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SOLAR-HYDROGEN FUEL-CELL VEHICLES

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Abstract—Hydrogen is an especially attractive transportation fuel. It is the least polluting fuel available, and can be produced anywhere there is water and a clean source of electricity. A fuel cycle in which hydrogen is produced by solar-electrolysis of water, or by gasification of renewably grown biomass, and then used in a fuel-cell powered electric-motor vehicle (FCEV), would produce little or no local, regional or global pollution. Hydrogen FCEVs would combine the best features of battery-powered electric vehicles (BPEVS)—zero emissions, high efficiency, quiet operation and long life—with the long range and fast refueling time of internal-combustion-engine vehicles (ICEVs). If fuel-cell technology develops as hoped, then hydrogen FCEVs will be a significant advance over both hydrogen ICEVs and solar BPEVs: they will be cleaner and more efficient than hydrogen ICEVs, have a much shorter refueling time than BPEVs and have a lower life-cycle cost than both. Solar-hydrogen fuel-cell vehicles would be general-purpose zero-emission vehicles, and could be an important component of a strategy for reducing dependence on imported oil, mitigating global warming and improving urban air quality, at an acceptable cost.

1. INTRODUCTION

Despite significant reductions in emissions over the past two decades, motor vehicles still account for 30% to 70% of emissions of all urban air pollutants (EPA, 1991), and up to 30% of emissions of carbon dioxide from the use of energy (DeLuchi, 1991). In most countries of the world, ground transportation uses petroleum fuels exclusively, and hence is vulnerable to supply and price volatility in the world oil market. These concerns have motivated researchers and policy makers to seek alternatives to gasoline and diesel fuel.

Hydrogen is an especially attractive alternative transportation fuel. It is the least polluting fuel that can be used in an internal combustion engine (ICE) and it is potentially available anywhere there is water and a clean source or power. The prospect of a clean, widely available transportation fuel has spurred much of the research on hydrogen fuels.

Hydrogen has been successfully demonstrated in experimental cars, buses, trucks and airplanes (Buchner and Povel, 1982; Stewart, 1984, 1986; Brewer, 1986; Peschka, 1986; Furuhama, 1988; Grünenfelder and Schucan, 1989; *Alternative Energy Sources for Road Transport, Hydrogen Drive Test*, 1990). If hydrogen is used in an internal-combustion engine (ICE), the only pollutant of concern is oxides of nitrogen (NO_x), which probably can be controlled to low levels over most parts of a driving cycle. (Small amounts of hydrocarbons [HCs] and carbon monoxide [CO] can be emitted from combustion of the lubricating oil in a hydrogen ICE). But if hydrogen is used in a fuel cell—an electrochemical device that converts the chemical-bond energy of hydrogen into electricity—even NO_x emissions (and any HCs and CO) are eliminated. A fuel cycle in which hydrogen is produced by solar electrolysis of water, or by gasification of renewably grown biomass, and then used in a fuel-cell powered electric-motor vehicle (FCEV), would produce little or no local, regional or global pollution.

Virtually all experimental hydrogen vehicles to date have used internal combustion engines (ICEs), and most general analyses of hydrogen transportation have focused on ICEVs (Buchner, 1984; DeLuchi, 1989; Ogden and Williams, 1989; Petkov, *et al.*, 1989; Plass and Barbir, 1991). Recent progress in fuel-cell technology has motivated us to expand the analysis of hydrogen transportation to include hydrogen FCEVs. Hydrogen FCEVs would combine the best features of battery-powered electric vehicles (BPEVs)—zero emissions, high efficiency, quiet operation and long life—with the long range and fast refueling time of ICEVs. In this paper we show that if fuel-cell technology develops as hoped, then hydrogen FCEVs will be a significant advance over both hydrogen ICEVs and solar BPEVs: they will be cleaner and more efficient than hydrogen ICEVs, have a much shorter refueling time than BPEVs and have a lower life-cycle cost than both. Solar-hydrogen fuel-cell vehicles would be general-purpose zero-emission vehicles, and could be an important component of a strategy for reducing dependence on imported oil, mitigating global warming and improving urban air quality, at an acceptable cost.

This paper examines the technology, performance, environmental impacts, safety, and economics of solar-hydrogen FCEVs. We compare hydrogen FCEVs with several other kinds of vehicles: with advanced gasoline ICEVs; with hydrogen ICEVs, in order to determine whether hydrogen is best used in ICEVs or FCEVs; and with BPEVs, to see which is the most attractive nonpolluting transportation alternative.

1.1. A brief history of hydrogen in transportation

Serious work on hydrogen ICEVs began in the 1930s, when Rudolph Erren converted over 1000 ICEVs to hydrogen and hydrogen/gasoline operation in England and Germany (Hoffman, 1981). However, interest in the fuel waned after World War II. A resurgence of research and experimental activity came in the late 1960s and early 1970s as Japan, West Germany and the United States began funding hydrogen programs. There are now important hydrogen development programs in Europe, North America, the Soviet Union and Japan (Stewart, 1986). The strongest hydrogen ICEV development efforts are in Japan and Germany.

Work on hydrogen FCEVs has developed more recently, in part because until recently fuel cells had been much too heavy, bulky and expensive to use in motor vehicles. In the past few years, however, advances in fuel cells (especially the proton-exchange-membrane fuel cell) have spurred interest in fuel-cell vehicles. There are several projects in North America. Energy Partners of Florida is designing and building a hydrogen-powered FCEV with a 20-kW PEM fuel cell, a 20-kW peaking battery and compressed-hydrogen storage (Ewan, 1991). Ballard Technologies of Canada is working on a program to demonstrate a 30-foot transit bus powered by compressed hydrogen and a PEM fuel cell (Prater, 1991). H-Power of New Jersey and Rolls-Royce have teamed to develop a hydrogen PEM fuel-cell vehicle. The U.S. Department of Energy is supporting two fuel cell-vehicle projects: the Georgetown Bus Project, which is using reformed methanol and a phosphoric acid fuel cell (Romano, 1990), and a project with General Motors, which is slated to deliver a methanol-fueled, PEM-powered fuel cell automobile by 1996 (USDOE, 1991a). There also are fuel-cell vehicle projects in Japan and Europe.

2. THE FUEL-CELL POWERED ELECTRIC VEHICLE (FCEV)

A fuel cell converts chemical energy in hydrogen and oxygen directly into electrical energy. It differs from both a rechargeable (or secondary) storage battery, such as is used in a battery-powered EV (BPEV), and a heat engine, although it is much more similar to the secondary battery than to the heat engine. Fuel cells and batteries are electrochemical devices; the main difference between them is that in a battery, the electricity-producing reactants are regenerated in the battery by the recharging process, whereas in a fuel cell, the electricity-producing reactants are continually supplied from an external source (e.g. the air and a hydrogen storage tank).

