1995) and Larson *et al.* (1996), coupled with pipeline and refueling station costs based on Ogden, *et al.* (1998a,b).

Cost estimates are given here in terms of US$ per unit of energy ($ per GJ). (On a higher heating value basis, the energy cost of $0.55/liter gasoline is equivalent to $16/GJ -- see Table 12). A capital charge rate of 15% per year is assumed in the calculations, unless indicated otherwise. Energy prices reflecting current conditions in either the São Paulo city area or in Brazil more generally (as appropriate) are used.

4.1. Hydrogen

Estimated levelized costs of compressed hydrogen gas (340 bar) delivered to a vehicle are shown in Figure 12 for a range of refueling station sizes (0.1 to 2.0 million standard cubic feet H_2/day, or stations able to serve about 65-1300 fuel cell cars or 8-160 fuel cell buses per day. The total fleet served would be 900-18,000 cars or 14-280 buses, as calculated in Table 13.).

Two near-term options shown in Figure 10 involve hydrogen production at the refueling station by steam reforming of natural gas in one case and electrolysis of water in the other. The two centralized (longer-term) options are production from biomass and from natural gas. For the centralized cases, the production plant and pipeline distribution system are built to serve tens to hundreds of refueling stations (depending on station size), thereby capturing economies of scale. An important conclusion that is evident from a first look at Figure 10 is that over the range of refueling station sizes considered, no single supply option is favored under all conditions.

4.1.1 Hydrogen Production On-Site at Refueling Stations

The following points regarding the cost of on-site H_2 production can be seen in Figure 10.

- The delivered cost of hydrogen fuel ranges from \$10/GJ to \$35/GJ, which is higher (substantially higher in some cases) than the untaxed price of gasoline today.

- Costs of onsite production of hydrogen via small scale steam reforming of natural gas are shown, assuming use of an advanced, low-cost reformer technology that has recently been introduced commercially for stationary hydrogen production (Farris, 1996; Halvorson *et al.*, 1997). Two sets of hydrogen costs are shown, corresponding to two sets of natural gas prices. The higher set of H_2 costs assume natural gas prices paid by industrial users in Brazil today: about \$17/GJ for the volume of gas consumed in the case of the smallest station size, down to \$10/GJ in the largest station case. For these higher-gas-price cases, the cost of hydrogen delivered to the vehicle is \$21-\$34/GJ, including the cost of reforming and dispensing equipment at the station. The lower set of costs assume a natural gas price (\$2.8/GJ) that is available as a special rate in São Paulo for CNG vehicles. For these cases, the cost of hydrogen delivered to the vehicle is \$10-\$15/GJ over the station size range indicated.

- The cost for onsite production of hydrogen via small scale electrolysis assumes an electrolyzer capital cost of \$300/kW H_2 output, with no scale economy for mass produced PEM electrolyzers over the size range considered in Figure 10 (0.1 to 2.0 million scf H2/day or 420 kW to 8.4 MW H2). Hydrogen costs are shown for two different electricity prices. The higher-price case (\$0.03/kWh) is based on the demand and energy charges that would be incurred in the São Paulo area for off-peak power based on rate schedules in effect at present. For this case, hydrogen costs about \$20/GJ. The low-price case (\$0.01/kWh) is an interruptible rate that is available when rainfall is adequate. In practice, this rate has been available roughly seven out of every ten years during the recent past. It appears that onsite electrolysis would be somewhat more expensive than most other options if the electricity cost is the relatively high off-peak rate of 3 cents/kWh. If off-peak power cost 1 cent/kWh, electrolytic hydrogen, at \$9-\$11/GJ, would be competitive with all other options.

- Solar photovoltaic electricity could also be used for electrolysis. With projected improvements in the cost of mass-produced thin film PV, the cost of hydrogen delivered to the vehicle might be as low as \$30 to \$40/GJ (not shown in Figure 10), which is nevertheless much more costly than most other sources of hydrogen shown in Figure 10.

4.1.2 Centralized Hydrogen Production, with Pipeline Delivery To Refueling Stations

Regarding the costs of centralized production of H_2:

- Estimates of the levelized costs of H_2 production from biomass and from natural gas are based on estimates by Williams *et al.* (1995). For biomass, the production plant capacity is 3000 tonnes wood chips per day (at 45% moisture content), a wood processing capacity comparable to a modern pulp and paper mill in Brazil today. For H_2 production from natural gas, the gas feed rate is 1.64 million Nm^3/day, which is typical for a modern, world-class natural gas conversion facility.

- Added to the hydrogen production costs are costs for pipeline distribution (Figure 11) and refueling station costs.

- The two sets of costs shown in Figure 10 (one for biomass- and one for natural gas-based hydrogen production) span the likely range of costs for centralized systems. The set of costs for natural gas-derived hydrogen assume a relatively low cost of gas ($2.5/GJ, consistent with large volume of consumption) and a cost for the pipeline delivery system ($1.7/GJ) reflecting a relatively short transmission distance and geographically concentrated demand (See Figure 11). The set of costs for hydrogen from biomass assume a feedstock cost of $2.5/GJ, representing a typical cost for wood from industrial plantations in Brazil today, and a relatively long pipeline transmission system, with delivery cost of $5/GJ.

- Costs for hydrogen derived from municipal solid waste are not shown in Figure 10, but would likely fall between the two sets of centralized options shown there. This conclusion is based on cost estimates of Larson *et al.* (1996), and an assumed tipping fee of $50/tonne of raw MSW, giving a cost of H_2 production of $7-$12/GJ. Pipeline transmission and refueling station costs would likely be close to those shown for the natural gas case in Figure 10, since the H_2 production plant could be built near São Paulo city, the source of the MSW. [(Tipping fees of US$20/tonne were used in feasibility studies carried out in the late 1980's for São Paulo. The proposals were never transformed into projects, indicating that fees were too low (Reis, 1998). At present, a private enterprise is proposing to build an incinerator and electric power plant if a dumping fee as high as US$ 70/tonne is collected (Reis, 1998).]

- Costs for hydrogen from coal are also not shown in Figure 10, but would be comparable to those shown for biomass, assuming a coal price of $1.5/GJ. This conclusion is based on Williams *et al.* (1995) (see Appendix B), wherein costs are estimated for hydrogen production from coal at a facility processing 5000 tonnes/day of coal—a plant capacity about five times as large as assumed for biomass-based production. The larger capacity is considered because transportation costs for coal are not as scale sensitive as for biomass (due to the higher volumetric energy density of coal), so that scale economies in the capital cost of the conversion plant can be exploited with coal. Hydrogen might also be produced from coal with underground sequestration of CO_2 and pipeline delivery to refueling stations. The sequestration of CO_2 might only marginally increase the cost of hydrogen (Williams, 1996).

4.2 Methanol

4.2.1 Near Term Options

Initially, to serve a modest number of methanol fuel cell vehicles, it should be possible to provide methanol transportation fuel using the existing methanol distribution system in Brazil. Petrobras built methanol handling facilities, including tanker terminals and distribution systems, starting in the late 1980s. Methanol has been used in Brazil since 1990 in blends with gasoline and ethanol. This mixture was introduced because of an ethanol shortage in 1989 caused by a large increase in neat-ethanol vehicles, combined with strong international sugar prices which stimulated greater-than-anticipated amounts of sugar production in lieu of ethanol. During the most critical period almost one million cubic meters (about 800,000 tonnes) of methanol was being consumed annually. Even with the present oversupply of ethanol in Brazil, methanol continues to be imported since MTBE is produced (in Rio Grande do Sul) and added to gasoline instead of ethanol. Brazil imports methanol at world market prices, which have fluctuated considerably, ranging of \$5-\$12/GJ during the past 15 years (less than \$100/tonne to over \$200/tonne).

If methanol were to be used for fuel cell vehicles in Brazil in the near term, there would probably be only minor costs incurred to convert existing gasoline/alcohol refueling stations to pure methanol. For reference, the cost for converting a gasoline refueling station to one dispensing 1100 gallons of methanol per day (serving about 1300 methanol fuel cell cars) has been estimated for the U.S.A. to be \$6000-\$52,500 (DOE 1990), or a modest \$5 to \$40/fuel cell car.

4.2.2 Longer Term Options

For an expanded methanol fuel supply in the longer term, options include expanding imports of methanol or producing methanol in Brazil from natural gas, coal, biomass, or municipal solid waste.

To expand import capacity would probably initially require some conversion of existing liquid fuel marine terminals and delivery tank trucks to methanol. At relatively low market penetrations of methanol fuel cell vehicles, infrastructure capital costs will be small (probably less than \$50/car) (Ogden *et al.*, 1998a). However, once the worldwide market for automotive methanol exceeds the excess methanol production capacity in the world (which might be when a million fuel cell vehicles are on the road) new production capacity would be needed somewhere in the world. Adding new natural gas-based production capacity would be by far the most expensive step in developing a new methanol refueling infrastructure. Infrastructure capital investments per car would be similar to those required to establish a hydrogen fuel infrastructure--\$340 to \$800/car, depending on the assumptions (see Table 14 and 15).

Although most methanol today, and for the next few decades is likely to be made from natural gas, methanol can also be made from other carbonaceous feedstocks, including coal, biomass, and municipal solid waste. In general, unless natural gas prices are considerably higher than today's levels, the cost of producing methanol from solid feedstocks will be higher than from natural gas, as shown in Table 16 (taken from Appendix B). This table shows detailed cost estimates (in 1991\$--multiply by 1.15 to get 1997\$) for methanol production from biomass costing \$2/GJ (with four different gasifier designs), from coal costing \$1.45/GJ, and from natural gas costing \$4.1/GJ. The assumed natural gas price is higher than the price of gas delivered to most methanol production facilities today, but is lower than the price paid by most gas users in Brazil today. Based on detailed cost estimates given elsewhere (Larson *et al.*, 1996), the cost of producing methanol from MSW (\$50/tonne dumping fee) would be \$10-\$15/GJ, or in the range shown in Table 16 for biomass.

Because of relatively high natural gas costs and relatively low biomass costs in Brazil, methanol production from biomass might be competitive with methanol from natural gas. It is estimated, for example, that 1.7 EJ/year of biomass (enough to provide 1.0 EJ/year of methanol—or fuel for 50 million fuel cell vehicles) could be produced on 4 million hectares of plantations in Northeast Brazil at a cost of \$1.7/GJ or less (see Appendix B, footnote 22), corresponding to a methanol production cost of about \$12/GJ. A new natural gas-to-methanol facility would produce methanol at this cost at a natural gas price of about \$5.5/GJ, which is the lowest gas price in São Paulo today for conventional industrial users consuming more than 1 million m^3 per day.

The cost of methanol delivery to refueling stations and filling station costs must be added to the production cost to determine final cost to the consumer. Delivery costs for methanol are estimated to be $2.2/GJ, assuming they are the same on a volumetric basis as for gasoline delivery ($1.2/GJ), and filling station costs would add another $1.4/GJ (Appendix B).

4.3 Summary of Delivered Fuel Costs

Figure 12 summarizes the hydrogen and methanol cost estimates discussed in the previous sections and includes comparisons with ethanol and gasoline prices. This figure shows total delivered fuel cost to consumers, including fuel production, fuel delivery to refueling station, and refueling station costs.

Costs for hydrogen produced at refueling stations and at centralized facilities are included. For the on-site production options, we consider:

- Electrolytic hydrogen from off-peak power using a typical off-peak electricity rate in São Paulo (3 cents/kwh on average).

- Electrolytic hydrogen from power available continuously at 1 cent/kWh.

- Hydrogen produced from natural gas in advanced small scale steam reformers using a gas price currently available in São Paulo for compressed natural gas vehicles, $2.8/GJ.

- Hydrogen produced from natural gas in advanced small scale steam reformers using the standard gas price (about $14/GJ) to industrial or commercial customers in São Paulo consuming between 5,000 and 50,000 m^3/day of natural gas.

- Hydrogen produced via PV powered electrolysis, assuming that PV power can be produced at about 7 cents/kWh. [This corresponds to future PV goals of 15% PV system efficiency, balance of system costs of $40/m^2$, and PV panel costs of $0.5/peak watt. For today's PV parameters, the cost of electricity would be considerably higher. Insolation of 16 MJ/m^2/day is assumed, and electrolysis efficiency (higher heating value of H_2/electricity input) is taken to be 80%.]

For centralized hydrogen production with pipeline delivery to refueling stations, we consider:

- Hydrogen from steam reforming of natural gas, with gas prices of $2.5/GJ (approximately the special automotive rate available in São Paulo today) and $5/GJ (approximately the standard industrial rate in São Paulo for the largest gas consumers).

- Hydrogen from coal, with coal costing $1.5/GJ.

- Hydrogen from biomass, with biomass costing $2.5/GJ.

- Electrolytic hydrogen from 1 cent/kWh hydropower located 1,000 km from São Paulo. The hydrogen goes to São Paulo via large pipeline (adding about $2.6/GJ), and is then distributed locally via small pipelines to refueling stations.

Methanol costs are shown assuming centralized production at large facilities in Brazil. Assumed feedstock costs are $2.5/GJ for natural gas, $1.5/GJ for coal, and $2.5/GJ for biomass. Truck delivery to refueling stations is assumed.

For ethanol and gasoline, both of which are widely distributed in Brazil today, current fully-taxed prices are shown (\$15.4/GJ for gasoline and \$17.3/GJ for ethanol). The tax adds about \$3.3/GJ to the price of ethanol and \$6.5/GJ to the price of gasoline. (Taxes are not included in the hydrogen and methanol costs shown in Figure 12.).

The delivered cost of hydrogen varies from about \$10/GJ for the lowest cost onsite production options to over \$40/GJ for PV hydrogen. If low energy prices are available at the refueling station, the cost of onsite hydrogen production is less than for centralized production.

Centralized hydrogen and methanol production (from any of the feedstocks considered) would appear to offer the lowest fuel costs (\$10-\$15/GJ)—comparable to gasoline and ethanol costs today. However, large hydrogen or methanol demands (several hundred thousand fuel cell cars) would be required to justify construction of such facilities. Initially when demand is relatively low on-site hydrogen production or methanol imports might be preferred. This approach has the advantage that it is possible to build one refueling station at a time, as demand dictates, and no additional infrastructure building is required. For the on-site production of hydrogen with typical industrial natural gas and electricity costs, hydrogen costs (at \$20-\$40/GJ) would generally be considerably higher than for centralized production. If low electricity or natural gas rates are available, hydrogen (at \$10/GJ) would be less costly than gasoline or ethanol today and less costly than centralized options.

Some of the relative cost rankings of fuels change when the cost per vehicle-kilometer for fuel cell vehicles is considered, due to different efficiencies for hydrogen, methanol, and ethanol fuel cell vehicles. The projected fuel economy for hydrogen fuel cell vehicles is about 50% greater than for methanol, ethanol or gasoline FCVs, so the fuel cost per vehicle-km is relatively lower. (Assumed vehicle performance parameters, based on detailed vehicle modeling discussed in Appendix A, are shown in Table 4.) Figure 13 shows a cost per v-km comparison for passenger automobiles described in Section 1 of this report for the same set of fuel supply options as in Figure 12.

The cost per v-km for a hydrogen FCV is less than for a methanol, ethanol, or gasoline fueled FCV, for many of the hydrogen supply options considered. Even with conventional energy prices for off-peak power and natural gas, the fuel cost per v-km for a hydrogen FCV using hydrogen produced at the refueling site is similar to that for a gasoline or ethanol FCV. Shown for reference is the estimated cost per v-km for a gasoline internal combustion engine vehicle (with an assumed fuel economy of 5.6 liters/100 km). All the fuel cell car options except for PV hydrogen (at PV electricity costs of 7 cent/kwh) have a lower fuel cost per v-km than the reference gasoline-IC engine vehicle.

5 Total Lifecycle Costs of Transportation with Fuel Cell Vehicles

The previous section of this report focussed on cost of fuels for fuel cell vehicles, but a better indication of the overall economics of fuel cell vehicle transportation systems is given by the total lifecycle cost, including vehicle capital costs, non-fuel operating/maintenance costs, and fuel costs. Estimates of the total lifecycle costs of fuel cell automobiles and of fuel cell buses are discussed here.

5.1 Total Lifecycle Costs for Fuel Cell Automobiles

Ogden *et al*, 1998a have estimated the capital costs for alternative fuel cell automobiles assuming commercially-mature technology and large-scale mass production. Table 17 summarizes ranges of estimated costs for fuel cell vehicle components such as fuel cells, fuel processors, peak batteries, and motors. Figure 14 shows the cost of drive train and fuel storage components for fuel cell automobiles, for a low and a high range of cost assumptions, for the vehicle designs in Table 2. For reference, these components in a comparable gasoline internal combustion engine car today would cost in the neighborhood of \$3700.

(Note: all costs in this paper are given in 1997 US$, unless otherwise indicated.) The hydrogen fuel cell car is the lowest cost option. A methanol FCV would cost an estimated $500-600 more, and a gasoline FCV about $850-1190 more. The extra costs are primarily due to the fuel processor, but also because a larger fuel cell is needed in vehicles with fuel processors.

Total lifecycle costs per vehicle-km for fuel cell automobiles, including capital, O&M, and fuel, are shown in Figure 15 for the same set of fuel sources shown in Figure 13. Of the three cost components shown for each fuel option, vehicle capital costs account for the largest share, while fuel costs are by far the smallest share. Capital costs for the hydrogen fuel cell cars are slightly lower than for ethanol, methanol, or gasoline fuel cell cars primarily because the liquid-fuel vehicles require on-board fuel processors (Figure 16a,b).

Surprisingly, the range in total lifecycle cost per v-km shown in Figure 15 for all of the fuel cell vehicles is rather small over the full range of fuel sources shown. Figure 15 also shows for reference the estimated cost per v-km for a gasoline internal combustion engine vehicle (with an assumed fuel economy of 5.6 liters/100 km). All the fuel cell car options except for PV hydrogen (at PV electricity costs of 7 cent/kwh) have a lower fuel cost per v-km than the reference gasoline-IC engine vehicle.