2.1. The Operation of a fuel cell

Several kinds of fuel cells are being developed: proton-exchange membrane (PEM), phosphoric acid, alkaline, molten carbonate and solid oxide. (Fuel cells generally are named after their electrolyte; hence the name PEM.) We will describe the operation of the PEM (also called the solid-polymer-electrolyte, or SPE, fuel cell), which appears to be the most promising fuel cell for automobiles in the near-to-mid term. In a PEM, hydrogen, either stored as such on board the vehicle or produced by reforming methanol into hydrogen and carbon dioxide (CO_2), is delivered to an electrode (the anode), where it separates, with the help of a platinum catalyst, into hydrogen ions and electrons. The electrons are collected into an external circuit and sent to perform useful work by turning an electric motor. The hydrogen ions – protons – are transported by an ion-conducting membrane (the proton-exchange membrane) to the opposite electrode, where they combine with oxygen from the atmosphere and the electrons returning from the motor to form water. The water is removed from the fuel cell. The reactions at each electrode are simply:[1]

$$\text{anode: } H_2 \rightarrow 2H^+ + 2e^-$$

$$\text{cathode: } 2H^+ + (\tfrac{1}{2})O_2 + 2e^- \rightarrow H_2O$$

2.2. The FCEV system

A fuel-cell vehicle is an electric-drive vehicle that uses a fuel cell system in place of, or perhaps in parallel with, a rechargeable storage battery. The fuel-cell system, like the battery, provides electricity to an electric drivetrain. An electric drivetrain has three major parts: (a) an electric traction motor; (b) an electronics package, including a motor controller, dc-to-ac inverter, and dc-to-dc converter; and (c) a transmission, which transmits power from the motor to the wheels (Fig. 1). The FCEV vehicle would have all the desirable features of the BPEV – no emissions, long life, low maintenance and quiet operation – plus an important additional advantage: it could be refueled for a 400-km driving range in a few minutes, whereas a battery holding enough energy for a 400-km range would take at least 20 to 30 minutes to recharge with extremely high-power recharging (which would require very high voltage and current), and several hours under typical recharging regimes.

A complete hydrogen fuel-cell system consists of several components: the fuel cell stack itself, which produces the electricity; a container to store the hydrogen or hydrogen-containing compound; an air compressor, to provide pressurized oxygen to the fuel cell (the power density of the fuel-cell system

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[1] The operation of a PEM or SPE fuel cell is the reverse of the operation of an SPE electrolyzer.

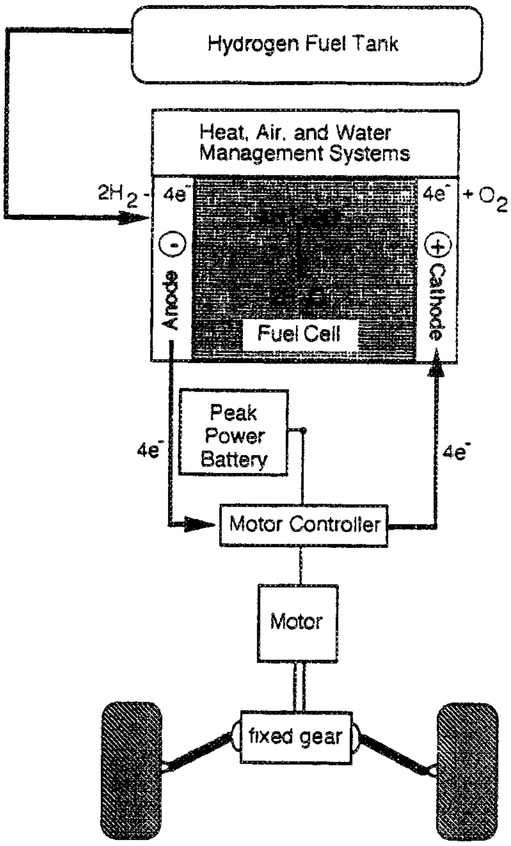

Fig. 1. Schematic of a hydrogen/PEM fuel cell/electric vehicle system. Not drawn to scale. This drawing is only illustrative: one could choose other components, fuels and designs. This figure is based in part on figures in Kuhn (1992) and Strasser (1990).

increases with the partial pressure of oxygen); a cooling system, to maintain the proper operating temperature; and a water management system, to keep the fuel-cell membrane saturated but at the same time prevent product water from accumulating at the cathode (Fig. 1). If the vehicle stores the hydrogen in the form of methanol, it also will have a reformer, to convert the methanol into hydrogen and CO_2. Finally, as discussed below, it may be cost effective to have a small battery or an ultracapacitor (or perhaps even a flywheel) as a supplemental power source.

In a hydrogen powered FCEV, the largest, heaviest and most expensive components are the fuel-cell stack, the supplemental peak-power source and the hydrogen-storage system. For each of these major components, several different technologies are available. In the following sections we discuss the major options, and our choices for the base-case analysis. Note, though, that we are not predicting that the technologies we have selected for our base case will prove to be the best in the long run; nor are we recommending that research and development be concentrated on these technologies. There is so much development work to be done on all the major components of fuel-cell vehicles that virtually any of the technologies identified here — or others not identified here — could prove to be the most attractive in the long run. As explained below, we have chosen technologies that on present evidence appear to be attractive for the near-to-middle term.

2.2.1. The fuel cell. Table 1 shows some of the major characteristics of four kinds of fuel cells that could be used in highway vehicles: phosphoric-acid, alkaline, PEM and solid-oxide. Today, many researchers believe that PEM fuel cells, which will be commercially available within a few years (Prater, 1990), are best suited for use in highway vehicles in the near term. Phosphoric-acid fuel cells are too large and heavy to be used in light-duty motor vehicles, although they may be satisfactory in heavy-duty vehicles. Alkaline fuel cells perform very well and have been projected to have a low materials cost (Appleby, 1990), but the electrolyte is so intolerant of CO_2 that the system must be supplied with either bottled oxygen or air scrubbed of CO_2. Most researchers have assumed that the extra cost and space requirement of storing pure oxygen or removing CO_2 from air make alkaline fuel cells unattractive for light-duty vehicles. However, if CO_2-tolerant alkaline electrolytes or low-cost air-separation or CO_2-removal methods are found, alkaline fuel cells could prove to be superior to PEM fuel cells for transportation. Solid-oxide fuel cells are projected to have excellent performance but are far from commercialization, and if started cold they will require a relatively long warm-up period to reach their operating temperature (although a battery could provide the energy required at startup) (Table 1).