5.2 Total Lifecycle Costs for Fuel Cell Buses

The largest future market for fuel cell vehicles (FCVs) will be passenger cars, but the FCV is likely to first be widely introduced in buses and trucks, because storage volumes for fuel cell fuels are less constrained. Also, the cost per unit of power for a bus engine is higher than that for a passenger vehicle engine, which provides an easier target for fuel cells. Furthermore, buses operate more frequently at lower engine loads. (For example, the average bus speed in Manhattan is less than 6 km/hour.) This provides a fuel efficiency boost for the fuel cell bus relative to an internal combustion engine, because efficiency increases with decreasing load for a fuel cell, while it drops with decreasing load for a diesel engine. Several commercially-oriented demonstration projects of fuel cell buses are well underway in the US, Canada and Europe, and rapid advances are being made. Ballard Power Systems, Inc. of Vancouver, Canada, introduced a prototype PEM fuel cell bus in 1993, followed by a second generation unit in 1995. A fleet of three commercial prototype buses has had several months of operation by the Chicago Transit Authority as of August 1998, and a similar fleet will soon start operation in Vancouver, British Columbia. Commercial offering of buses from at least two or three companies is expected before 2002.

Cost comparisons are described here for urban fuel cell and diesel buses in the context of New York City, based on Larson, et al. (1996). While there are many factors that make the situation for São Paulo different from that in New York, the comparative results between fuel cell and conventional diesel buses are likely to be indicative for other urban areas, including São Paulo. Because fuel costs are a relatively small part of the total per-km lifecycle cost of owning and operating a bus, it is important to examine total lifecycle costs. Table 18 shows a comparison of the total estimated cost per bus-km for a conventional (New York City) diesel engine bus and for a comparable hydrogen fuel cell bus.

The capital cost shown in Table 18 for the diesel bus, $251,000 (1997$), is based on a recently contracted price for diesel buses by the New York City Transit Authority. The capital cost for the fuel cell bus, about $345,000, is a preliminary estimate for mass production of a commercially mature hydrogen/PEM fuel cell bus from Ballard that would meet the same safety and accessory specifications as conventional buses in New York City (Howard, 1995). The market entry price for the fuel cell bus (at a scale of production of about 100 units) has been estimated by Ballard to be $575,000 to $690,000 (Howard, 1995).

While the fuel cell bus may have a higher first cost, it's lifetime is expected to be considerably longer than for a diesel engine bus. A 50% longer lifetime is assumed in the calculations here, based on the replacement schedule authorized by the U.S. Federal Transit Authority (FTA) for diesel and electric-trolley buses, respectively. The FTA, which provides funds to urban transit authorities for purchase of buses, authorizes diesel bus retirement after 12 years operation and electric trolley bus retirement after 18 years.

Operation and maintenance costs are well established for diesel buses, but are uncertain at this time for fuel cell buses. However, once FCBs come into common use, O&M costs can probably be expected to be lower than for a diesel engine bus because the FCB has fewer moving parts subject to wear, vibrates less, and operates at lower average temperatures. For illustrative purposes in Table 18 the annualized O&M costs for the FCB are taken to be two-thirds of that for the diesel bus.

Forty-foot, wheelchair-equipped hydrogen/PEM fuel cell buses are expected to achieve fuel consumption levels between 1.1 to 1.6 Nm^3 hydrogen per kilometer (depending on duty cycle). The average of this range, 1.35 Nm^3/km, corresponds to 2.31 km/liter diesel equivalent (Table 18). For comparison, the average fuel economy for comparable diesel engine buses in New York City today is 1.35 km/liter diesel (Pellegrin, 1995).

Figure 17 shows total lifecycle cost ($/bus-km) for a hydrogen fuel cell bus over a range of delivered hydrogen fuel prices. Also shown is the total lifecycle cost for diesel buses for diesel fuel prices of $0.3 to $0.4 per liter ($9.5/GJ to $13.9/GJ). For reference, diesel prices are about $0.3/liter in São Paulo and in the U.S.A today, and the projected price of diesel fuel to the transport sector in the U.S.A. in 2015 ranges from $0.3 to $0.4 per liter (EIA, 1996).

In the range of $10-15/GJ for delivered hydrogen fuel, the total cost per bus-km for the fuel cell bus is comparable to that for the diesel bus, with diesel prices of $0.3-$0.4/liter. There are a number of uncertainties which might shift (up or down) the relative competitiveness of FCBs predicted here, including uncertainties in capital cost, O&M cost, and operating life. In addition, the discount rate assumed in amortizing the purchase price of the bus has a significant impact on the total per-km cost, because of the large fraction of the total per-km bus cost attributed to capital charges (Table 18). Results shown in Figure 17 are for a real discount rate of 10%. With a lower discount rate, the attractiveness of the fuel cell bus relative to the diesel engine bus increases, because of the higher capital cost of the fuel cell bus. In the U.S.A., urban bus service is typically a public service, with public funds expended to purchase buses, so a discount rate lower than 10% might be more realistic, at least in the U.S. context.

6 Conclusions

The fuels that can satisfy a future fuel cell transportation system in Brazil will depend to a large extent on the vehicle designs that are developed. At present, much of the focus of vehicle developers is on hydrogen vehicles and on liquid-hydrocarbon vehicles. The latter require fuel processing systems to convert the liquid fuel to the hydrogen-rich gas required by the fuel cell. Potentially interesting fuel cell fuels in Brazil examined in this report include hydrogen, methanol, and ethanol. Brazil has an abundance of options for providing these fuels in the near and long term.

In the near term, small quantities of hydrogen can probably be purchased in the commercial market, which today provides some 7.5 million m^3/day to industrial users. Perhaps 250,000 Nm^3/day might be available in this fashion—enough to fuel a fleet of about 80,000 fuel cell cars or 1200 fuel cell buses.

Alternatively, hydrogen might be produced at refueling stations, from either steam reforming of natural gas or by electrolysis, both of which are commercially available technology options today. Natural gas is already available in the area, and the city has a distribution network. Furthermore, gas supplies will increase very soon through increase in domestic production and importation through pipelines. If the gas price presently available in São Paulo for compressed natural gas vehicles is available at hydrogen production/refueling stations, this could be an economically attractive fuel supply option. Electrolytic hydrogen production at refueling stations is an option that is especially attractive if the available electricity tariff for interruptible supply contracts (about $0.01/kWh) can be secured. At conventional off-peak rates for electricity (about $0.03/kWh), electrolytic hydrogen would be considerably more expensive than hydrogen from natural gas at the CNG vehicle rate, though less costly than hydrogen from gas at prevailing industrial rates.

Ethanol is readily available in Brazil today and could be used in fuel cell vehicles designed for this fuel. On a cost per unit energy basis, ethanol would be some 50% more costly than on-site production of hydrogen at refueling stations, assuming the lower natural gas or electricity prices discussed in the previous paragraph.

Little methanol is made in Brazil, but it can be easily imported for short term. Brazil imported about one million m^3 /year of methanol in the recent past during periods of ethanol shortages. The cost of methanol in the near term would follow world-market price trends.

In the longer term, once the demand for fuel cell vehicles grows substantially, there would be a greater number of options for fuel supply.

Projected natural gas resources are such that gas-derived hydrogen could fuel a very substantial fraction of a Brazilian fuel cell vehicle transportation system. Thus, decentralized production of hydrogen from gas will continue to be an option. Once demand reaches a high enough level, centralized production of hydrogen with pipeline distribution to refueling stations will also be an option that will be economically attractive relative to decentralized production, if the CNG vehicle rate for natural gas is not available. As with any option for centralized hydrogen production, the commitment to building a hydrogen pipeline infrastructure requires a large demand level to be in place first.

The amount of hydroelectricity that is likely to be available at sufficiently low cost ($0.01/kWh) to make electrolytic hydrogen competitive with natural gas or other long term options is likely to be inadequate to make a major contribution to fuel supply in a future fuel cell transportation system in Brazil. Still, one to two million cars could probably be fueled from off-peak power electrolysis at competitive costs. If gas at the CNG vehicle rate is not available, the electrolysis option will be attractive even for more typical off-peak electricity rates ($0.03/kWh).

Solar-PV electrolysis is another option, but cost projections for this indicate that it will be a more expensive option than any of the others considered in this report.

Other long-term options for fuels' supply examined in this report are centralized methanol or hydrogen production in Brazil from natural gas, coal, or biomass. Gas prices must be relatively high ($5-$6/GJ) before hydrogen or methanol from coal or biomass will become competitive. Any centralized methanol production is likely to have difficulty competing for some time with the cost of imported methanol, which will typically be made at large facilities from very-low-cost remote gas sources. But biomass, including byproducts of sugarcane processing and dedicated energy plantations, is potentially Brazil's largest primary energy resource for fuels production. Municipal solid waste (MSW) is another biomass resource that can be converted to methanol or hydrogen. MSW would not be able to provide a large share of total fuel supply, but it might be an attractive option from the standpoint of reducing landfill requirements around São Paulo.

Ethanol derived from sugarcane is also a potentially significant fuel resource. Current levels of ethanol production could fuel all automobiles in Brazil today, if these were all fuel cell vehicles.

While there is a fairly large range in the cost per unit of energy among hydrogen, methanol, and ethanol from different sources, the estimated total cost per km for transportation (including vehicle capital cost, operating and maintenance cost, and fuel cost) does not vary substantially among all of the options examined in this report, and the total cost per km is slightly lower in almost all cases than the cost for a comparable vehicle with an internal combustion engine fueled by gasoline at gasoline price prevailing in Brazil today. This suggests that decisions about which fuels and fuel sources will be adopted in Brazil will be made largely on the basis of factors other than total lifecycle cost per km. Important considerations are likely to be vehicle performance (especially performance of on-board reformers for liquid fuels), vehicle first cost, fuel-supply infrastructure capital investment requirements, and greenhouse gas emissions and other environmental considerations.

Table 1
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 3 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 H2 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 H2 PEM fuel cell buses in Vancouver, BC
1997	Ballard and Daimler Benz form $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 onobard methanol reformer
1997	Ford joins Daimler-Benz and Ballard in $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	Shell International Petroleum and Ballard/Daimler Benz (DBB) form alliance to develop hydrocarbon reformer technology for fuel cell vehicles.
1998	Nissan announces plans to sell methanol fuel cell cars with Ballard fuel cells starting 2003-2005.

SOURCE: Ogden et al, 1998a

Table 2
Model Results: Comparison of Alternative Fuel Cell Vehicle Designs

Fuel Storage/ H2 Generation System	Vehicle mass (kg)	Peak Power (kW) (FC/Battery)	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
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
Ethanol POX	1395	89.4 (39.4/50.0)	65	80	71	654

See Table 3 for assumptions.
* FUDS = Federal (United States) Urban Driving Schedule; FHDS = Federal Highway Driving Schedule; Mpeg = miles per equivalent gallon of gasoline.

SOURCE : Ogden et al, 1998a

Table 3
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)r	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%
$V_{comp/exp}$	0.067 Volts
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 Ethanol 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	12 kg tank, 13 gallon capacity total weight 50 kg
Driving schedules	FUDS, FHDS
Regenerative braking recovered up to battery capabilities	

SOURCE : Ogden et al, 1998a (See Appendix A, which includes notes for this table.)

Table 4
Assumed Characteristics Of Fuel Cell Automobiles

	Hydrogen PEMFC Car	Methanol PEMFC Car	Gasoline PEMFC Car	Ethanol PEMFC Car
Fuel economy (a, b)	106 mpg gasoline equiv.	69 mpg gasoline equiv.	71 mpg gasoline equiv.	71 mpg gasoline equiv.
Miles/yr (c)	11,140	11,140	11,140	11,140
Fuel Storage (c)	H2 gas @5000 psi	Methanol	Gasoline	Ethanol
Fuel stored onboard (c)	1550 scf H_2 (3.75 kg)	13 gallons methanol	13 gallons gasoline	13 gallons ethanol
Range (mi) (c)	425	460	940	654
Energy use per year (GJ/yr) (a)	13.7	21.1	20.5	20.5
Fuel use per year (d)	40,000 scf H_2/yr	306 gallons methanol/yr = 914 kg/yr	157 gallons gasoline/yr = 3.74 bbl/yr	231 gallons ethanol/yr = 692 kg/yr

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) and that 1 scf of hydrogen contains 343 kJ (HHV); 1 gallon of ethanol contains 0.0886 GJ (HHV) or 1 kg of ethanol contains 29.6 MJ (HHV).

b. Based on simulations of PEMFC automobile fuel economy and range. (See Table 3).

c. Typical annual mileage for a passenger car in the United States.

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

SOURCE : Ogden et al, 1998b

Table 5
Hydrogen Market in Brazil - 1984 to 1994 (tonnes/year)

Year	Ammonia	Methanol	Clor-Alkali Industry By-Product	Petrochemical Industry	Iron and Steel Industry*	TOTAL
1984	186,926	18,470	21,436	20,834	9,363	257,029
1985	200,928	22,207	22,149	20,834	11,579	277,697
1986	199,388	26,262	24,698	20,834	11,876	283,058
1987	211,588	30,980	23,848	20,834	7,727	294,977
1988	205,448	26,868	25,166	20,834	7,727	286,043
1989	217,787	30,728	26,669	20,834	10,886	307,423
1990	206,303	78,563	26,133	20,834	11,405	343,238
1991	197,561	81,515	28,667	20,834	11,027	339,604
1992	188,675	77,972	29,612	20,834	11,216	328,309
1993	212,114	78,384	28,070	20,834	12,159	351,561
1994	223,590	89,165	30,075	20,834	10,707	374,371

These numbers are for hydrogen consumption, except for chlor-alkali industry, where they are for hydrogen production. Note, 1 tonne hydrogen = 11,300 Nm^3.

* Hydrogen used in the production of iron-esponja (US/BA), and for iron ore reduction at ACESITA

SOURCE: de Souza, Samuel and da Silva, 1996.

Table 6
Daily Natural Gas Delivered by COMGAS by Citygate

	SUZANO	CAPUAVA	CUBATÃO	S.BERNARDO	S.JOSÉ	PINDA	TOTAL
JULY 98	Volume (m^3/day)						m^3/day
01	1,327,638	1,166,323	953,653	349,754	165,628	0	3,962,996
02	1,275,081	1,155,695	724,353	409,814	168,409	0	3,733,351
03	1,190,000	1,102,408	889,845	316,222	159,780	0	3,658,254
04	1,093,967	901,683	1,063,608	272,507	145,434	0	3,477,219
05	797,757	827,001	1,100,982	224,201	94,779	0	3,044,720
06	1,263,899	1,062,332	980,012	219,062	174,294	0	3,709,599
07	1,347,141	1,176,246	1,091,183	137,337	162,664	0	3,913,572
08	1,315,367	1,118,751	963,297	271,670	173,909	0	3,842,993
09	1,155,658	1,007.196	1,124,665	106,062	127,706	0	3,521,277
10	1,221,404	1,052,470	1,007,677	209,105	142,515	0	3,633,171
11	1,123,047	984,909	1,106,920	122,967	138,807	0	3,476,649
12	957,134	725,706	1,084,618	138,288	96,900	0	3,093,645
13	1,308,066	1,035,082	955,284	276,916	183,302	0	3,758,890
14	1,280,937	1,148,375	726,739	324,102	181,261	1,662	3,643,065
15	1,301,351	1,175,591	617,965	517,439	187,723	8,191	3,608,279
16	1,406,026	1,341,072	993,566	213,744	177,645	13,107	4,147,160
17	1,426,125	1,276,928	956,161	259,509	173,234	11,721	4,103,578
18	1,208,498	1,136,683	1,051,939	161,766	129,966	21,015	3,708,867
19	833,257	1,027,669	1,037,740	196,742	94,742	14,670	3,204,721
20	1,339,407	1,242,523	1,103,443	186,394	185,279	16,866	4,053,912
21	1,403,951	1,114,206	1,077,264	249,035	190,106	16,760	4,051,322
22	1,393,334	1,248,166	1,127,599	197,628	172,370	19,251	4,158,348
23	1,374,093	1,213,162	1,063,746	258,764	186,783	19,255	4,125,803
24	1,347,434	1,215,718	1,106,343	227,114	176,012	19,275	4,091,898
25	1,123,201	1,058,175	1,114,988	212,088	118,149	19,186	3,645,788
26	840,444	867,456	1,103,790	141,632	100,502	22,612	3,076,637
27	1,242,200	1,169,906	1,057,798	153,007	148,197	22,615	3,793,721
Méd DU	1,319,192	1,167,442	966,997	264,812	172,728	14,889	3,899,432
Méd SA	1,134,183	1,020,112	1,084,363	192,332	133,089	20,101	3,577,131
Méd DO	857,148	862,183	1,081,783	175,266	96,731	18,641	3,082,431
Média	1,217,720	1,094,457	1,007,229	234,928	153,929	18,156	3,716,641
Máx. Mes	1,426,125	1,341,072	1,127,599	517,439	190,106	22,615	4,158,348
Recorde	1,641,142	1,524,775	1,348,021	744,762	190,106	22,615	4,212,168
m^3/month	**32,878,436**	**29,550,332**	**27,195,196**	**5,343,060**	**4156,096**	**226,177**	**100,348,296**

SOURCE: Personal communication to J.R.M. from COMGAS Director, Antonio R. C. de Paula Leite, 1998.

Table 7
Methanol Production Capacity 1995a

REGION	1000 Metric Tonnes/y	EJ/yr (LHV)	Methanol FCV cars fueled (millions)
North America	9550	0.19	9.8
Europe	7280	0.14	7.5
South America	3590	0.07	3.7
Far East and Asia	4680	0.09	4.8
Middle East and Africa	3460	0.07	3.6
WORLD	28,260	0.56	29.0

In 1995 total methanol demand was 23.4 million metric tonnes 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. CMAI 1995 World Methanol Analysis, p. 25.