For these and other reasons, most vehicle research, development and demonstration programs are using, or planning to use, PEM fuel cells. We have specified a PEM fuel cell here, sized to provide the driving range and cruising power — but not the peak power — for a light-duty vehicle.

2.2.2. The peak-power device. Although technically a fuel cell could be sized to provide the peak power for a vehicle, several systems analyses have indicated that it would be more cost-effective to use a small, high-power battery to provide the peak power instead (Patil and Huff, 1987; Swan, 1989; Romano, 1990; Adcock, *et al.*, 1992). The cost of a battery scales roughly with the amount of energy it can store, whereas the cost of a fuel cell scales with its power, and as a result a battery with a relatively large power capacity but modest energy storage capacity would be relatively inexpensive, compared to a fuel cell sized to meet the maximum power demand of a vehicle. Thus, in most designs for FCEVs, the fuel cell provides the cruising power and the battery provides the peak power.

The peak-power device in a fuel cell vehicle need not be an electrochemical battery; it could be an ultracapacitor (a charge storage device) or a flywheel

Table 1. Characteristics of fuel cells

Type of Fuel Cell	Status[a] (1991)	Power Density[b]		Temperature[c] (°C)	Contaminated by:
		(kW/kg)	(kW/liter)		
Phosphoric acid	CA	0.12[d]	0.16[d]	150-250	CO
Alkaline	CA	0.1-1.5[e]	0.1-1.5[e]	65-220	CO_2[f], CO
Proton exchange membrane	D/L	0.1-1.5[g]	0.1-1.5[g]	25-120	CO[h]
Solid oxide	L	1-8[i]	1-4[i]	700-1000[j]	

[a] CA = commercially available; D = development of prototypes; L = Laboratory cells.

[b] These figures are for the fuel cell stack only; they do not include fuel processing or auxiliary systems. The ranges shown are our estimates based on data in the references noted below. For several reasons, a point estimate cannot be given. The power density is a function of the air pressure, which is a design variable, and of the technology of the fuel cell and electrolyte, which is evolving. Also, there are not enough details in the original sources for us to be certain that the same parts are being counted (or not counted) in the weight and volume estimates that go into the calculation of power density.

[c] From Lemons (1990), unless indicated otherwise.

[d] This is the power density of the 36-kW brassboard PAFC fuel cell stack being developed for the U.S. Department of Energy bus project (Chi *et al.*, 1990). The fuel cell uses reformed methanol.

[e] Based on performance data and projections in Strasser (1990) and Appleby (1990).

[f] The ambient concentration of CO_2 is sufficient to degrade an alkaline fuel cell. Commercially available alkaline fuel cells must run on pure hydrogen and pure oxygen. However, Appleby (1990) suggests that quarternary amine anion exchange membranes with fluorinated backbones may be tolerant of CO_2.

[g] Based on performance data and projections in Ballard (1990), Appleby (1990) and Prater (1992).

[h] At 80°C, the allowable concentration of CO in the fuel is only a few ppm (USDOE, 1991b).

[i] Based on design specifications and projections in Myles and McPheeters (1990), Dees and Kumar (1990) and Hsu and Tai (1990).

[j] Myles and McPheeters (1990).

(an electromechanical battery). Ultracapacitors have extremely high power density, but, at present, very low energy densities (Burke, 1991). However, if energy performance goals are achieved, then ultracapacitors will be quite attractive as peak-power devices for fuel cell vehicles.

Because the battery in the FCEV will provide peak power, rather than driving range, it should have a very high power density (in W/kg and W/l). In a BPEV, however, the battery must supply the full driving range of the vehicle, as well as the peak power, and so should have high energy density (in Wh/kg and Wh/l) as well. For our base-case analysis, we have chosen the bipolar, high-temperature lithium/disulfide (Li/S) battery, for two reasons. First, the battery offers both high power density and high energy density. It could be configured to provide very high power density in an FCEV or high energy density in a BPEV (Nelson and Kaun, 1991). Second, some cost and performance data are available for this battery (summarized in DeLuchi, 1992). Consequently, we have assumed in the base-case analysis that the bipolar Li/S battery would be used in both BPEVs and FCEVs, configured for high power density in the FCEV, and high energy density in the BPEV.

However, even if it is successfully commercialized, the high-temperature Li/S battery will have at least one serious drawback: if it is not used for long periods of time, it will consume a substantial amount of energy—perhaps its own—to maintain itself at its operating temperature of over 400°C (we account for heating energy in our analysis). Because of this, we discuss the performance and cost implications of using other batteries or peak-power devices.

2.2.3. Hydrogen storage. The hydrogen fuel needed by the fuel cell can be provided by reforming methanol into hydrogen and CO_2, or by storing hydrogen on board the vehicle. We do not present costs for methanol FCEVs in this analysis. (For a cost analysis of fuel cell vehicles using methanol and hydrogen made from biomass, see DeLuchi, *et al.*, 1991.) Hydrogen can be stored on board a vehicle as a compressed gas, a metal hydride, a cryogenic liquid, a liquid hydride, a cryoadsorbed gas or a cooled and compressed gas (Table 2; DeLuchi, 1989, 1992). Recently, Werth (1992) has applied for a patent on an iron oxidation/reduction system in which hydrogen is generated on board the vehicle from water and sponge iron. As we explain next, we have chosen high-pressure gas storage because it is simple, reasonably light and compact, commercially available and safe (we discuss safety later), and in principle should allow for fast refueling.

Because hydrogen is the lightest element, it is difficult to store compactly, and no hydrogen storage system can begin to approach the volumetric energy density (in mJ/l) of gasoline storage (Table 2). In the past, analysts have ruled out storing hydrogen as a compressed gas because at the pressures typically considered—3000 psi or so—the system would be unacceptably bulky. However, if the storage pressure were increased to at least 8000 psi, compressed gas storage in carbon-wrapped aluminum-lined vessels would be attractive compared to most other hydrogen-storage options. In fact, as shown in Table 2,

Table 2. Characteristics of hydrogen storage systems[a]

Storage System	Installed fuel-system energy density[b]		Container Cost[c]	Refuel Time[d]	Station Cost[e]
	(mJ/liter)	(mJ/kg)	($-OEM/gJ)	(minutes)	($/gJ)
Gasoline tank	32.4	34.0	20	2-3	0.6
H-Power iron oxidation/reduction	5.8?	5.0?	500?	?	3?
Carbon-wrapped aluminum cylinder, 8000 psi	3.4	7.0	4000	3-5	4-6
Liquid hydrogen	5.0	15.0	1000-2000	5+	3.5-5(11)[f]
Cryoadsportion	2.1	6.3	2000-4000	5	4-5
Thermocooled pressure vessel	2.5	8.2	4000+?	5+	5+ (8+)[f]
FeTi metal hydride	2-4	1-2	3300-5500	20-30	3-4
Organic liquid hydride	0.5	1.0	?	6-10	?