SOURCE : Ogden et al, 1998a

Table 8a
Electrolysers Characteristics

Manufacturer	Electrolyser CO	Norsk Hydro	De Nora Pernelea	Lurgi Bamag	Teledyne Energy System
Electrolyser model	EI - 250	--	--	--	--
Type	unipolar	bipolar	Bipolar	bipolar	bipolar
Internal Pressure	150 mm of H_2O	100 - 300 mm of H_20	200 mm of H_2O	30 bar	4.2 - 9.1 kg/cm^2
Temperature (°C)	70	75 - 80	75	--	40
Cell voltage	1,85	--	1,9	--	--
Cell efficiency	81%	--	--	--	--
Energy consumption kWh/Nm^3	4.4	4.1 (I 0,1)	4.7	4.3 - 4.6	6.4

SOURCE: de Souza, S.N.M. and E.P. da Silva, 1996a.

Table 8b
Estimated Capital Cost And Efficiency Of Small Electrolyzers

SOURCE	Date Of Estimate	Type	Efficiency (HHV) = H2 out/ AC Elec in	Plant Size (MW H2 out HHV)	H2 out million scf/day (continous operation)	Cost 1994$ $/kW H2 out HHV
LLNL	1994	Alkaline	0.81	2.0	0.48	1076
Ogden & Nitsch	1993	Alkaline	0.81	8.1	1.93	490
Ogden &Williams	1989	Alkaline(Unipolar)	0.60 0.70 0.80	0.025 0.04 0.1-2.0	0.006 0.010 0.024-0.48	2863 1300 416
Fein & Edwards	1984	Alkaline (Bipolar)/PEM	0.56 0.56 0.63 0.80 0.81	0.025 0.04 0.1 0.5 2.0	0.006 0.010 0.024 0.12 0.48	3970 2680 2080 940 495
Hamilton Standard	1994	PEM	0.80	0.0089	0.0021	278
DTI	1994	PEM	0.80	0.0036	0.001	253
LLNL	1994	PEM	0.80	0.0020	0.0005	1249

SOURCE: Based largely on Table 2 of Thomas and Kuhn, 1995, on Ogden and Nitsch, 1993, and on Fein and Edwards, 1984.

Table 9
Energy Balances for Methanol or Hydrogen Production from Natural Gas, Biomass, or Coal

Feedstock ⟹	**Biomass**				**N. Gas**	**Coal**
Process	IGT gasifier	MTCI gasifier	BCL gasifier	Shell gasifier	Steam reforming	Shell gasifier
METHANOL						
Energy Inputs						
Feedstock (GJ/GJ methanol product)	1.77	1.63	1.65	1.48	1.42	1.54
Electricity (kWh/GJ methanol product)						
Pumps	1.12	0.01	0.03	0.30	0.08	0.10
Compressors	8.44	35.38	29.72	7.89	13.05	9.37
Lockhopper	1.53	0.00	0.00	1.03	0.00	0.69
Oxygen	13.20	0.00	0.00	16.56	0.00	18.92
Total	24.29	35.39	29.74	25.77	13.13	29.08
Steam (kg/kg dry feed)	1.02	1.37	0.38	0.92	3.23	1.91
Energy Ratio (ER)[a]	0.566	0.615	0.606	0.677	0.704	0.649
Fraction of Electricity Input From:						
Waste heat	0.615	0.609	0.696	0.309	0.446	0.416
Purge gases	0.000	0.000	0.000	0.154	0.000	0.248
External sources	0.385	0.391	0.304	0.537	0.554	0.336
Thermal Efficiency[b]	0.539	0.568	0.576	0.610	0.674	0.613
HYDROGEN						
Energy Inputs						
Feedstock (GJ/GJ hydrogen product)	1.50	1.32	1.37	1.27	1.11	1.29
Electricity (kWh/GJ hydrogen product)						
Pumps	0.99	0.01	0.04	0.29	0.05	0.11
Compressors	7.77	26.21	22.84	6.21	7.69	8.28
Lockhopper	1.30	0.00	0.00	0.88	0.00	0.58
Oxygen	11.17	0.00	0.00	14.22	0.00	15.87
PSA	11.88	9.23	8.90	11.62	2.75	11.03
Total	33.11	35.45	31.79	33.23	10.49	35.87
Steam (kg/kg dry feed)	1.30	1.37	0.95	1.65	2.66	2.99
Energy Ratio (ER)[a]	0.669	0.759	0.732	0.788	0.897	0.774
Fraction of Electricity Input From:						
Waste heat	0.109	0.033	0.317	0.032	0.219	0.086
Purge gases	0.000	0.000	0.000	0.151	0.000	0.138
External sources	0.891	0.967	0.683	0.817	0.781	0.776
Thermal Efficiency[b]	0.564	0.611	0.636	0.645	0.844	0.640

(a) The energy ratio is defined as: [the energy content (HHV basis) of the product (methanol or hydrogen)]/(the energy content of the feedstock input to the process,excluding any additional feed used for electricity production).

(b) The thermal efficiency is defined as: [the energy content (HHV basis) of the product (methanol or hydrogen)]/(the sum of energy content of all primary-energy inputs to the process). The inputs include the feedstock plus additional feed used to produce the electricity and heat that must be provided from external sources. No external heat addition is required for any of the methanol cases. External cooling is required in the fossil fuel cases.

SOURCE: Williams *et al.*, 1995 (See Appendix B)

Table 10
Energy Balances for Methanol and Hydrogen Production from MSW

Gasifier ==➔	BCL	MTCI	T.S.	BCL	MTCI	T.S.
	HYDROGEN			METHANOL		
MSW feed capacity to plant						
As received (short tons per day)	1392	1490	1444	1392	1490	1444
Dry (short tons per day)	1155	1155	1155	1155	1155	1155
Million Btu per hour	650	628	622	650	628	622
RDF feed capacity to gasifier						
As fed (tons per day)	1157	1239	n.a.	1157	1239	n.a.
Dry (tons per day)	960	960	n.a.	960	960	n.a.
Million Btu per hour	624	603	n.a.	624	603	n.a.
Hydrogen output capacity						
Million Btu per hour	378.8	405.2	467.5			
Million std. cubic feet per day	26.9	28.8	33.2			
Methanol output capacity						
Million Btu per hour				317.5	350.7	401.0
Thousand gallons per day				117.6	129.9	148.5
Electricity balance (MW)						
Required by process	13.0	16.2	26.2	16.3	19.8	27.3
Produced from waste heat	14.8	8.4	7.0	17.5	11.0	9.8
Purchased	-1.8	7.8	19.2	-1.2	8.8	17.5
Overall Energy Performance						
Energy ratio[a]	0.58	0.65	0.75	0.49	0.56	0.64
Thermal efficiency[b]	0.60	0.58	0.59	0.50	0.49	0.51

(a) The energy ratio is defined as the higher heating value (HHV) energy content of the fuel produced divided by the HHV energy content of the raw MSW feed to the plant.

(b) The thermal efficiency is defined as the HHV energy content of the fuel produced divided by the HHV of all energy inputs, including the raw MSW feed and the primary energy that would be needed to generate the purchased electricity. For the latter, for consistency, it is assumed that the electricity would be generated in a gasifier/gas turbine combined cycle using MSW as the gasifier feedstock.

SOURCE: Larson *et al.*, 1996.

Table 11
Primary Resources for Hydrogen, Methanol and Ethanol Production in Brazil, with Associated Maximum Number of Fuel Cell Vehicles that Could be Fueled Therefrom

Resources	Estimated Potential Size of Resource	Fuel Production Potential	Maximum Number of Fuel Cell Vehicles that Could be Fueled
Existing eight industrial hydrogen production sites plus refineries	250,000 Nm^3/d H_2	H_2: 1.17 million GJ/yr	Cars: 83,000 Buses: 870
Brazilian natural gas resources in year 2000 (Petrobras)	53 x 10^6 Nm^3/d gas	H_2: 623 million GJ/yr	Cars: 44.2 million Buses: 460,000
		Meth: 549 million GJ/yr	Cars: 27.0 million Buses: 254,000
Natural gas pipeline from Bolivia to SP (at capacity in year 2000)	20 million m^3/d gas	H_2: 235 million GJ/yr	Cars: 16.7 million Buses: 174,000
		Meth: 207 million GJ/yr	Cars: 10.2 million Buses: 96,000
Off-peak hydropower	1000 to 2000 MW_e	H_2: 25-50 million GJ/yr	Cars: 1.8 - 3.6 million Buses: 19,000 - 37,000
Current Brazilian fuel ethanol production		Eth: 321 million GJ/y	Cars: 15.9 million Buses: 148,000
Excess bagasse in SP state (2% of total bagasse produced)	6.8 million GJ/yr	H_2: 5.0 million GJ/yr	Cars: 350,000 Buses: 3,700
		Meth: 4.1 million GJ/yr	Cars: 203,000 Buses: 1900
Sugarcane tops and leaves in Sao Paulo state (half of total generated)	169 million GJ/yr	H_2: 124 million GJ/yr	Cars: 8.8 million Buses: 92,000
		Meth: 102 million GJ/yr	Cars: 5 million Buses: 47,000
Biomass tree plantations (potential in NE Brazil)	12,600 million GJ/yr	H_2: 9,200 million GJ/yr	Cars: 650 million Buses: 6.8 million
		Meth: 7,600 million GJ/yr	Cars: 380 million Buses: 3.5 million
MSW in Sao Paulo city	25 million GJ/yr	H_2: 15 million GJ/yr	Cars: 1.1 million Buses: 17,000
		Meth: 12 million GJ/yr	Cars: 570,000 Buses: 8,700
World methanol production capacity		Meth: 560 million GJ/yr (28 million tonnes)	Cars: 28 million Buses: 260,000
Excess methanol prod. capacity (7% of total)		Meth: 39.2 million GJ/yr	Cars: 2 million Buses: 18,000
New methanol facility (10,000 tonne per day)		Meth: 74.6 million GJ/yr	Cars: 3.7 million Buses: 35,000
LNG imports	10 million m^3/day gas (Equivalent amount to fuel for 2000 MW_e combined cycle power plant fueled by LNG)	H_2: 118 million GJ/yr	Cars: 8.3 million Buses: 87,000
		Meth: 103 million GJ/yr	Cars: 5.1 million Buses: 48,000

Table 12
Conversion Factors And Economic Assumptions

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

1 million standard cubic feet (scf)
= 26,850 Normal cubic meters (mN^3)
= 343 GJ (HHV)

1 million scf/day = 2.66 tons/day
= 3.97 MW H2 (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 mN_3 = 12.8 MJ (HHV); 1 kg H_2 =141.9 MJ (HHV) = 414 scf

1 gallon gasoline = 130.8 MJ (HHV) = 115,400 BTU/gallon (LHV)
Gasoline Heating value = 45.9 MJ/kg (HHV) = 43.0 MJ/kg (LHV)
$1/gallon gasoline = $7.67/GJ (HHV)

1 gallon methanol = 64,600 BTU/gallon (HHV)
= 56,560 BTU/gallon (LHV)
Methanol Heating value = 22.7 MJ/kg (HHV) = 19.9 MJ/kg (LHV)
$1/gallon methanol = $15.4/GJ (HHV)

All costs are given in constant $1993.

Capital recovery factor for H_2 production systems, distribution systems, and refueling stations = 15%

SOURCE : Ogden et al, 1998a

Table 13
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 80 FC Buses/day	Total fleet of 8900 FCV cars Total fleet of 140 FCV Buses

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

Hydrogen use per day per FCV (scf H_2/day) =
Annual mileage (mi)/365 days/yr /Equiv. Fuel Economy (mi/gallon gasoline equiv. energy)
x Gasoline HHV (GJ/gallon)/ H2 HHV (GJ/scf)

For a passgenger car
Annual mileage = 11,400 miles
Equiv. fuel economy = 106 mpg gasoline equiv. (HHV basis)
Gasoline HHV = 0.1308 GJ/gallon
Hydrogen HHV = 343 kJ/scf

Hydrogen use per day (scf/day) for an average passenger car =
= 11400 mi/yr/(365 day/yr x 106 mpg) x (0.1308 GJ/gallon/.000343 GJ/scf H_2)
= 112 scf/day

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

1 million scf/day/ (112 scf/day/car) = 8900 cars

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

We assume that the vehicles refuel when the tank is close to empty. If the range of the vehicle is known, we can estimate how many times it must refuel per year, and how many vehicles are refueled on average per day.

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

For a passenger car, the number of cars fueled per day at a station dispensing 1 million scf H_2/day would be

Cars refueled per day = 11400 mi/425 mi/365 day/yr x 8900 cars = 654 cars/day

SOURCE : Ogden et al, 1998a

Table 14
Projected Capital Cost Of Methanol Refueling Infrastructure Development

ITEM	COST
Convert Gasoline Refueling Station to Methanol	$45,000/station(a) (for a station dispensing 1100 gallons MeOH/day)
Methanol Delivery truck	No cost (use existing gasoline trucks)(a) $140,000 (per new 8500 gallon MeOH truck)(a)
Marine Terminal Bulk Storage Tank for Methanol (for a terminal with 1.3 million bbl storage = 20 days storage)	$2.50/bbl MeOH (convert gasoline storage) (a) $15/bbl MeOH (build new MeOH storage)(a)
Other terminal equipment	$1/bbl MeOH (a)
Methanol Overseas Shipping Costs	Capital cost for new 250,000 dwt tanker = $50 million (d) trans cost= 3-5 cents/gallon (b, c)
Methanol Production Plant (from NG)	$880-1540 million(c) (10,000 metric tonnes/day) $330-570 million (c) (2500 metric tonne/day)

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.

SOURCE : Ogden et al, 1998a

Table 15
Capital Cost Of Methanol Infrastructure Per Car

ITEM	CAPITAL COST	#CARS SERVED	CAPITAL COST PER CAR ($/CAR)	CAPITAL COST PER CAR (1995$ PER CAR)
Refueling station conversion (1100 gallons/day) (1990$)	$45,000	1244	36	42
Marine Terminal Conversion (1990$)	@$18.5/bbl storage capacity 6500 barrels (minumum)	2.4 cars/bbl of storage capacity 15,400 cars (minimum)	8	9
Tanker Shipping Capacity (1986$)	$200/dead weight ton for a new 250,000 dwt ultra large tanker	3-15 million cars (if tanker makes 10-50 deliveries/yr)	$3-17	4-25
New Production Capacity (1988$)	$880-1540 million (10,000 metric tonnes/day) $330-570 million (2500 metric tonnes/day)	3.8 million cars 0.94 million cars	230-400 350-600	290-500 440-750

SOURCE : Ogden et al, 1998a

Table 16
Estimated Production Costs (In 1991$) for Methanol from Biomass, Natural Gas, and Coal

FEEDSTOCK 6	BIOMASS				N. GAS	COAL
PROCESS 6	IGT gasifier	MTCI gasifier	BCL gasifier	Shell gasifier	Steam reforming	Shell gasifier
Feedstock input capacity						
Dry tonnes/day	1650	1650	1650	1650	1224	5000
GJ/hour	1326	1334	1338	1326	2700	6188
Output production capacity (a)						
Tonnes/day	794	868	858	950	2012	4252
GJ/hour	750	820	811	897	1901	4016
Annual feed and output						
Feed (106 GJ/year)	10.45	10.52	10.55	10.45	21.29	48.79
Product output (10^6 GJ/year)	5.91	6.47	6.39	7.07	14.99	31.66
Installed Equipment Costs (10^6 $)						
Feed preparation, including drying (b)	17.32	13.21	13.17	38.78	0.00	67.96
Gasifier (c)	29.74	33.72	12.72	29.74	0.00	120.06
High temperature gas cooling (d)	0.00	0.00	0.00	39.67	0.00	113.27
Oxygen plant (e)	21.55	0.00	0.00	28.77	0.00	95.42
Sulfur removal (f)	0.00	0.00	0.00	0.00	0.00	36.25
Reformer feed compressor (g)	0.00	15.94	11.88	0.00	0.00	0.00
Reformer (h)	21.39	0.00	17.20	0.00	50.00	0.00
Shift reactor (i)	1.98	0.00	2.00	0.00	0.00	0.00
CO2 removal (j)	20.20	15.38	14.34	22.05	0.00	59.50
Methanol synthesis & purification (k)	35.87	38.05	37.75	40.37	66.25	108.54
Steam turbine cogeneration plant (l)	17.18	22.85	22.12	16.70	17.11	57.67
Utilities/auxiliaries (m)	41.31	34.79	32.80	54.02	33.34	164.67
Subtotal	206.55	173.95	163.98	270.09	166.69	823.33
Contingencies (n)	41.31	34.79	32.80	54.02	33.34	164.67
Owners costs, fees, profits (n)	20.65	17.39	16.40	27.01	16.67	82.33
Startup (o)	10.33	8.70	8.20	13.50	8.33	41.17
Total Capital Requirement (10^6 $)	278.84	234.83	221.37	364.62	225.04	1111.49
Working Capital (n)(10^6 $)	20.65	17.39	16.40	27.01	16.67	82.33
Land(p) (10^6 $)	2.08	2.08	2.08	2.08	4.26	7.40
Variable Operating Costs (10^6 $/year)						
Feed (q)	20.90	21.03	21.10	20.90	87.28	70.74
Catalysts and chemicals (r)	1.67	0.67	2.24	0.67	2.58	10.87
Purchased energy (s)	2.77	4.47	2.89	4.90	5.45	15.47
Subtotal	25.33	26.17	26.23	26.46	95.30	97.07
Fixed Operating Costs (10^6 $/year)						
Labor (t)	1.08	1.08	1.08	1.08	1.00	3.14
Maintenance (u)	6.20	5.22	4.92	8.10	5.00	24.70
General Overhead	4.73	4.10	3.90	5.97	3.90	18.09
Direct Overhead	0.49	0.49	0.49	0.49	0.45	1.41
Subtotal	12.50	10.88	10.39	15.64	10.35	47.34
Total Operating Costs (10^6 $/year)	37.83	37.06	36.62	42.11	105.65	144.41
PRODUCTION COST ($/GJ of CH_3OH)						
Capital (v)	7.50	5.78	5.52	8.19	2.41	5.58
Labor & maintenance	2.40	1.79	1.98	2.31	0.86	1.84
Purchased energy	0.47	0.69	0.45	0.69	0.36	0.49
Feedstock	3.53	3.25	3.30	2.95	5.82	2.23
TOTAL PRODUCTION COST	13.90	11.51	11.24	14.14	9.46	10.14
Natural gas price ($/GJ) for same total cost (w)	7.23	5.55	5.36	7.40	4.10	4.58
Biomass price($/GJ)for same total cost as coal (x)	-0.12	1.16	1.33	-0.71	n.a.	n.a.

SOURCE : Williams et al, 1995. (Appendix B, which includes notes for this table)

Table 17
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

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.

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.

A study by Directed Technologies for the USDOE estimated a cost in mass production of $2712 for a hydrogen/air fuel cell plus auxiliaries with net output of 85 kW power (about $32/kW). Directed Technologies is now working with Ford Motor Company on fuel cell vehicles as part of the PNGV program. (Ref: B.D. James, G.N. Baum and I.F. Kuhn, Directed Technologies, Inc. "Technology Development Goals for Automotive Fuel Cell Power Systems," prepared for the Electrochemical Technology Division, Argonne National Laboratory, Contract No. W-31-109-Eng-28, February 1994.)

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

SOURCE : Ogden et al, 1998a

Table 18

Comparison of lifecycle costs for hydrogen fuel cell bus and conventional diesel bus, based on current New York City public diesel bus fleet characteristics and projected performance and costs of Ballard hydrogen fuel cell buses.

	Diesel Engine Bus	**Hydrogen Fuel Cell Bus**
Fuel economy (a)	1.35 km/liter diesel	0.75 km/Nm^3 hydrogen
MJ/km (b)	28.6	16.7
km/liter diesel equivalent	1.35	2.31
Purchase price (1997$) (c)	250,625	343,021
Levelized annual maintenance cost (1997$/year) (d)	7,456	4,970
Bus lifetime (years) (e)	12	18
Annual bus travel (km/year) (e)	40,000	40,000
Assumed discount rate (%/yr)	10	10
Capital charge rate (f)	0.147	0.122
Levelized total lifecycle cost (1997$ per bus-km)		
Capital	0.920	1.05
O&M	0.186	0.124
Fuel, where P = fuel price in $1997/GJhhv	$0.0286xP_d$	$0.0167xP_h$
TOTAL ($/bus-km)	$1.11 + 0.0286xP_d$	$1.17 + 0.0167xP_h$

(a) The diesel engine bus fuel economy is the current New York City average [Pellegrin, 1995], which is relatively low because of the slow average speeds in Manhattan: 5.8 km/hr. The fuel economy for the fuel cell bus is assumed to be the mid-point of the range estimated by Howard [1995] for a Ballard hydrogen/PEM fuel cell bus on an urban drive cycle.

(b) Higher heating value of diesel is 38.7 MJ/liter. Higher heating value of hydrogen is 12.6 MJ/Nm^3.

(c) The capital cost for the diesel bus is based on a recently contracted price for diesel buses by the New York City Transit Authority [Pellegrin, 1995]. The capital cost for the fuel cell bus is a preliminary estimate for mass production of a commercially mature hydrogen/PEM fuel cell bus from Ballard [Howard, 1995]. The market entry price for the fuel cell bus (production of about 100 units) is estimated to be $575,000 to $690,000 [Howard, 1995].

(d) For the diesel bus, these are O&M costs based on the standard maintenance schedule, procedures, and replacement parts of the New York City Transit Authority, assuming (in 1997$) a cost of $42.1/person-hour (which includes administrative and other overhead and indirect costs), and maintenance consisting of monthly inspections (41 person-hours/year and negligible parts costs), a suspension system and body upgrade after 3 years (112 p-h and $5775 in parts), a major overhaul of the transmission and engine after 6 years (140 p-h and $46200 in parts), and a suspension and body upgrade after 9 years (112 p-h and $5775 in parts). Estimates of the O&M costs for the fuel cell bus are uncertain at this time, but are likely to be lower than for a diesel engine bus because of fewer moving parts, lower operating temperatures, and less vibration. Levelized O&M cost for the fuel cell bus are assumed to be

(e) The assumed bus lifetimes of 12 years for the diesel and 18 years for the fuel cell correspond to the replacement schedule authorized by the U.S. Federal Transit Authority (FTA) for diesel and electric-trolley buses, respectively. The FTA, which provides funds to urban transit authorities for purchase of buses, authorizes bus retirement after 12 years operation, over which time it is assumed that an average of 500,000 miles would be traveled. The FTA standard for electric trolley buses is 18 years/750,000 miles. These standards imply an average annual mileage of 41,700 miles. The average annual travel distance per bus in New York City is only about 25,000 miles [Pellegrin, 1995], because bus speeds there are slower than the average for U.S. urban areas.

(f) The capital charge rate is $i/[1-(1+i)^{-N}]$, where i is the assumed discount rate and N is the amortization period in years, which is assumed equal to the bus lifetime.

SOURCE: Adapted from Larson, et al. (1996).

Figure 1
Fuels for Fuel Cell Vehicles

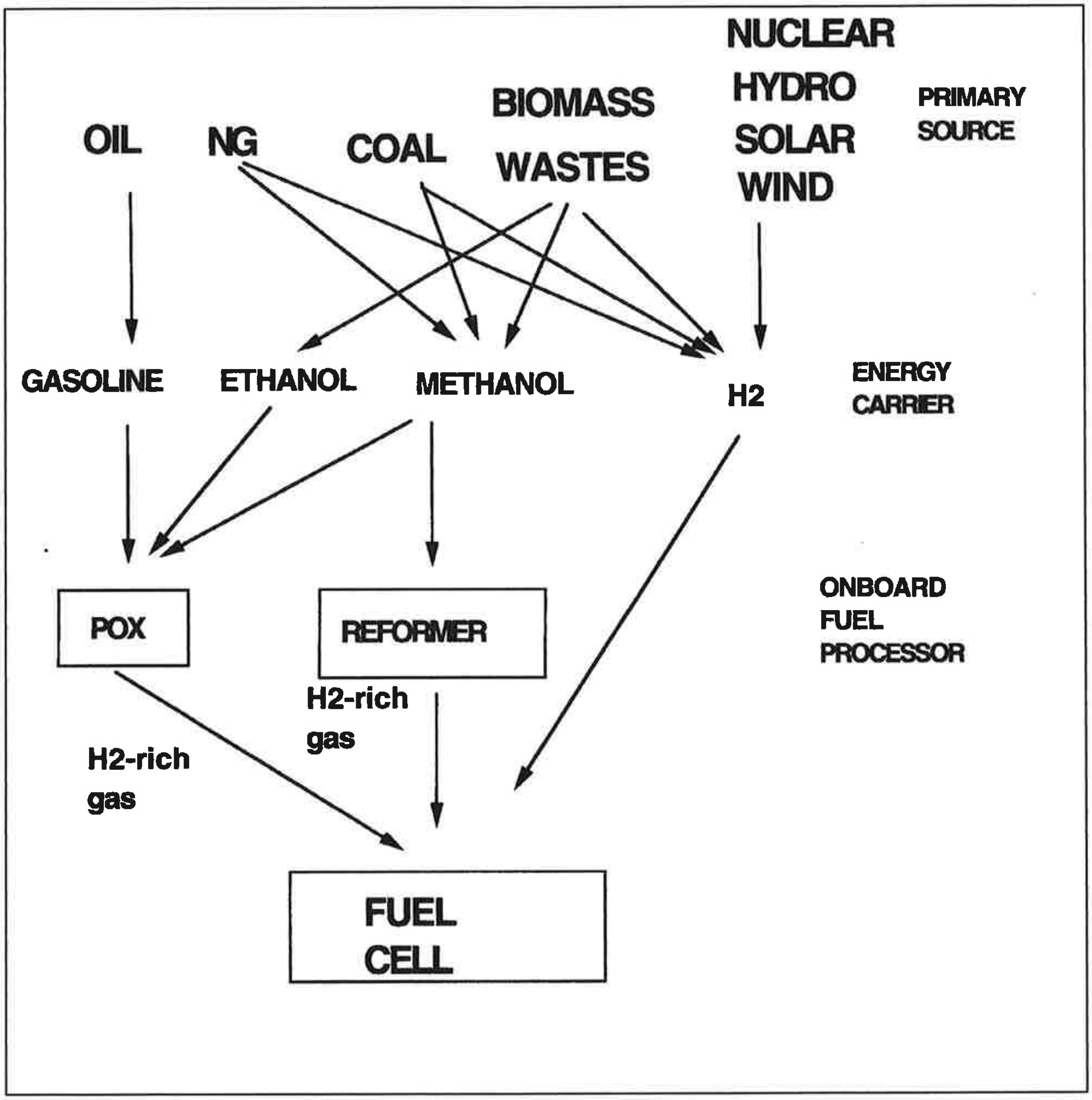
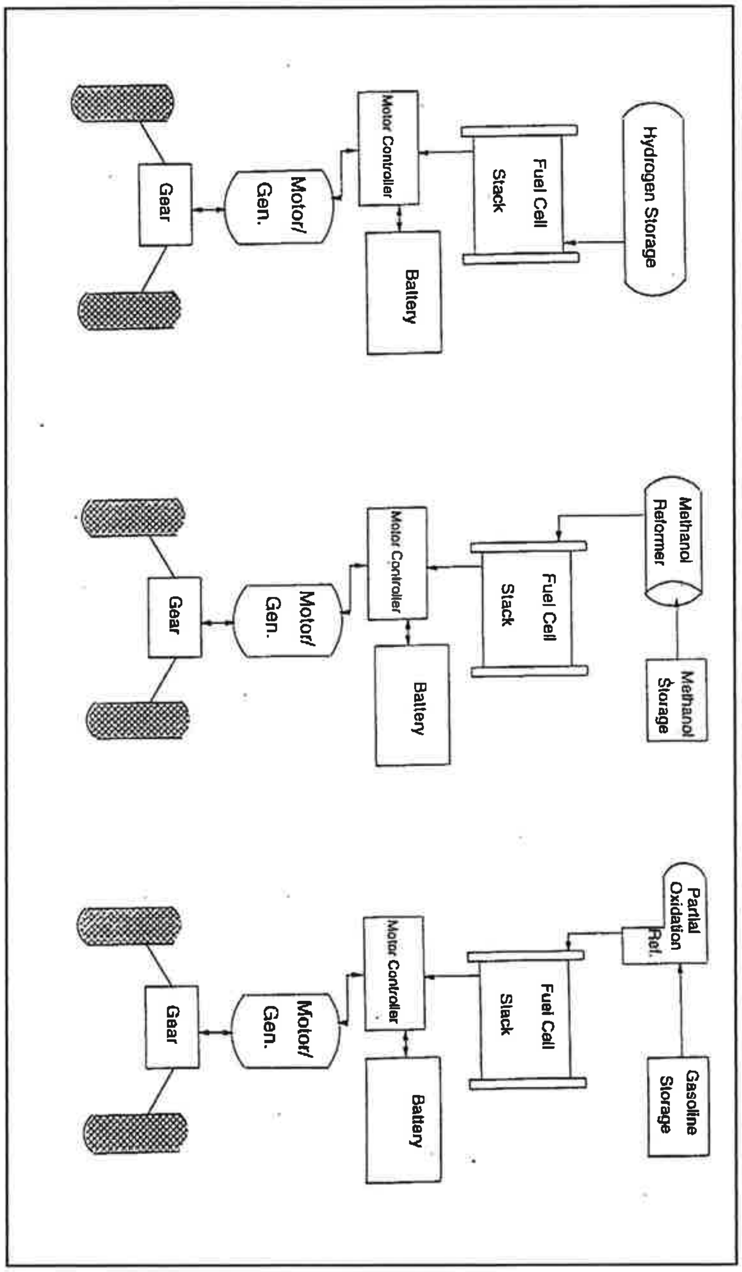
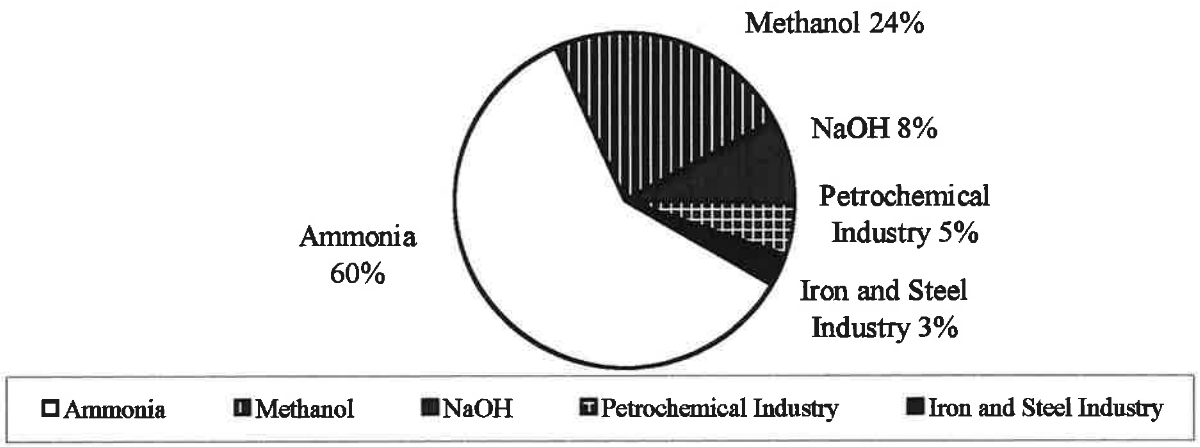