[a] See DeLuchi (1992) for sources and additional notes.
[b] Weight and volume of container, fuel and auxiliaries.
[c] Cost to the original equipment manufacturer (OEM), per gJ of storage capacity.
[d] Time to deliver fuel; does not include time to pull in, pull out or pay.
[e] The full ownership and operating cost of the station. The cost of hydrogen is not included here.
[f] The estimate in parentheses includes the cost of liquefying hydrogen; the other estimates do not.

only liquid-hydrogen storage, and perhaps the iron oxidation/reduction system proposed by Werth (1992), would be substantially more compact than would compressed-gas storage at 8000 psi. Ultra-high-pressure storage would be more compact than cryoadsorption and most metal hydrides. It also would be lighter than any other option except liquid-hydrogen storage. And thanks to recent drops in the price of carbon fiber (Takagashi, 1991; Price, 1991), carbon-wrapped aluminum-lined cylinders would be economically competitive with many other forms of hydrogen storage (Table 2).

In addition to being much lighter, compressed-gas storage would have two other important attributes: it would be simple, and in principle would allow for fast refueling. In fact, of all forms of hydrogen storage, high-pressure storage (in principle) most closely replicates gasoline storage and refueling. (We say "in principle," because to our knowledge no-one has built an ultra-high-pressure vehicular storage and refueling system, but there appear to be no major technical obstacles to doing so.) For our cost analysis, summarized below, we obtained estimates from manufacturers and consultants of the cost of every major part of a storage and refueling system designed specifically for ultra-high-pressure hydrogen storage and refueling (DeLuchi, 1992).

Still, key advances in either liquid hydrogen or metal-hydride storage, or the successful development of H-Power's iron oxidation/reduction system (Werth, 1992), could make any of these systems more attractive than ultra-high-pressure storage. In the cost-scenario analyses (discussed below) we present the results of assuming different storage systems.

2.3. Summary of technical development challenges facing fuel cell vehicles

Although the successful development and eventual commercialization of fuel cell vehicles does not depend on technical "breakthroughs," in the way that battery development has been supposed to, it does require the resolution of many design and engineering challenges, and success is by no means guaranteed. Important issues are summarized below.

1. The fuel cell, peak-power device, motor, electronics and fuel-storage system must be designed and arranged to fit into as small a space as possible, without creating safety hazards. (For example, high-voltage components must be completely isolated.) The modularity of the components and the electronic (as opposed to mechanical) connections between them will afford designers and systems engineers some flexibility in separating and arranging the parts.
2. Because BPEVs so far have been targeted for comparatively low-power, short-range applications, there is little experience with electric drive systems in long-range, high-power and rapid-transient applications. Furthermore, most EVs have been developed for commercial or institutional users, who presumably take better care of their vehicles and use them more predictably than the general public does. However, because FCEVs in principle could be used in virtually in any application, by virtually any type of user, it is important to design and test electric drives for the types of uses (and abuses) that hitherto have been assumed to be irrelevant to EVs.

   Similarly, it will be important to test advanced FCEVs and BPEVs under a wide range of weather conditions. In recent tests a PEM fuel-cell system was able to start instantly at 3°C, but took 15 minutes to achieve full power (Prater, 1992). The developers feel that this time "certainly" can be reduced.
3. Advanced electronics systems capable of controlling two power sources (the fuel cell and the peak-power device) and three battery-recharging paths (from the fuel cell, from regenerative braking and from external outlets) have been developed only

recently. The ultimate cost, performance and reliability of these systems is not yet known.

4. At least four challenges face the developers of PEM fuel cells:[2] (a) improve the performance and reduce the cost of the membrane, without compromising its mechanical properties or making it susceptible to impurities in the gas stream;[3] (b) find a simple and effective way to keep the membrane moist, but at the same time not allow product water to build up at the cathode (Springer, *et al.*, 1991); (c) reduce the size and energy consumption of the air-compression system (Swan, *et al.*, [1991] suggest that it might be best to have a variable-speed "smart" air compressor, programmed to operate at the optimal efficiency point depending on the load; such a compressor might not even operate at low loads); and (d) reduce the weight, bulk and manufacturing cost of the stack plates and assembly.

For alkaline fuel cells, the major challenge is to find a CO_2-tolerant electrolyte or an inexpensive way to remove CO_2 from the air. Success in either area will make alkaline fuel cells very attractive. Solid-oxide cells are still in the early-development stage.

5. Although as discussed above there are many candidate peak-power devices for fuel cell vehicles, none are yet completely satisfactory. The ultimate choice of the peak-power device, and of its capacity and operating profile compared to the capacity and operating profile of the fuel cell, will be based on several factors: an analysis of the cost and performance of the peak-power device and the fuel cell; the characteristics of the driving cycle; and the amount, availability and cost of the energy sources (regenerative braking, the fuel cell, or the outlet) used to recharge the battery.
6. As discussed above, there are many ways to store hydrogen on board a vehicle (Table 2), but those that have been developed thus far are expensive and bulky. The development of an inexpensive, compact, safe and easy-to-refuel hydrogen storage system will greatly improve the economics and marketability of fuel cell vehicles.
7. The methanol reformers that are available today take a relatively long time to warm up and cannot follow rapid changes in power demand. (Note that it is only the reformer and not the PEM fuel cell itself that cannot load follow; PEM fuel cells can load follow virtually instantaneously [Amphlett,*et al.*, 1991]) The U.S. DOE is sponsoring research addressing these problems (USDOE, 1991b). Present external reformers also are bulky and relatively complicated and moderately expensive. These latter problems would be solved by the successful development of internal-reforming solid-oxide fuel cells.
8. Electric-drive technology is evolving and being refined, and engineers and designers are addressing several issues: the optimal system voltage, the choice of motor, (e.g. ac induction vs. dc brushless permanent-magnet vs. switched-reluctance), the choice of power-switching device (e.g. insulated-gate bipolar transistors [IGTBs] or metal-oxides semi-conductor field-effect transistors [MOSFETs]) and whether to use a single-speed (fixed-ratio) transmission or a two-speed transmission (Appleyard, 1992; Braess and Regar, 1991). These issues cannot be considered separately from one-another, or from the choice of battery or peak-power device. Note, though, that electric drivetrains already are satisfactory technically (Wallace, 1992); the remaining tasks are to further improve performance and reduce cost, rather than solve fundamental technical problems.
9. Present air-conditioning systems can consume a substantial fraction of the energy in an EV storage battery. Work is underway to develop more efficient heating and cooling systems, and to reduce the heat load (Dieckmann and Mallory, 1991).

3. THE CHARACTERISTICS OF THE VEHICLES ANALYZED IN THIS PAPER

In the following sections we will compare the efficiency, environmental impacts and life-cycle cost of gasoline ICEVs, hydrogen-powered FCEVs, BPEVs and hydrogen-powered ICEVs. The first step in this comparison is to specify the attributes of the vehicles (Table 3). In our analysis, the baseline gasoline vehicle, from which all the alternative vehicles are hypothetically derived, is an advanced year-2000 version of the 1990 Ford Taurus, a popular mid-size car whose price, power and fuel economy were close to the U.S. fleet-wide averages for 1990. Our hypothetical year-2000 Taurus features new designs and com-

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[2] Until recently, this list would have included "reducing the amount of platinum catalyst used in the PEM fuel cell." However, recent reductions in catalyst loading (to 9.1 mg/cm^2 [Wilson, *et al.*, 1991], combined with our modestly optimistic assumptions about the maximum power density of future PEM fuel cells (1250 mA/cm^2-active area, at 0.55 volts), result in only 3.6 mg of platinum per vehicle with a 25-kW fuel cell—about twice as much as is used in the catalytic converters of gasoline ICEVs (DeLuchi, 1992). Allowing for a 50% increase in the price of platinum due to the increased demand per vehicle (FCEVs vs. ICEVs), the total cost of platinum in the FCEV still would be less than $100 at the manufacturing level. At these quantities and costs, platinum use in PEM-FCEVs is not much of a concern. We estimate that if in the future all vehicles in the world used PEM fuel cells, the extra yearly mine production (compared to the all-ICEV case) probably would be 2 to 3 orders of magnitude less than 1989 platinum reserves (56 million kg), and total annual world mine production of platinum probably still would be 2 orders of magnitude less than 1989 reserves (allowing for some recycling of platinum; based on Loebenstein, 1990).

[3] The thickness of the membrane is a key design parameter for PEM fuel cells: thinner membranes cost less and have lower protonic resistance (and therefore higher power density), and might even simplify water management (Springer, *et al.*, 1991), but they also might deteriorate more quickly or be damaged more easily.

Table 3a. Characteristics of ICEVs in the analysis[a]

	Gasoline (baseline) (640-km range)	Hydride (400-km range)	Liquid Hydrogen (400-km range)	Compressed Hydrogen (400-km range)
Energy Storage System	Metal Tank	Iron/Titanium Hydride	Cryogenic Dewar	Carbon-Wrapped Aluminum Vessel (550 bar)[c]
Maximum power at wheels (kW)	101	n.e.	n.e.	n.e.
Vehicle life (km)	193,000	212,400	212,400	212,400
Volume of energy system (liters)[c]	63	n.e.	n.e.	n.e.
Weight of complete vehicle (kg)[d]	1371	1831	1326	1425
Coefficient of drag	0.28	n.e.	n.e.	n.e.
Fuel economy (mpg-equivalent)[e]	25.9	27.4	31.3	32.2
(liters/100 km)	9.1	8.6	7.6	7.3

[a] The gasoline vehicle is a year-2000 version of the 1990 Ford Taurus. The other vehicles are "built" hypothetically from this. n.a. = not applicable. n.e. = not estimated. The vehicle life and the coefficient of drag are input directly into the model; the other parameters are calculated by the model. See text here and DeLuchi (1992) for details.

[b] As one increases the storage pressure the bulk of the storage system decreases but the cost increases. We chose 550 bar because our trade-off analysis indicated that it represents the best balancing of these two opposing tendencies.

[c] The sum of the volume of the energy storage system (battery, gasoline tank, methanol tank or hydrogen container), the fuel cell and the methanol reformer (from Table 4).

[d] Including one passenger and fuel to 40% of tank capacity.

[e] Gasoline-equivalent fuel economy in miles/gallon is calculated as the mile/million-Btu fuel economy of the alternative vehicle in combined city and highway driving in the year 2000, divided by 125,000 Btu/gallon-gasoline (34,830 kg/ liter). We use the higher heating value of hydrogen (286 kJ/mole), and count electricity consumption from the outlet at 3413 Btu/kWh. See DeLuchi (1992) for further details.

ponents that raise the fuel economy substantially above the level in 1990, make the vehicle safer, reduce emissions to the levels required in Tier I of the 1990 U.S. Clean Air Act Amendments and increase the power-to-weight ratio. It also has relatively high horsepower and a very high power-to-weight ratio.

We assume that the EVs would have a shorter driving range and lower peak performance (in terms of the

Table 3b. Characteristics of BPEVs and hydrogen FCEVs in the analysis[a]

	FCEV (400-km range)	FCEV (240-km range)	BPEV (400-km range)	BPEV (240-km range)	BPEV (160-km range)
Energy Storage System	Carbon/Aluminum Tank (550 bar)	Carbon/Aluminum Tank (550 bar)	Bipolar High-Temperature Li/S	Bipolar High-Temperature Li/S	Bipolar-High Temperature Li/S
Battery type	bipolar Li/S	bipolar Li/S	see above	see above	see above
Maximum power at wheels[b]	73	69	85	75	70
Maximum fuel-cell power (kW)[c]	25	25	n.a.	n.a.	n.a.
Vehicle life (km)	256,800	256,800	256,800	256,800	256,800
Volume of energy system (liters)	268	201	237	155	114
Weight of complete vehicle (kg)	1238	1167	1462	1275	1184
Coefficient of drag	0.23	0.23	0.23	0.23	0.23
Fuel economy (mpg-equivalent)	74.0	76.3	120.0	129.2	134.1
(liters/100 km)	3.2	3.1	2.0	1.8	1.8

[a] The EVs are based on the year-2000 Ford Taurus described in Table 3a. See text and DeLuchi (1992) for details. See also notes to Table 3a.

[b] We calculate the peak power of the EV and FCEV motor given the peak power of the ICE, the desired high-end acceleration of the EV relative to the high-end acceleration of the ICEV and the mass, drag, and rolling resistance of the EV and ICEV. In the base case, we assume that the ratio of the maximum acceleration of the EV at 60 mph to the maximum acceleration of the ICEV at 60 mph is 0.80:1.00. Note, though, that the EVs would perform better than the ICEVs at low speeds. The maximum power of the hydrogen ICEVs was not estimated because it is not a part of the hydrogen-ICEV cost model, which is different from the fuel-cell EV cost model.