Figure 2
Possible Fuel Cell Vehicle Configurations



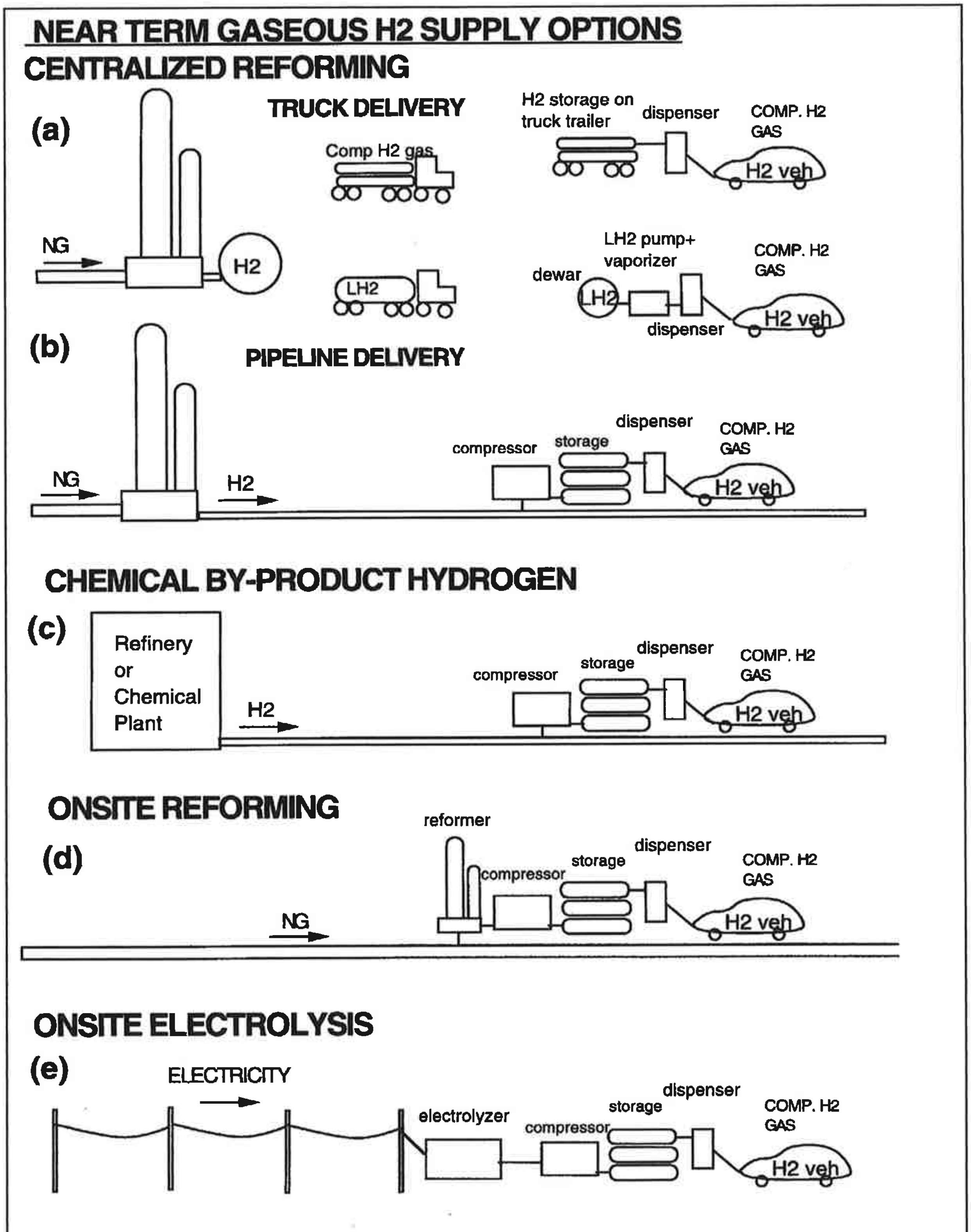
SOURCE : Ogden et al, 1998a

Figure 3
Brazilian Market Composition of H2 in 1994



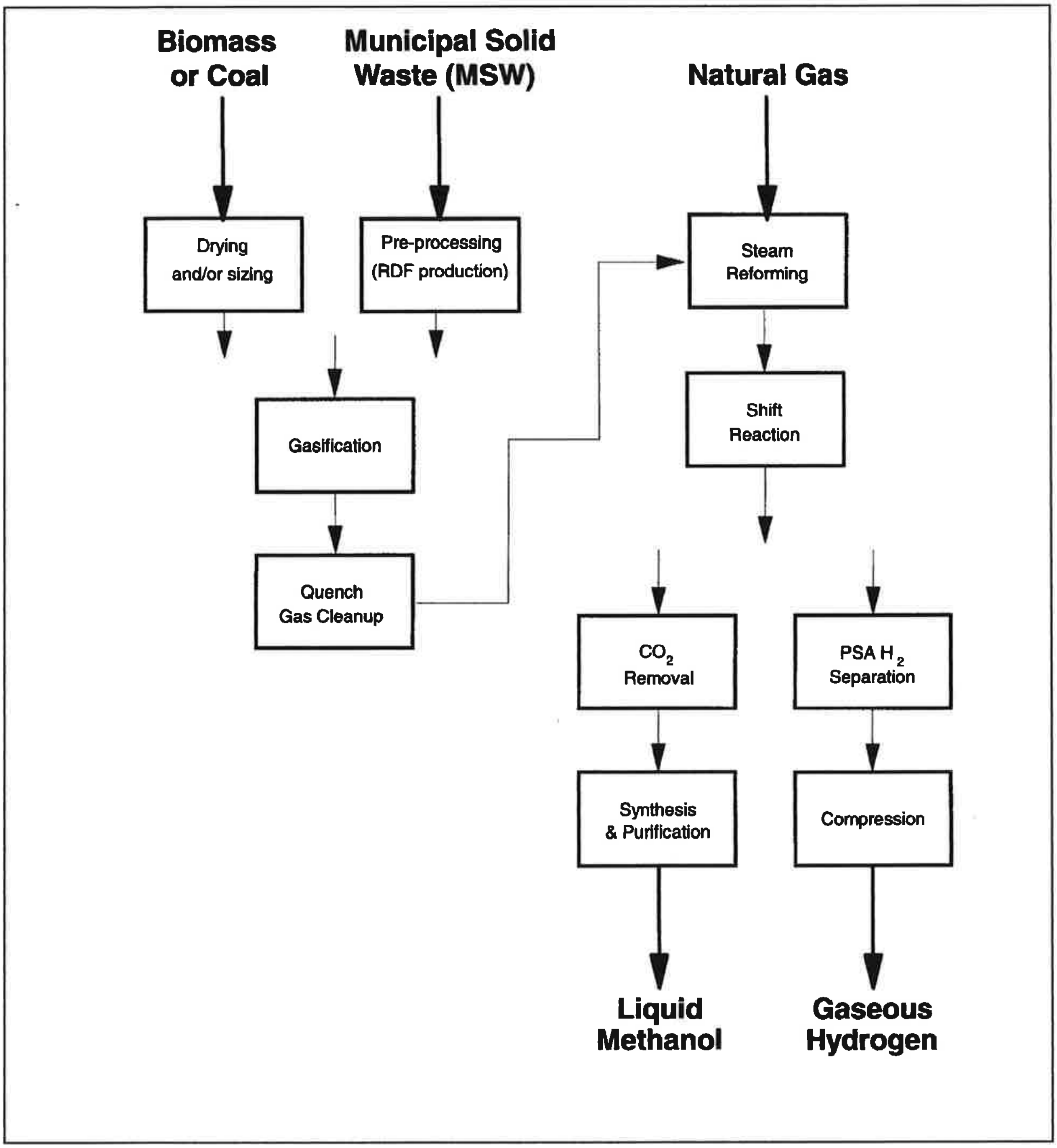
Source : See Table 6

Figure 4



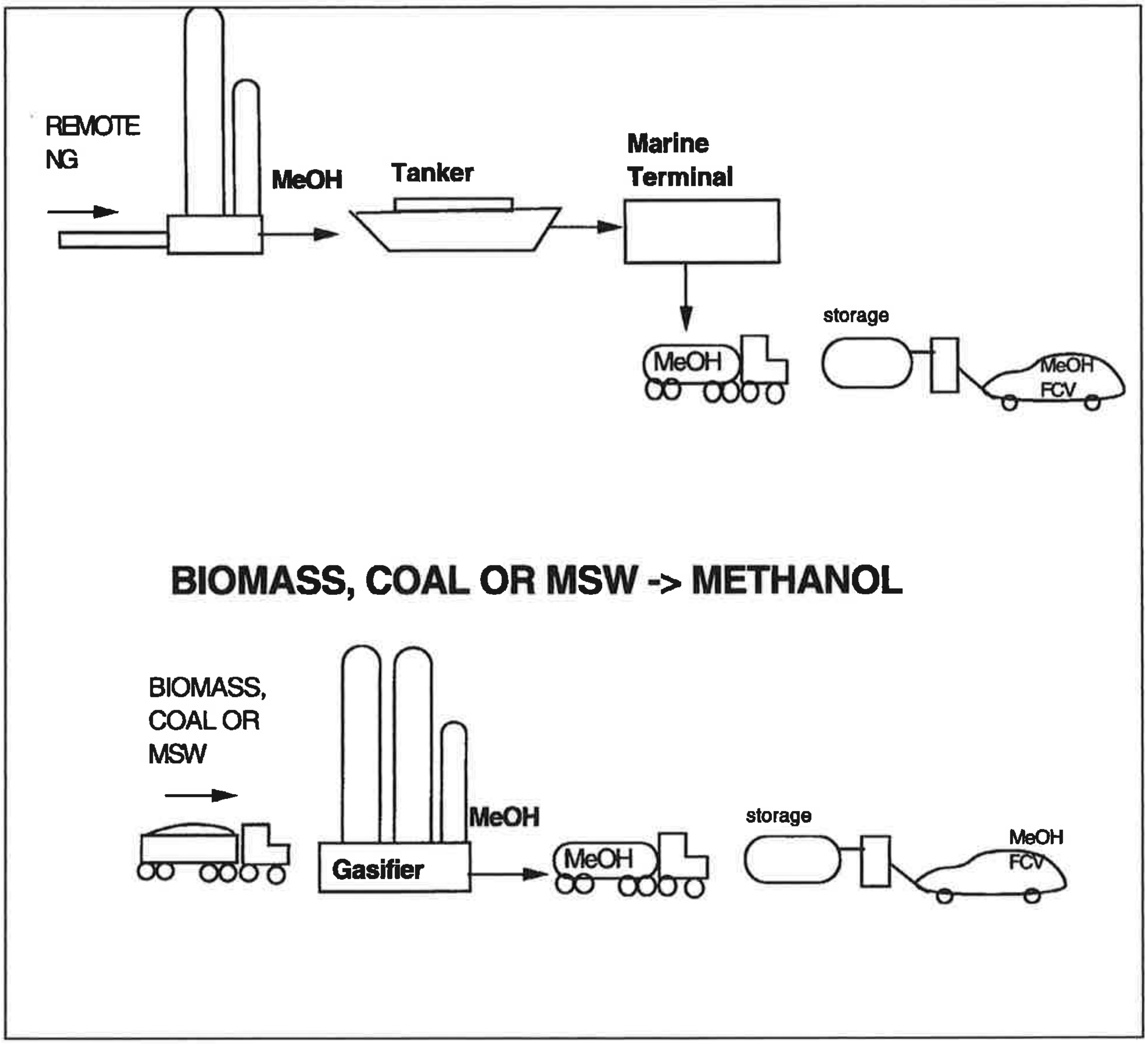
SOURCE : Ogden et al, 1998a

Figure 5
Thermochemical Conversion of Biomass, MSW, Coal, or Natural Gas to Methanol or Hydrogen



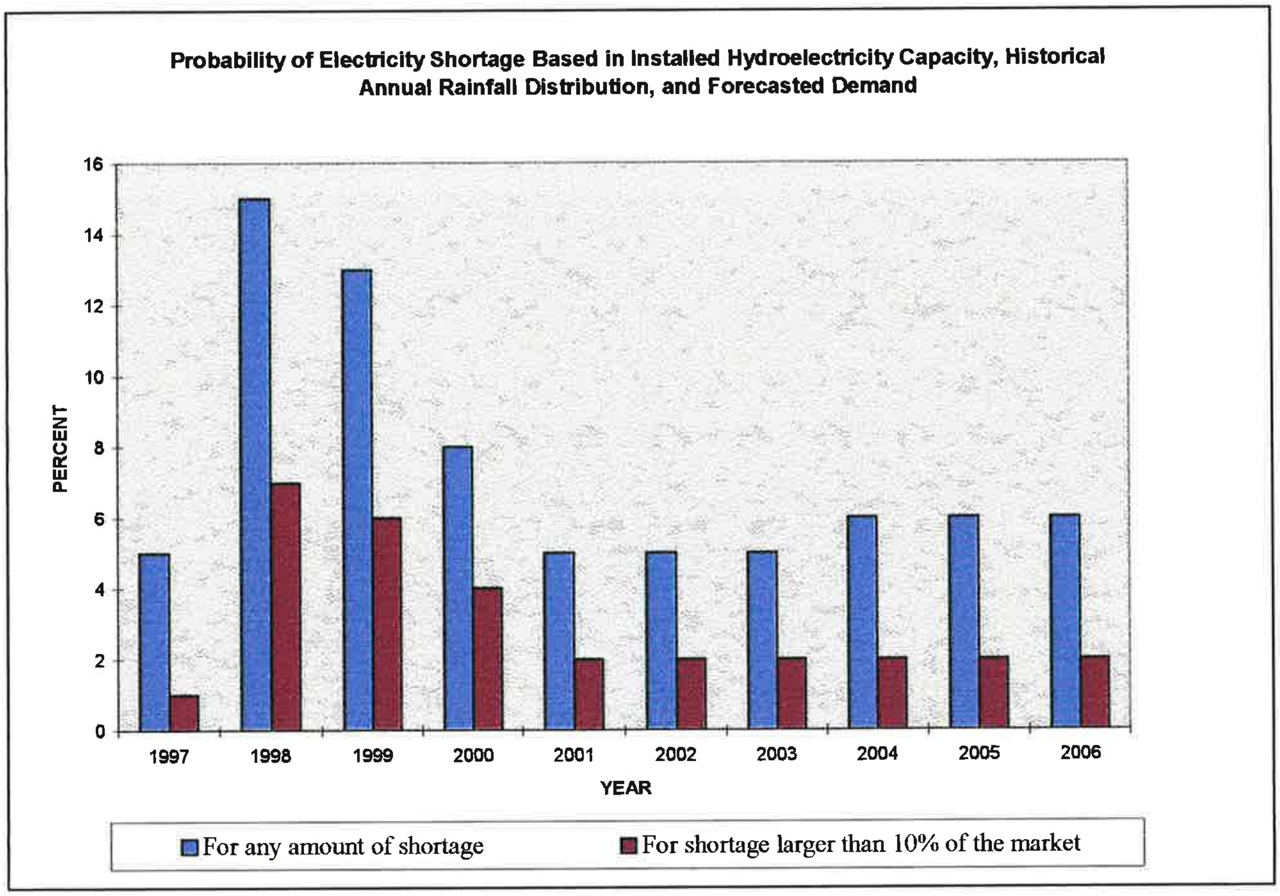
SOURCE : Adapted from Larson et al, 1996

Figure 6
Methanol Supply Options



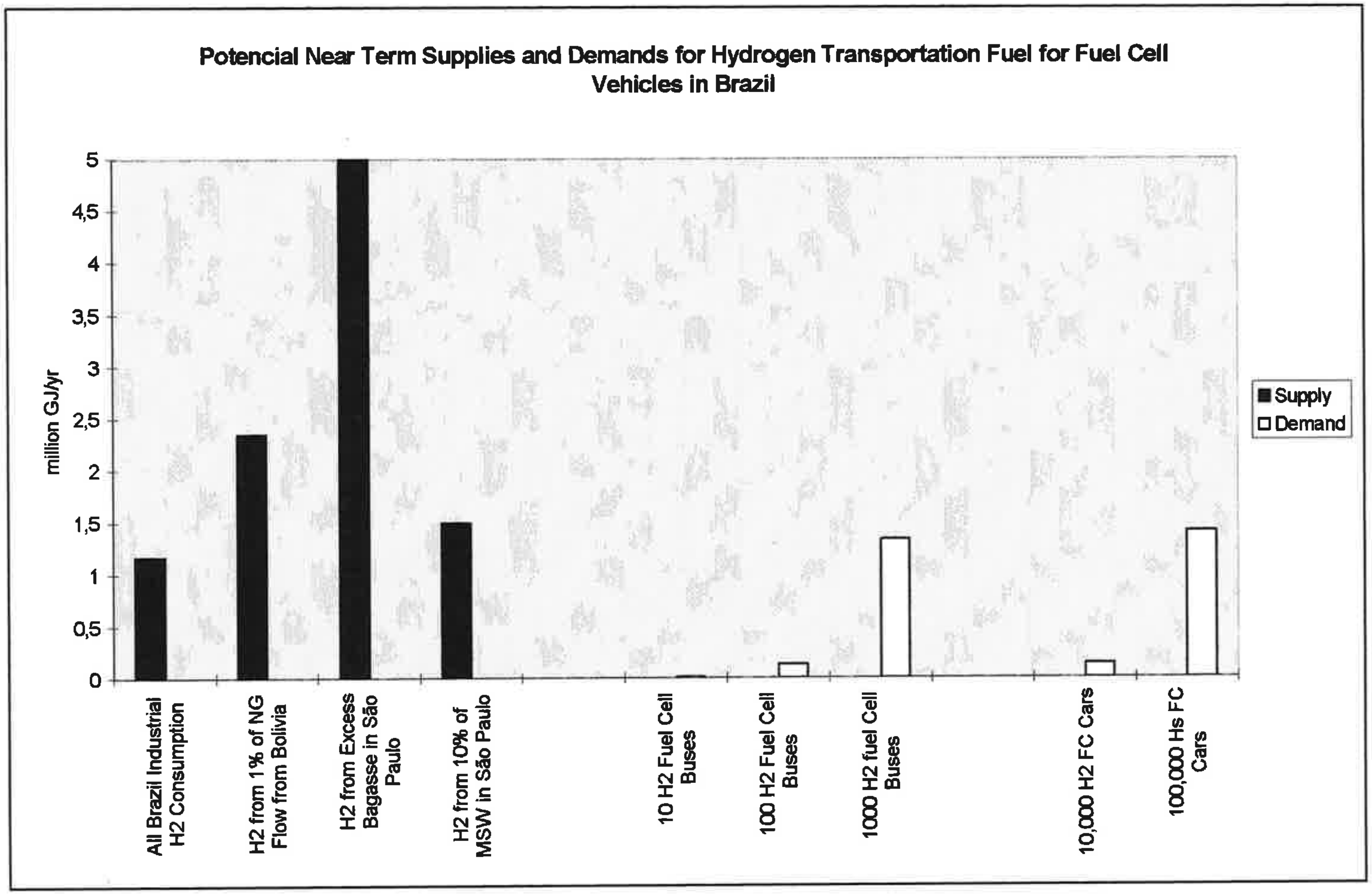
SOURCE : Ogden et al, 1998a

Figure 7
Future Hydroelectricity Shortage Patterns



SOURCE : ELETROBRAS, 1997

FIGURE 8a



Potencial Near Term Supplies and Demands for Hydrogen Transportation Fuel for Fuel Cell Vehicles in Brazil
million GJ/yr
5
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
Supply
Demand
All Brazil Industrial H2 Consumption
H2 from 1% of NG Flow from Bolivia
H2 from Excess Bagasse in São Paulo
H2 from 10% of MSW in São Paulo
10 H2 Fuel Cell Buses
100 H2 Fuel Cell Buses
1000 H2 fuel Cell Buses
10,000 H2 FC Cars
100,000 Hs FC Cars

FIGURE 8b

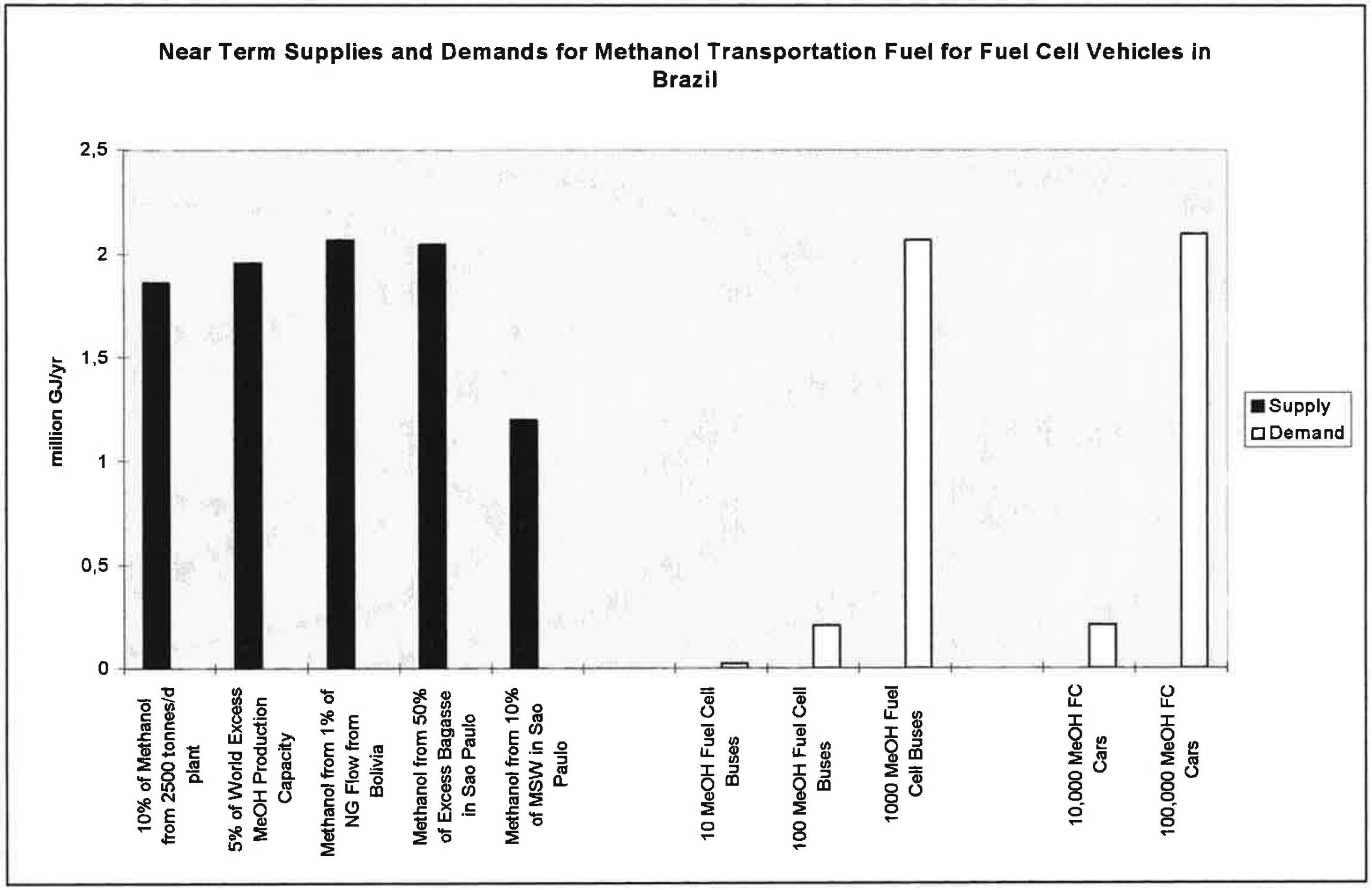

Near Term Supplies and Demands for Methanol Transportation Fuel for Fuel Cell Vehicles in Brazil
million GJ/yr
2,5
2
1,5
1
0,5
0
10% of Methanol from 2500 tonnes/d plant
5% of World Excess MeOH Production Capacity
Methanol from 1% of NG Flow from Bolivia
Methanol from 50% of Excess Bagasse in Sao Paulo
Methanol from 10% of MSW in Sao Paulo
10 MeOH Fuel Cell Buses
100 MeOH Fuel Cell Buses
1000 MeOH Fuel Cell Buses
10,000 MeOH FC Cars
100,000 MeOH FC Cars
Supply
Demand

FIGURE 8c

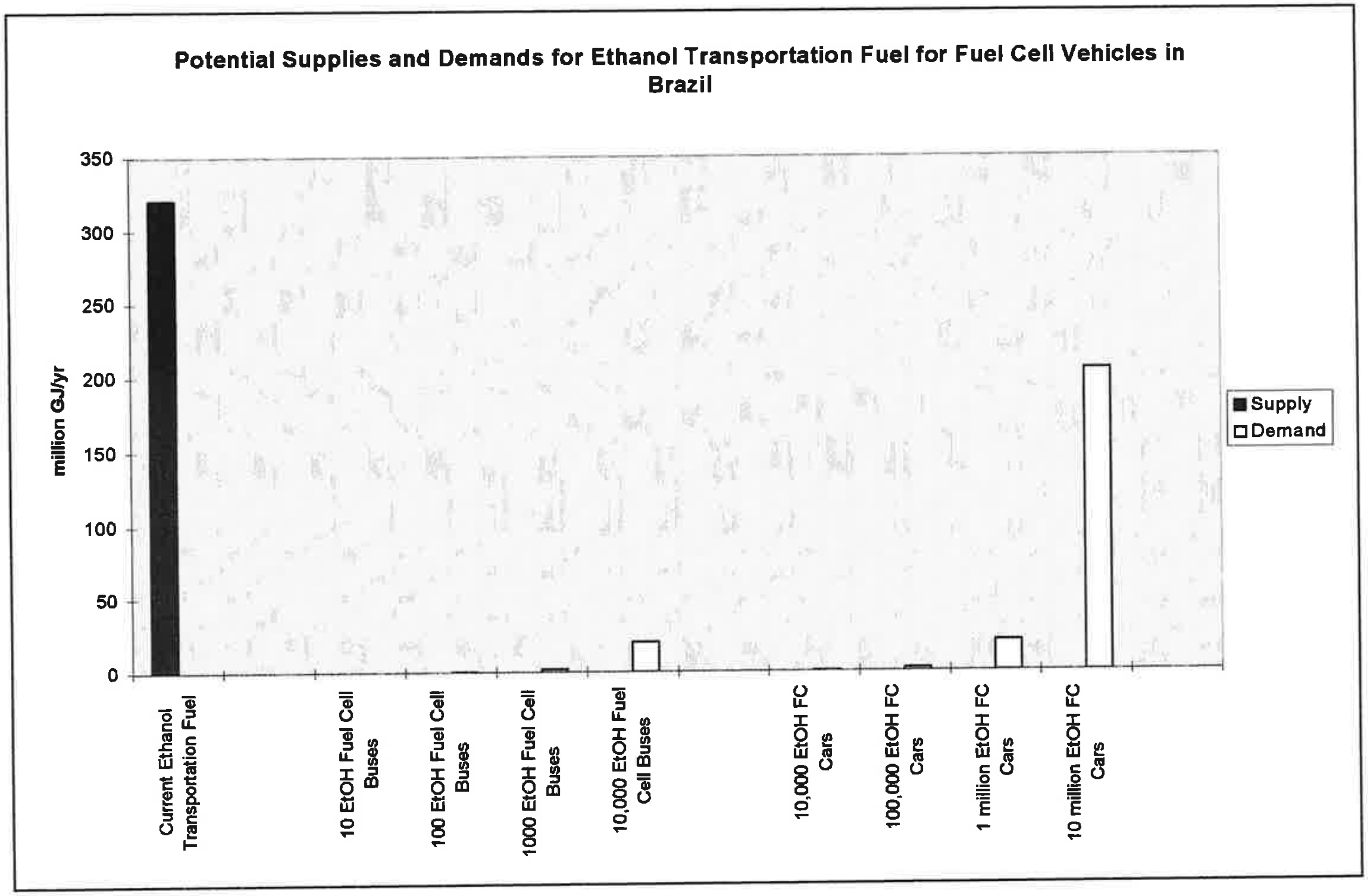
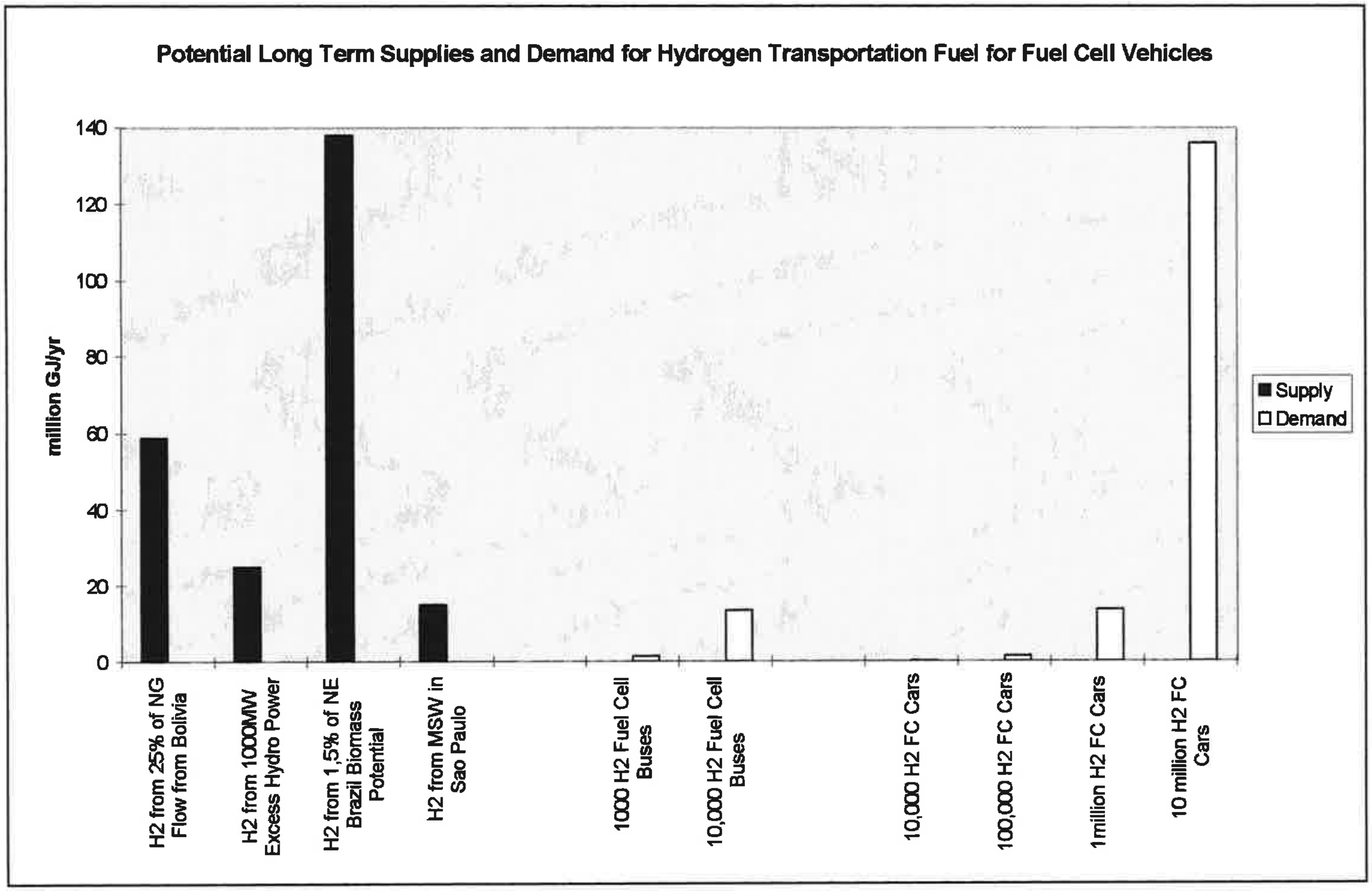
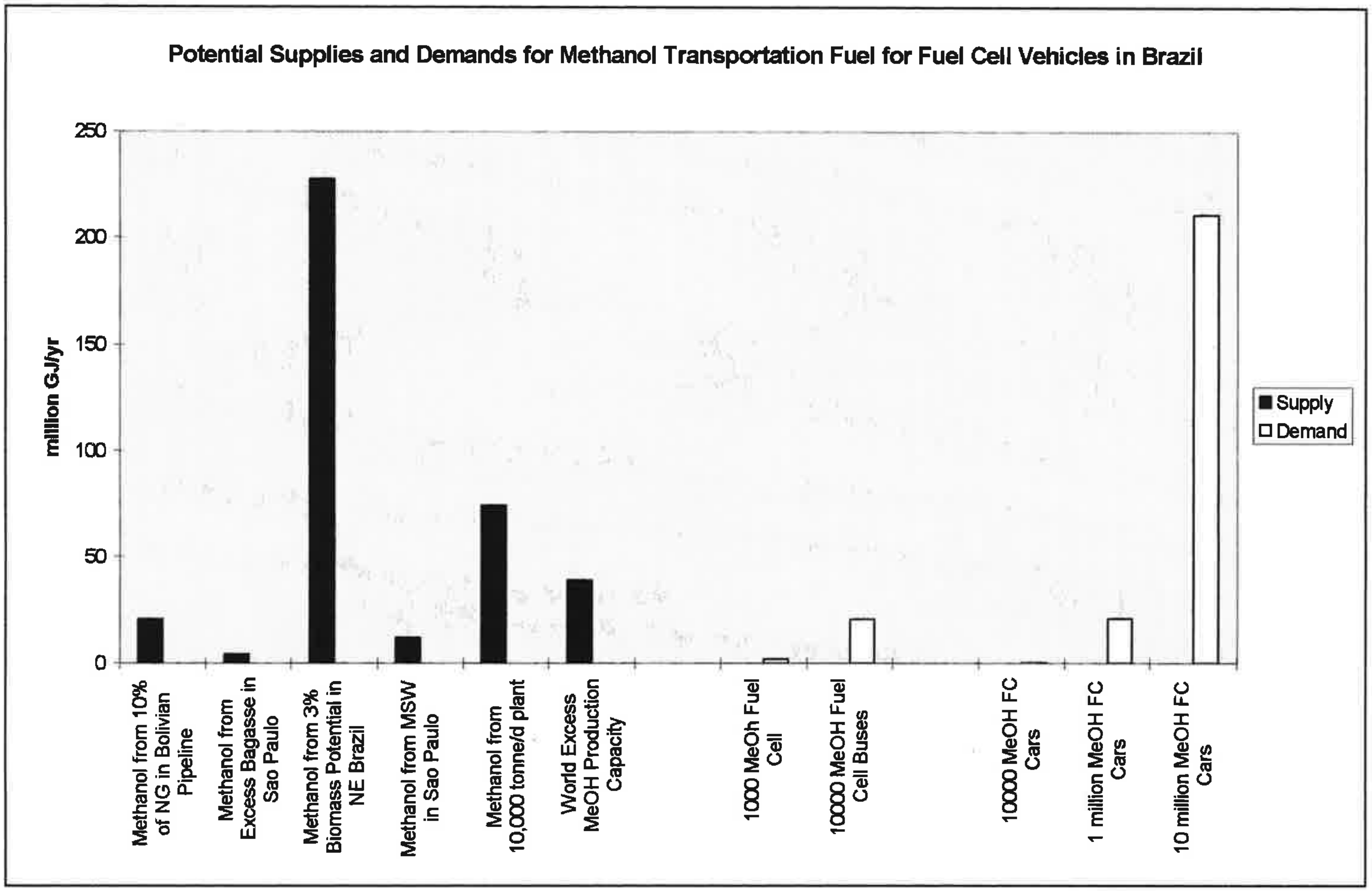

Potential Supplies and Demands for Ethanol Transportation Fuel for Fuel Cell Vehicles in Brazil
million GJ/yr
350
300
250
200
150
100
50
0
Current Ethanol Transportation Fuel
10 EtOH Fuel Cell Buses
100 EtOH Fuel Cell Buses
1000 EtOH Fuel Cell Buses
10,000 EtOH Fuel Cell Buses
10,000 EtOH FC Cars
100,000 EtOH FC Cars
1 million EtOH FC Cars
10 million EtOH FC Cars
Supply
Demand

FIGURE 8d



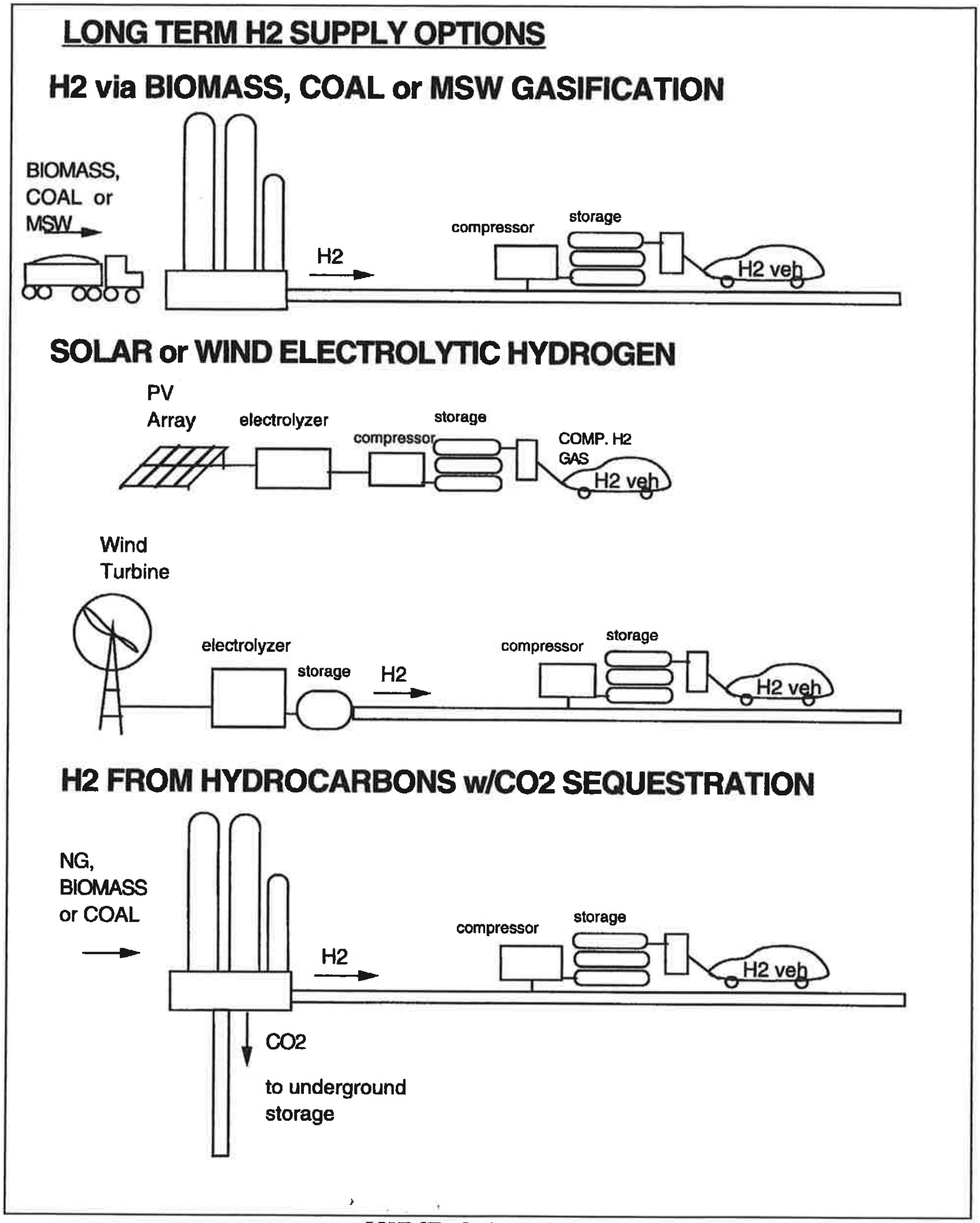
Potential Long Term Supplies and Demand for Hydrogen Transportation Fuel for Fuel Cell Vehicles
million GJ/yr
140
120
100
80
60
40
20
0
H2 from 25% of NG Flow from Bolivia
H2 from 1000MW Excess Hydro Power
H2 from 1,5% of NE Brazil Biomass Potential
H2 from MSW in Sao Paulo
1000 H2 Fuel Cell Buses
10,000 H2 Fuel Cell Buses
10,000 H2 FC Cars
100,000 H2 FC Cars
1million H2 FC Cars
10 million H2 FC Cars
Supply
Demand