[c] This is the gross maximum power output of the fuel cell; the power requirement of the auxiliaries is deducted from this to determine the net power available to the drivetrain from the fuel cell. By trial-and-error runs of the cost model we find the combination of gross maximum fuel-cell power and maximum battery power that result in the lowest life-cycle cost per km, subject to constraints on battery size and performance.

cmaximum instantaneous power delivered to the wheels at 60 mph, accounting for any differences in vehicle weight, rolling resistance and aerodynamic drag) than the baseline ICEV, but, as discussed below, not necessarily a worse *overall* performance. Our selection of range and peak performance for the EVs is based on our qualitative balancing of several factors: longer range and higher peak performance would make the EV more attractive to consumers and more comparable to the baseline gasoline vehicle, but also would be relatively costly, because fuel cells, batteries and to a lesser extent hydrogen storage systems are more expensive per unit of energy or power provided than are gasoline tanks and gasoline ICEs.

3.1. Driving range

The life-cycle cost of a gasoline ICEV is virtually independent of its driving range, because gasoline storage is virtually free. However, batteries and hydrogen storage systems are bulky and expensive and often heavy, and as a consequence the life-cycle cost and performance of BPEVs and hydrogen FCEVs and ICEVs definitely will be related to the amount of energy stored on board. In theory, there would be an "optimal" range for these vehicles: the point at which the cost of providing the last increment of additional driving range (energy storage) equaled the benefit of the additional driving range. Although we do not know what this optimal driving range for BPEVs would be, we are fairly sure that it would be less, and perhaps substantially less, than the range of a gasoline ICEV, because range will be more expensive to provide in a BPEV than in ICEV (because a battery is so much more expensive than a gasoline tank). For our base-case cost analysis, we assume that 400 km is the "minimally acceptable" driving range for all-purpose vehicles, and that 250 km is the minimum for special-purpose urban vehicles. Although the FCEV likely would have a longer range than the BPEV, because the fuel-storage system (especially for methanol) would not be as expensive or heavy as are even the most advanced batteries, we estimate costs for the FCEV at the same driving ranges (400 km and 250 km) as for the BPEV, in order to compare the results for the FCEV with the results for the BPEV. Summary performance and cost statistics are given for both the 400-km and the 250-km cases. (Details are in DeLuchi, 1992). In the scenario analysis presented below, we estimate costs for BPEVs and FCEVs at other driving ranges. We also assume a 400-km range for the hydrogen ICEVs (even though hydride and perhaps compressed-hydrogen ICEVs probably would not have such a long range), in order to be able to compare the ICEV cost results with the results for BPEVs and FCEVs.

3.2. Peak performance and overall performance

The assumed maximum power output of the motor, like the assumed driving range, affects the life-cycle cost of the vehicles. In our base cases we assume that the BPEV and FCEV would have 80% of the maximum acceleration capability of the ICEV at 60 mph (Table 3). We chose a lower peak performance for the EVs because of the high cost of providing power in an electric vehicle, but the particular figure we chose (80%) is arbitrary. In cost scenario analyses discussed later, we examine the effect of different assumptions about the peak performance. Note, though, that even though the EVs are assumed to have lower *maximum* performance than the ICEVs, they would not necessarily have a worse *overall* performance. In fact, they actually would perform better than the ICEV in the lower load regimes that characterize a large part of urban driving. There are two reasons for this. First, an electric motor can deliver high torque at low rpm, whereas an ICE cannot. Since power is the product of torque and rpm, the high-torque electric drive can attain higher power at lower rpm than can the ICE. Second, with an electric drive, there need not be any appreciable lag between the application of the pedal and the response of the motor, because the power flow is electrical. In an ICE, the response lags somewhat because of lags in the mechanical linkages and friction in the flow of air and fuel. For both these reasons, high power can be made available more rapidly – and to feel as if it is available more rapidly – with an electric drive than with an internal-combustion-engine drive. Experience with properly designed EVs has borne this out.

We assume that the BPEV and the FCEV would have the same peak performance, in order to compare the cost results. (Note that because the BPEV would weight more than the FCEV, it must have a higher peak power in order to have the same peak performance as the FCEV.)

3.3. Vehicle life and other factors

The assumed vehicle life is an important cost parameter, because it affects the amortized initial cost-per-km of the vehicle. It is well known that electric motors last many times longer than heat engines in the same application. What is not well known, however, is how the life of the drivetrain affects the life of the vehicle. We expect that lifetime advantage of the EV over the ICEV would be less than the advantage of the electric drive over the ICE drive, because vehicles are scrapped for reasons other than failure of the drivetrain. Still, experience in England does indicate that electric fleet vehicles can last much longer – in some cases, several times longer – than their ICEV fleet counterparts (Hamilton, 1988; see DeLuchi, 1992, for further discussion). On the other hand, this experience with fleet vehicles might not be entirely applicable to future household EVs, which would have different drivetrains and would be used differently. We assume that the EVs would have a 33% longer life than ICEVs. In scenario analyses we examine the effect of different assumptions about vehicle life.

DeLuchi (1989) suggests that in the best case hydrogen ICEVs might have a slightly longer life than gasoline ICEVs; we assume so here (Table 3) to give hydrogen ICEVs every advantage in the comparison with hydrogen FCEVs.

We also assume that the BPEV and FCEV would have lower aerodynamic drag and a lighter body than would the gasoline ICEV, because higher energy efficiency pays off in increased performance and longer driving range (or lower fuel storage costs), as well as in lower fuel costs, and these benefits are more important in EVs than in ICEVs. This assumption is consistent with the design of several recent advanced BPEVs and FCEVs, which are lightweight and aerodynamic and very energy efficient (General Motors, 1990; Ewan, 1991; Tange and Fukuyama, 1992). We assume that the hydrogen ICEVs also would have a lighter body than would the gasoline ICEV, but implicitly assume that they would have the same aerodynamic drag as the gasoline ICEV, because aerodynamic drag is not a parameter in the hydrogen ICEV cost model. However, we do assume that the hydrogen ICEs would run ultra lean, in order to improve fuel economy (Table 3).

To recap, we compare FCEVs, BPEVs, and ICEVs in the year 2000. The year-2000 baseline gasoline ICEV is a very efficient, powerful and clean midsize car. The year-2000 BPEV and the FCEV are assumed to have a somewhat shorter range and lower peak performance than the year-2000 gasoline vehicle, but better low-end performance and longer life. In scenario analyses discussed later, we examine the life-cycle-cost implications of making the FCEV and the BPEV have the same peak-power and nearly the same range as the gasoline ICEV.