FIGURE 8e



Potential Supplies and Demands for Methanol Transportation Fuel for Fuel Cell Vehicles in Brazil
million GJ/yr
250
200
150
100
50
0
Supply
Demand
Methanol from 10% of NG in Bolivian Pipeline
Methanol from Excess Bagasse in Sao Paulo
Methanol from 3% Biomass Potential in NE Brazil
Methanol from MSW in Sao Paulo
Methanol from 10,000 tonne/d plant
World Excess MeOH Production Capacity
1000 MeOh Fuel Cell
10000 MeOH Fuel Cell Buses
10000 MeOH FC Cars
1 million MeOH FC Cars
10 million MeOH FC Cars

Figure 9



SOURCE : Ogden et al, 1998a

Figure 10
Delivered Cost of Hydrogen Transportation Fuel ($/GJ) vs Station Size

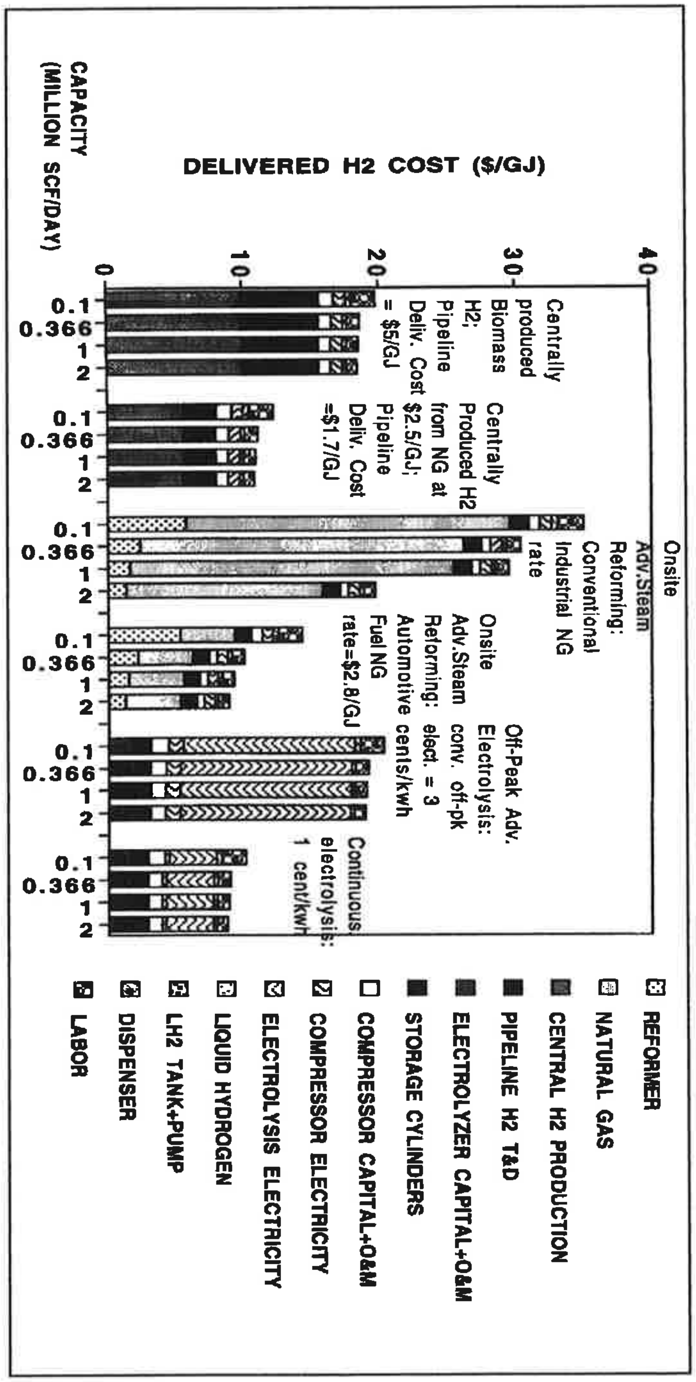
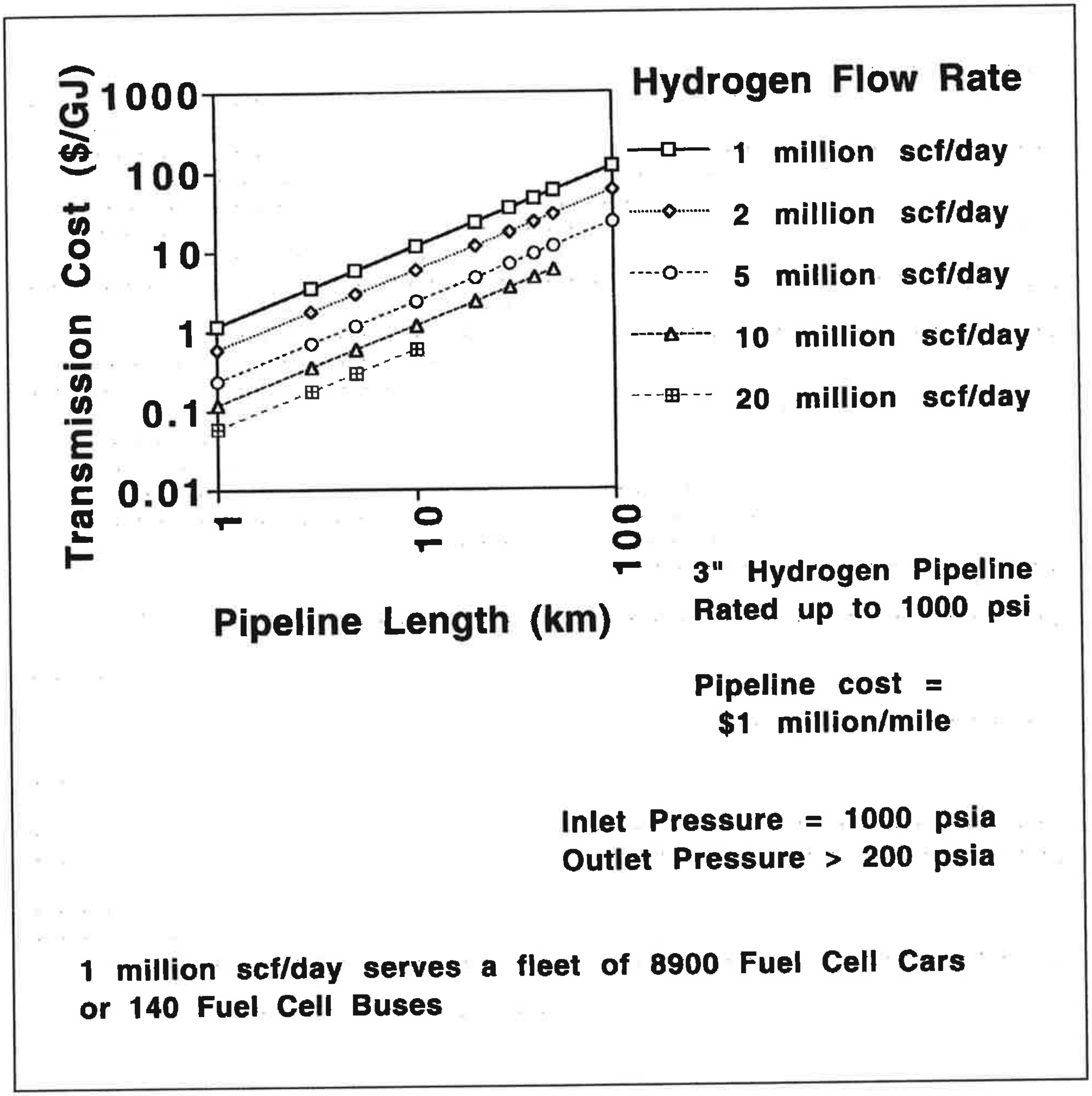


Figure11
Cost of Hydrogen Pipeline Transmission vs Pipeline Length and Flow Rate



SOURCE: Ogden et al, 1998a

Figure 12
Delivered Cost of Transportation Fuels from Various Primary Sources ($/GJ)

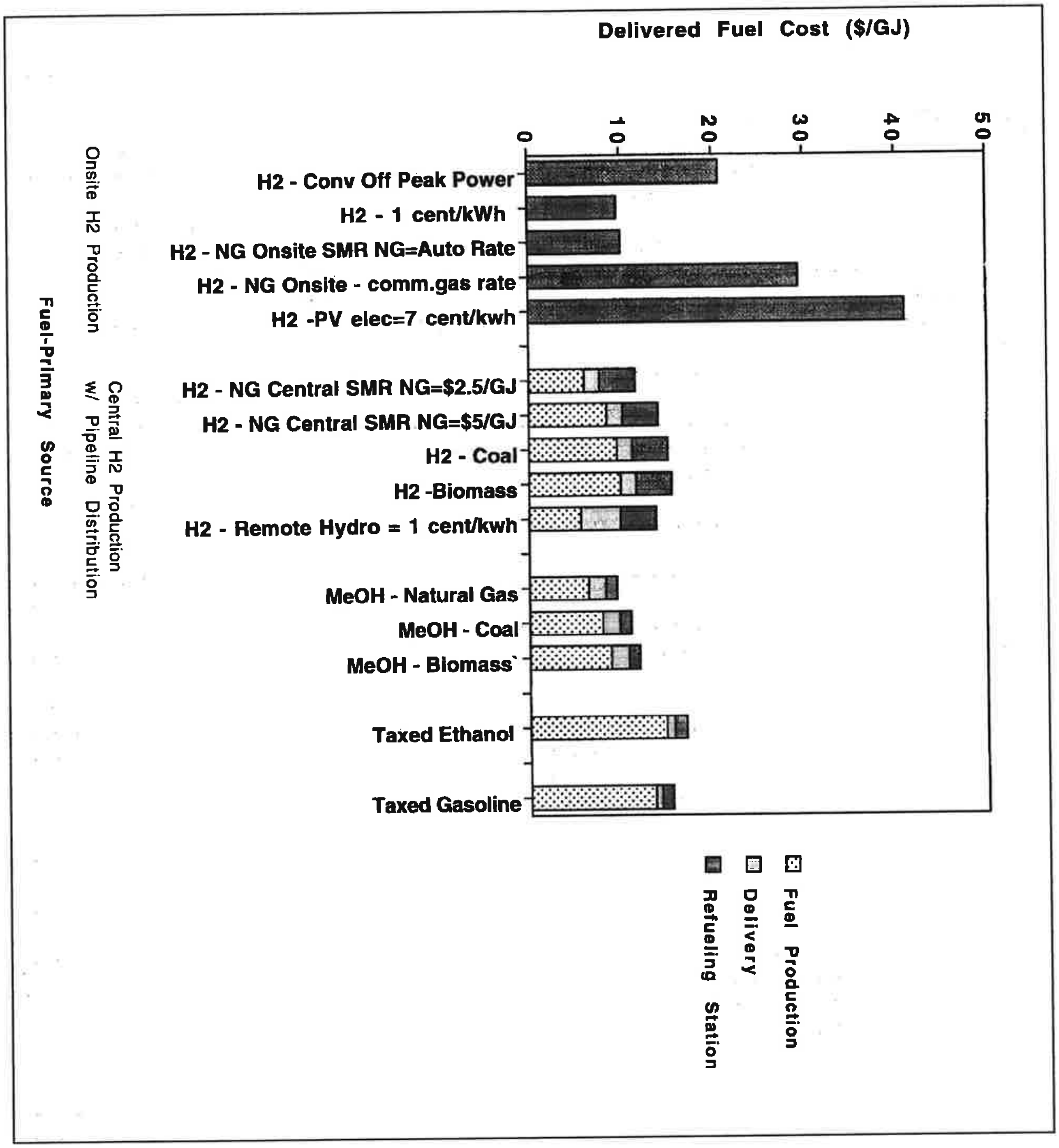


Figure 13
Fuel Cost per km for Fuel Cell Automobiles for Various Fuels and Primary Sources ($/km)

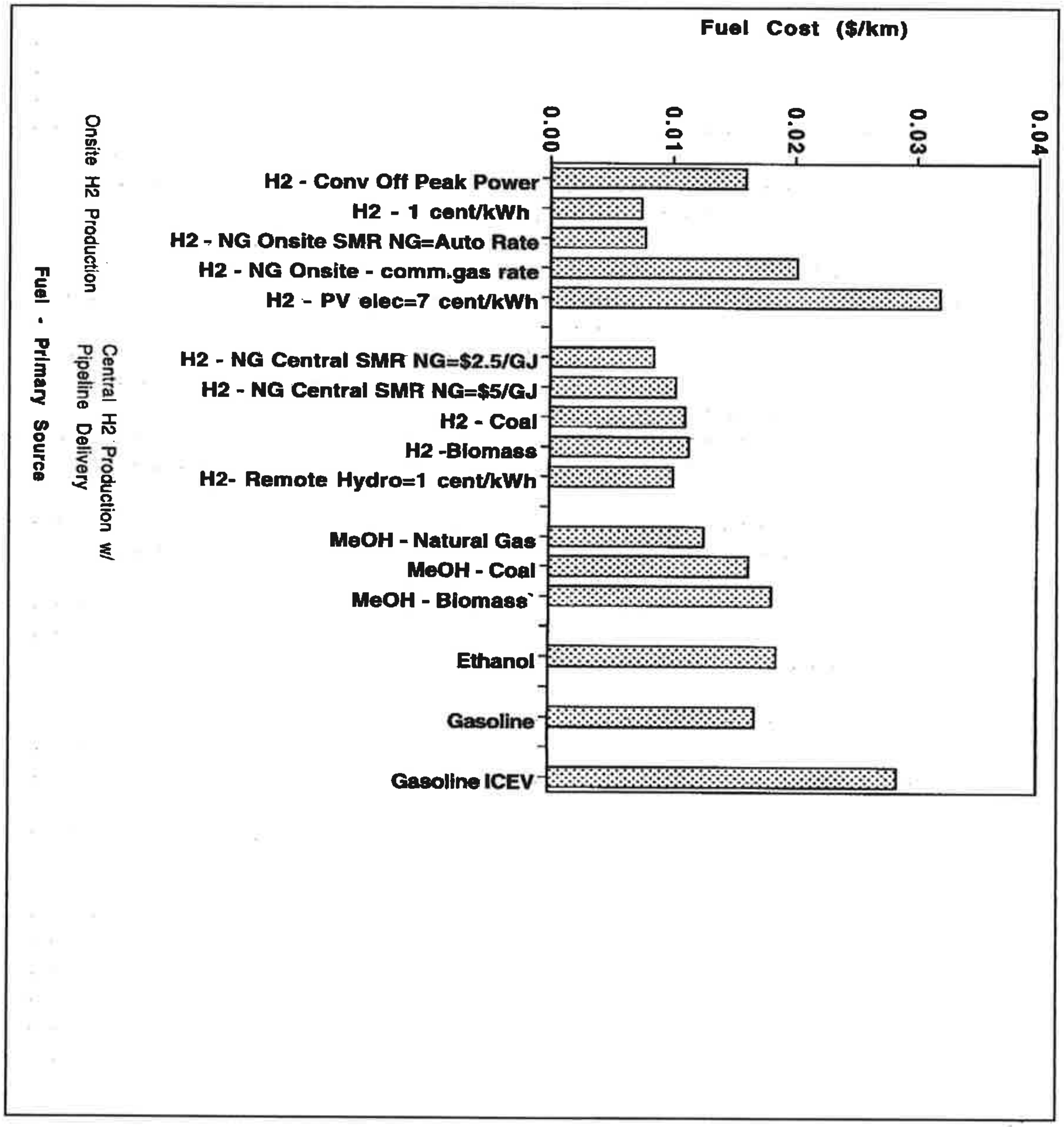


Figure 14
Capital Cost of Fuel Cell Vehicle Drive Train and Fuel Storage Components ($)