4. CALCULATED VEHICLE CHARACTERISTICS: WEIGHT, BULK AND ENERGY EFFICIENCY

4.1. System weight

Table 4 shows the calculated weights of the individual components of the FCEVs and BPEVs, and the total extra weight, compared to the gasoline ICEV, for the baseline vehicles of Table 3. The analysis indicates that hydrogen FCEVs could weigh less than gasoline ICEVs (Table 3). With an FCEV, the extra weight of the hydrogen storage system, fuel cell and battery, compared to a gasoline tank, would be more than offset by the weight savings resulting from replacing the ICE powertrain with an electric powertrain. Thus, vehicle weight per se will not be especially important in the design of the FCEV. (Requiring the FCEV to have the same performance as the gasoline vehicle would not change this conclusion qualitatively.) Of course, it still will be important to keep the vehicle as light as possible in order to reduce fuel consumption and improve performance.

If advanced batteries (e.g. bipolar lithium/iron-disulfide, bipolar lithium/polymer or zinc/air) are developed successfully, weight *per se* will be a constraint in the design of BPEVs only if the driving range is very long (and the battery thus relatively large). Tables 3 and 4 show that a 400-km BPEV with a very advanced battery (Li/S) might weigh only 100 kg more than a comparable gasoline ICEV, even though it has a 400-kg battery, because of the lighter weight of the electric drivetrain compared to the ICE drivetrain, and the weight-reduction measures we assume will be applied to EVs. If the BPEV has only a 250-km range, it might even weigh less than the ICEV, as indicated in Table 3. However, the use of batteries with a lower energy density than the Li/S, or the failure to reduce the weight of the rest of the vehicle as much as possible (as assumed here), would increase the weight considerably. The BPEV then would weigh several hundred kg more than the comparable gasoline vehicle, and would need a much more powerful motor than would the FCEV to provide the same performance as the FCEV. In fact, if the Li/S battery were not available and a battery with lower specific energy, such as sodium/sulfur, were used instead, it no longer would be practical to provide a 400-km range, because the battery and the vehicle would be too heavy.

The LH_2 ICEV in our analysis weighs less than the gasoline ICEV, because the minor extra weight of the LH_2 tank compared to the gasoline tank is more than offset by the assumed extra weight-reduction measures applied to the hydrogen vehicle. (Also, LH_2 fuel weighs less than the amount of gasoline providing the same range.) However, the hydride ICEV is several hundred kg heavier than the gasoline ICEV, because of the very low mass energy density of hydride storage. The compressed-hydrogen (CH_2) ICEV weighs only slightly more than the gasoline ICEV, because the weight of the storage tank is nearly canceled by the weight-reduction measures assumed to be applied to the rest of the vehicle, but it is nearly 200 kg more than the CH_2 FCEV, because ICE drivetrain is much heavier than the electric drivetrain.

4.2. Bulk and range

Fitting the energy-storage and power systems into the vehicle will be a challenge in the design of FCEVs and BPEVs with more than a 300-km range. As shown in Tables 3 and 4, the battery in the 400-km BPEV and the complete fuel cell/hydrogen/battery system in the 400-km FCEV displace about 250 liters. The battery in the BPEV is slightly less bulky than the fuel-cell system. The compactness of the electric drivetrain compared to the replaced ICE system (engine, fuel system, cooling system, electrical system, exhaust system, pollution control system, etc.) would mitigate but not obviate the space problem, even in an FCEV or BPEV designed from the ground up. For example, the battery tunnel in General Motors' 2-seat "Impact" BPEV is less than 200 liters (General Motors, 1990), which is not nearly enough space to

Table 4. Weight, volume and cost of components of FCEVs and BPEVs (400-km range)

	Retail prices[b] $		Weight (kg)		Volume[c] (liters)	
	BPEV	FCEV	BPEV	FCEV	BPEV	FCEV
Traction battery, storage tray and auxiliaries	13,625	4205	430	126	237	75
Fuel storage system[d]	0	2692	0	66	n.a.	108
Fuel-cell stack and associated auxiliaries	0	4496	0	50	n.a.	85
Difference between the EV & the ICEV powertrain[e]	(2839)	(3298)	(281)	(305)	n.e.	n.e.
Extra weight and drag-reduction measures on EV[f]	141	93	(138)	(151)	n.a.	n.a.

[a] The results shown here are from the model and input data described in DeLuchi (1992) and apply to the baseline vehicles of Table 3. n.e. = not estimated. n.a. = not applicable. 0 = negative value.

[b] The retail price includes the vehicle licensing fee, shipping cost and taxes.

[c] These are estimates of the water volumes of the components themselves and do not account for unuseable void spaces created by packing and arranging the components.

[d] The estimate of the weight of the fuel-storage system of the FCEV includes the weight of valves, fuel lines, regulators, and fuel (added to 40% of capacity.) However, the estimate of the volume of the fuel-storage system does not include the volume of fuel lines, valves or regulators.

[e] The EV powertrain consists of all parts in an EV and not in an ICEV, except the fuel-cell system, fuel storage system and battery, which here are treated separately. The ICEV powertrain includes all parts that are in an ICEV but not in an EV: the engine, transmission, driveline, fuel system, cooling system, pollution control equipment and so on.

The difference in volumes between the two powertrains could not be estimated because of the difficulty of determining the water displacement volume of the engine, transmission, fuel system, exhaust system, pollution control, electronics, etc., in a modern vehicle. Note, though, that an electric powertrain requires much less space than does an ICE powertrain.

[f] We assume that the EV would have a lower aerodynamic drag and body weight than the ICEV, because there would be a greater benefit to improving the efficiency of an EV than of an ICEV. See text here and DeLuchi (1992) for further discussion. The figures shown here include extra support structure for EV batteries, which accounts for the difference between the BPEV and the FCEV.

house the components of the 400-km FCEV or the battery of the 400-km BPEV analyzed here. And the Impact was designed from the ground up, partly with the intention of maximizing the space available for the battery.

If the vehicle range were 250 km instead of 400 km, the bulk of the components in the FCEV and the BPEV (especially in the BPEV) would be much more manageable – for example, they could fit into the battery tunnel of the GM Impact. However, if the bipolar LI/S battery or other advanced batteries (such as the bipolar lithium/polymer or Electrofuel's zinc/air) do not develop as expected, other batteries, with a lower volumetric power density and volumetric energy density, might have to be used in both the FCEV and the BPEV. In this case, the volume of the battery or fuel-cell system would increase considerably. For example, a sodium/sulfur battery in a BPEV would be nearly 50% larger than the base-case LI/S battery assumed here. A bipolar lead/acid peak-power battery in a FCEV would be more than three times larger than the LI/S battery, and as a result the whole fuel-cell system would be more than 60% bulkier than the base-case fuel-cell system. In an FCEV an ultracapacitor would be about twice as large as the Li/S battery providing the same range, and the resulting fuel-cell-plus-battery system about 20% larger than the base-case system. (One could take advantage of the ultracapacitor's extremely high power/energy ratio and design it to handle very high power but not store much energy, in which case the bulk of the ultracapacitor would be reduced, but the driving range at maximum power would also be reduced.)