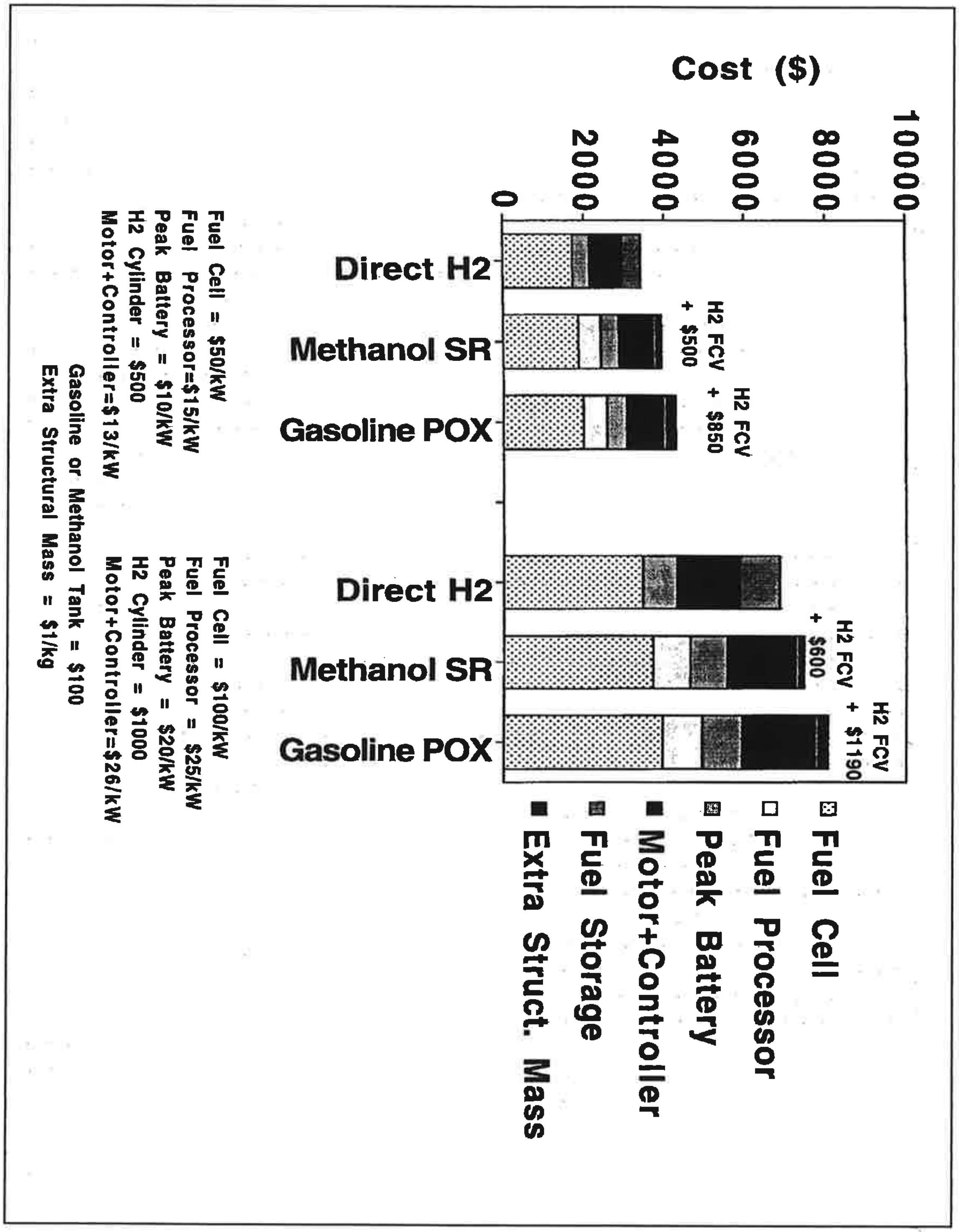


Figure 15
Lifecycle Cost of Transportation for Fuel Cell Automobiles with Various Fuels an Primary Sources ($/km)

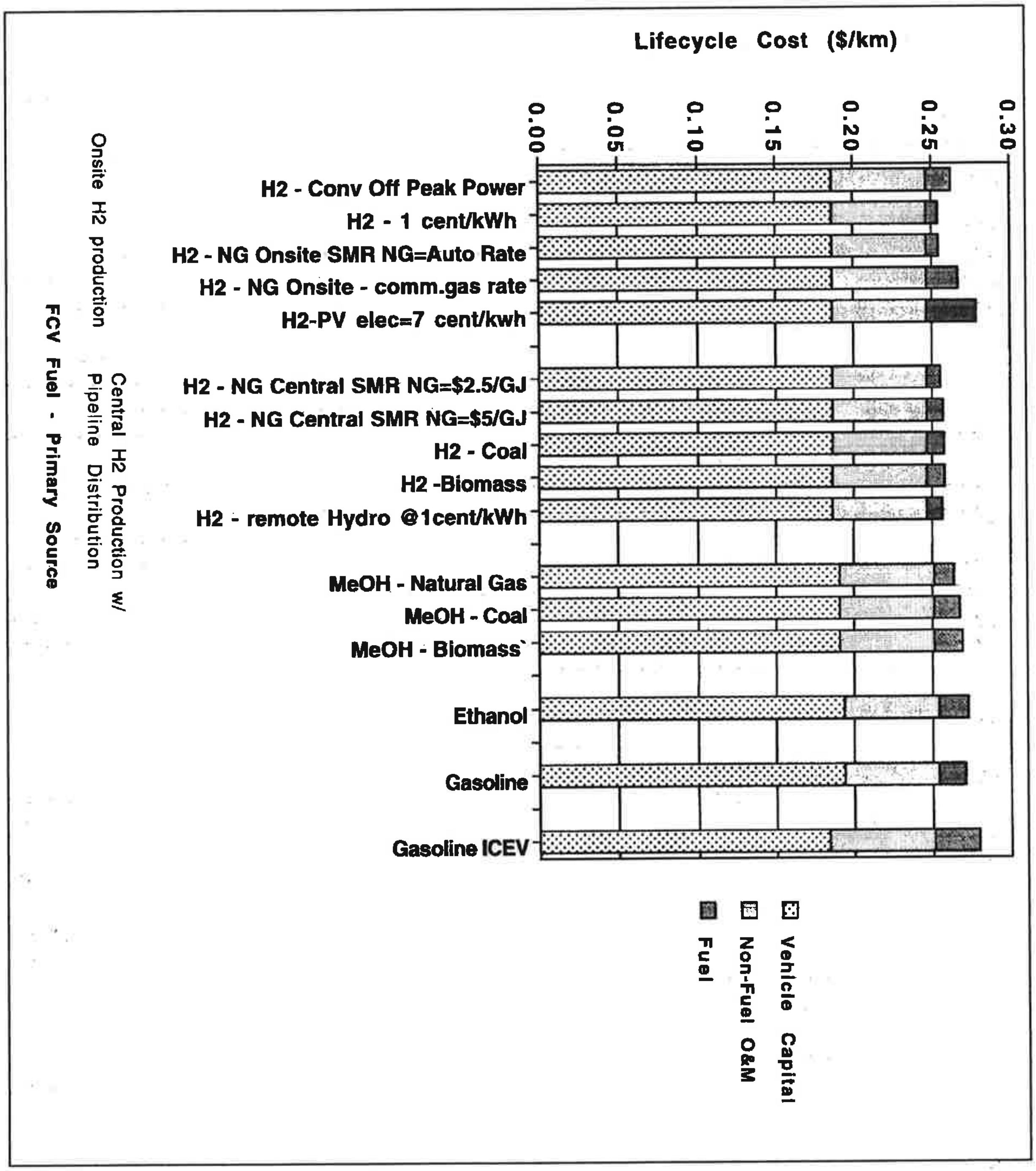
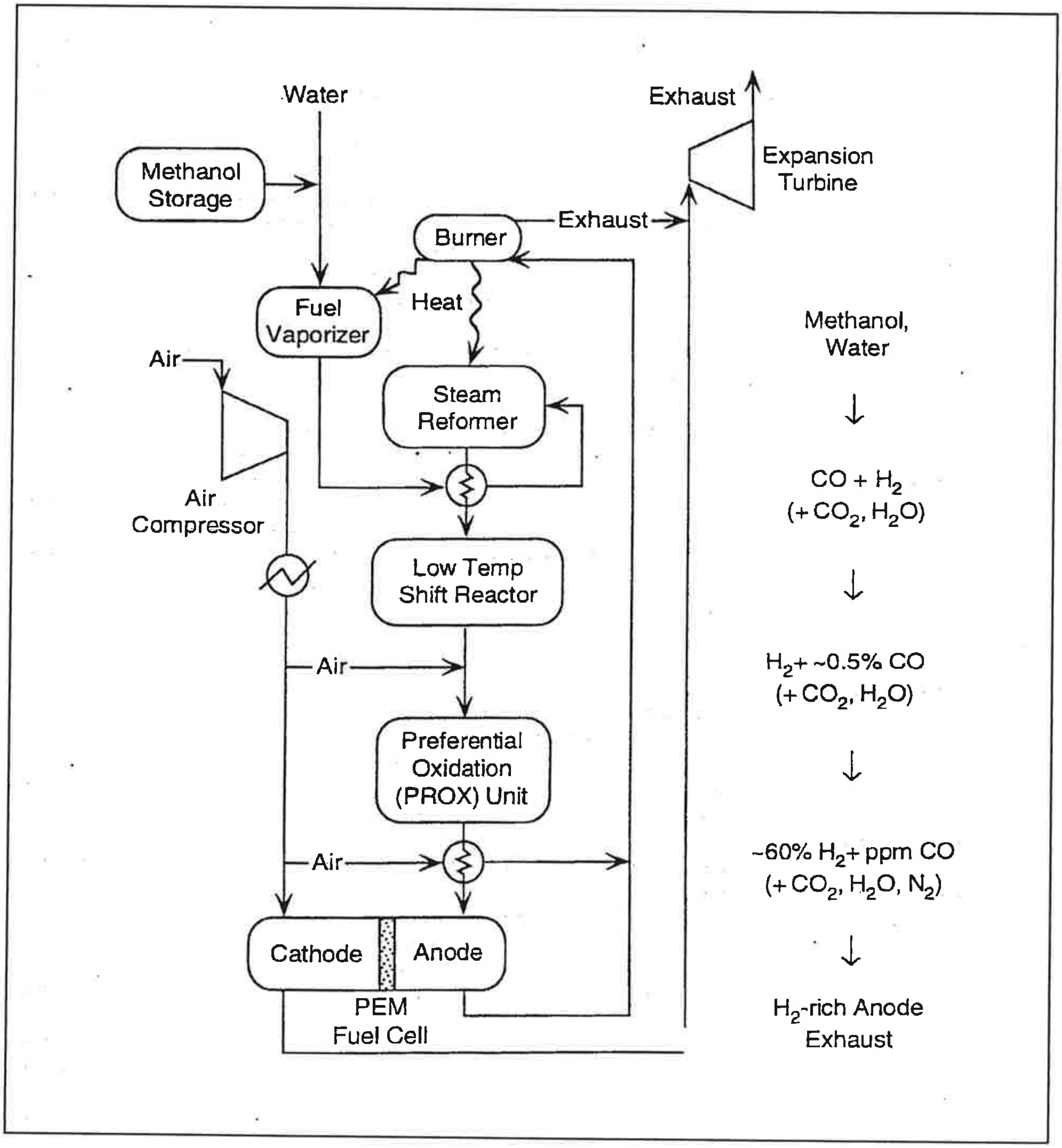


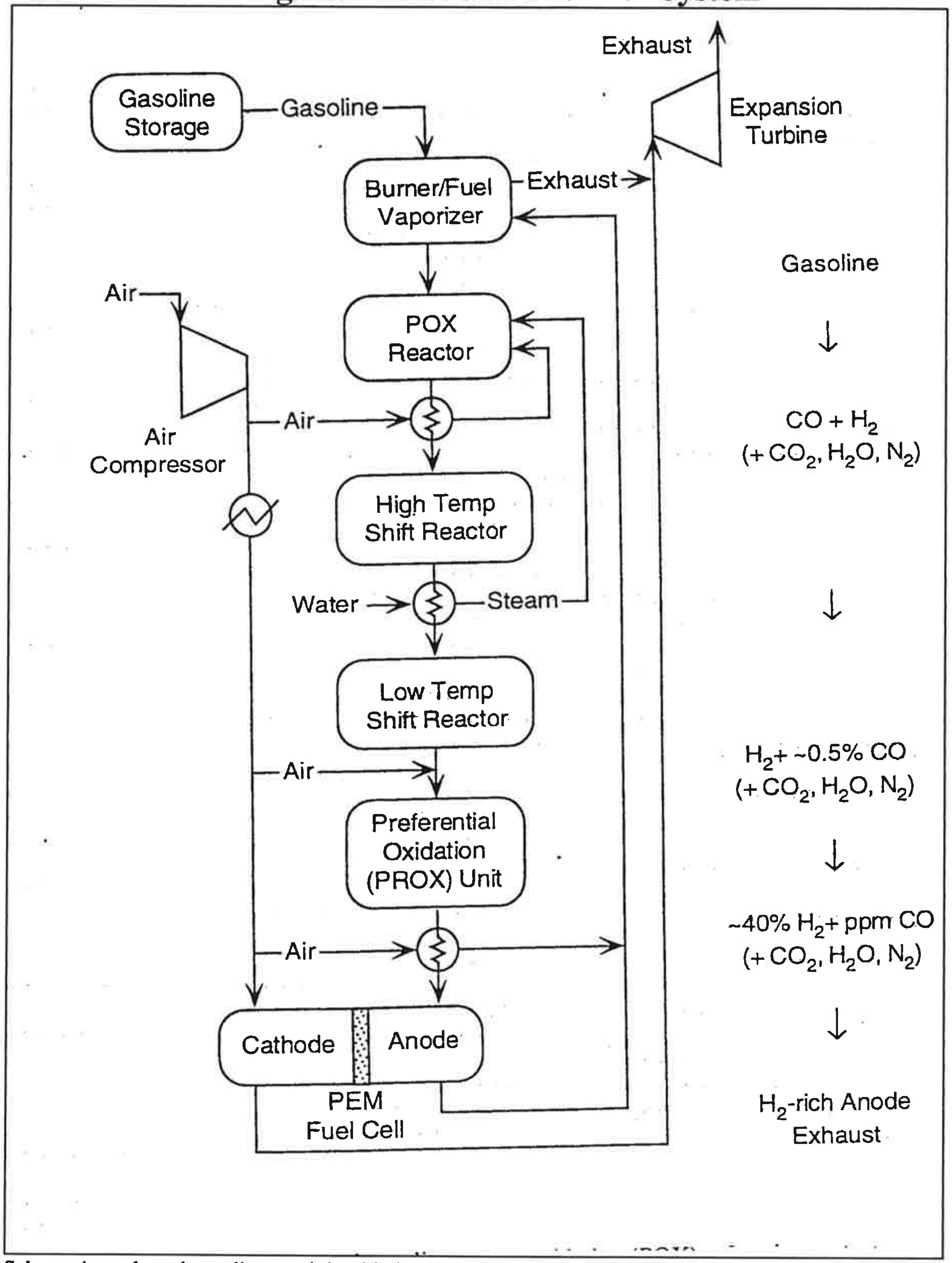
Figure 16a
Methanol Steam Reformer System



Schematic on-board methanol steam reforming system.

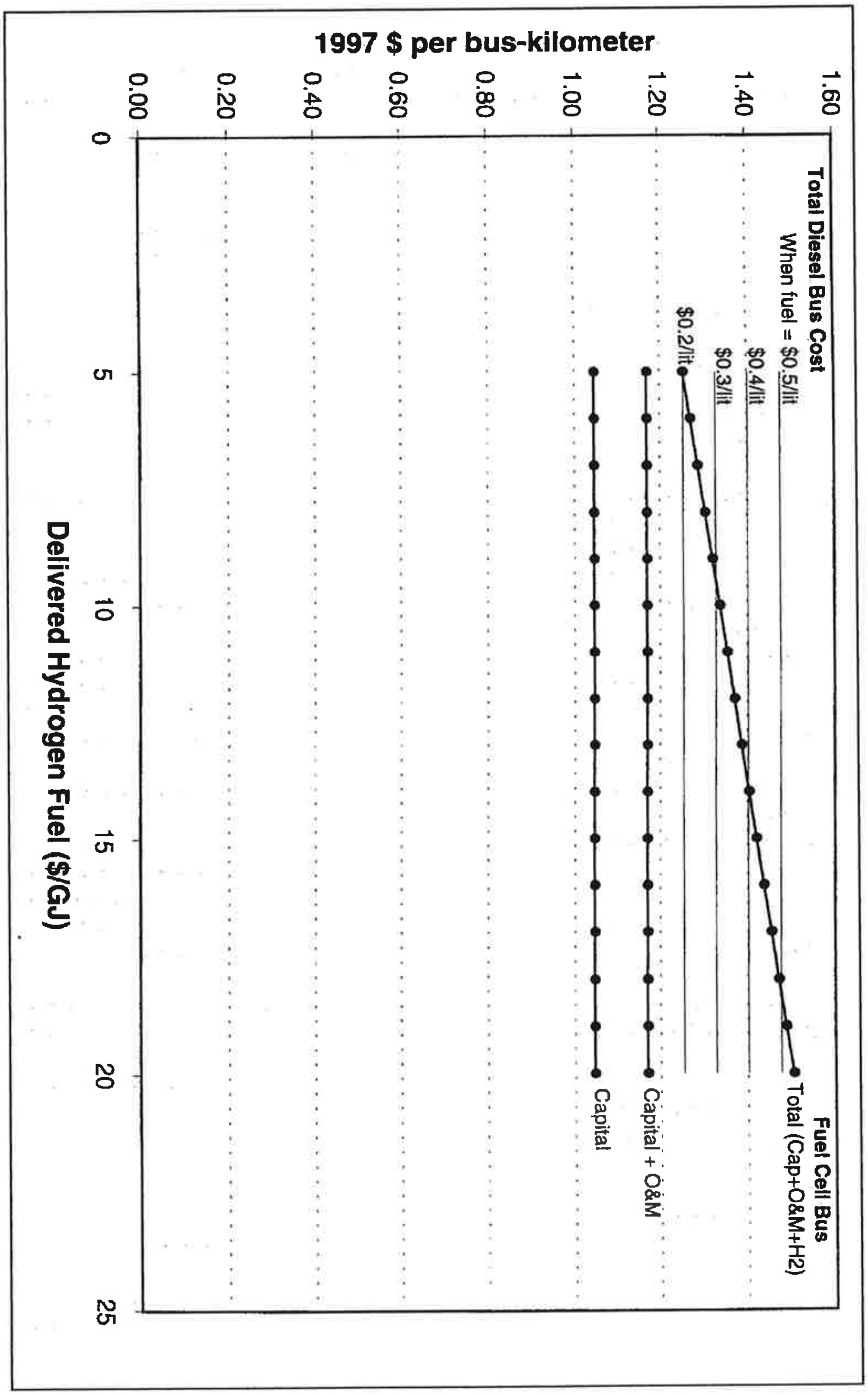
SOURCE : Ogden et al, 1998a

Figure 16b - POX Reformer System



Schematic on-board gasoline partial oxidation (POX) reforming system.
SOURCE : Ogden et al, 1998a

Figure 17 - Fuel Cell Bus and Diesel Bus Lifecycle Cost Comparison



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