The challenge in designing an FCEV or BPEV with a long driving range will be to accommodate the energy and power systems without seriously sacrificing the space available for passengers and luggage. In the case of the FCEV, the bulk of the hydrogen storage container could be reduced by increasing the pressure, but this would be costly, and beyond a certain point would not even be very effective, because of nonideal gas behavior. A better idea would be to integrate the storage tanks into the frame of the vehicle. This would require a rescission of the regulation that now requires that pressure vessels periodically be removed from the vehicle to be tested.

4.3. FCEVs vs. BPEVs: system efficiency

Energy for BPEVs or FCEVs can be produced from solar power or from biomass. The efficiency with which this energy is used, expressed here as gJ of useful energy provided to the wheels of the vehicle per gJ of primary energy input, is important in three ways. First, the efficiency of hydrogen or electricity use affects the fuel cost per kilometer. This effect of efficiency is accounted for in the life-cycle cost analysis described later in this paper. Second, the efficiency of energy use often determines total emissions of greenhouse gases (also discussed below). Third, the overall efficiency of converting solar energy into energy at the wheels determines total land requirements for solar- or biomass-hydrogen energy production.

Table 5 shows the overall and stage-by-stage efficiency of four energy-production-and-use pathways: (a) solar electricity used by battery-powered electric vehicles; (b) solar-electrolytic hydrogen used in fuel-cell vehicles; (c) biomass-derived hydrogen used in fuel-cell vehicles and (d) biomass-derived methanol used in fuel-cell vehicles.

Several points are noteworthy. First, the FCEV pathway using solar electricity would use solar energy about 50 times more efficiently than the FCEV pathways using biomass, because of the inefficiency of photosynthesis compared to photovoltaic (PV) solar-energy conversion, and the relatively high loss of energy in converting biomass to fuels. As discussed in Ogden and DeLuchi (1992), this means that biomass/FCEV systems would require much, much more land than would the PV/FCEV system. Second, because the production of bioenergy would require so much land, it would be especially important to produce and use biofuels efficiently. In this regard, biomass-hydrogen FCEVs would be slightly superior to biomass-methanol FCEVs, because of the extra energy loss in converting biomass to methanol (compared to converting it to hydrogen) and the extra energy consumption of the methanol reformer would exceed slightly the energy requirement of compressing hydrogen. (If hydrogen were stored as a hydride, or in some other form that required less energy than compression to high pressures, then the overall efficiency advantage of hydrogen FCEVs would be greater.) Third, the solar-power BPEV system would be about twice as efficient as the solar-hydrogen FCEV system, because of the loss of energy in converting electricity to hydrogen and the hydrogen back to electricity, and about 100 times more efficient than the biomass/FCEV systems, because of the low efficiency of photosynthesis. Direct use of solar power in BPEVs would be the most efficient use of solar energy.

5. ENVIRONMENTAL IMPACTS OF FUEL-CELL AND BATTERY-POWERED VEHICLES

5.1. Urban air quality

The great attraction of hydrogen fuel-cell vehicles is pollution-free operation. While a host of undesirable compounds are emitted from gasoline and diesel fuel vehicles, or are formed from the emitted compounds, a hydrogen FCEV would emit only water. Hydrogen FCEVs would not produce carbon monoxide (CO), nonmethane organic compounds (NMOCs; involved in the production of ozone), nitrogen oxides (NO_x; also involved in ozone production), particulates, sulfur oxides (SO_x), oxidants (such as ozone), carcinogenic aromatic compounds (such as benzene), toxic metals (such as lead), aldehydes or greenhouse gases. They would be environmentally superior even to hydrogen ICEVs, which produce some NO_x as a result of the relatively high temperature of the internal-combustion engine and small amounts of CO and NMOCs from combustion of the lubricating oil (Table 6). (PEM fuel cells operate far below the temperature required to produce NO_x, and do not consume oil.) Only battery-powered EVs can match the zero-emission performance of hydrogen-powered FCEVs (Table 6).

Solar FCEVs and BPEVs are the cleanest personal-transportation options available. The extent to which they would improve urban air quality depends, of course, on the extent to which they would penetrate the vehicle fleet. Because FCEVs could be refueled much more quickly than could BPEVs, and likely would have a lower life-cycle cost (see section 7.3), they probably could attain a greater market

Table 5. Energy efficiency of fuel pathways (primary energy to wheels)[a]

Solar Electricity Used by BPEVs:
Efficiency of stage: 0.15 0.85 0.92 0.81 0.88[b]
Sunlight → PV (dc) → power conditioning → ac transmission → recharger and battery → powertrain → wheels
Energy into stage: 1.00 0.15 0.128 0.117 0.095 0.084

Solar Electricity Used by Hydrogen FCEVs:
Efficiency of stage: 0.15 0.85 0.85 0.92 0.91 0.46 0.88[b]
Sunlight → PV (dc) → power cond. → H_2 prod. → H_2 trans. → compression → fuel cell → powertrain → wheels
Energy into stage: 1.00 0.15 0.128 0.109 0.100 0.092 0.042 0.037

Biomass-Derived Hydrogen Used in FCEVs:
Efficiency of stage: 0.003 0.70 0.92 0.91 0.46 0.88[b]
Sunlight → green biomass → H_2 production → H_2 trans. → compression → fuel cell → powertrain → wheels
Energy into stage 1.00 0.003 0.0021 0.0019 0.0018 0.0008 0.00071

Biomass-Derived Methanol Used in FCEVs:
Efficiency of stage: 0.003 0.66 0.98 0.39 0.88[b]
Sunlight → green biomass → MeOH production → methanol distribution → fuel cell → powertrain → wheels
Energy into stage: 1.00 0.003 0.0020 0.0019 0.0008 0.00067

[a] All paths start with one GJ of biomass energy or electricity. The paths consist of only those stages that consume either the primary energy source (electricity or bio-energy) or the end-use fuel (methanol, electricity or hydrogen). The energy efficiency of stage S_i is defined as: net GJ of product out of S_i and into S_{i+1} divided by total GJ (feedstock plus process energy) into S_i. PV = photovoltaics. (Note that it is more meaningful to compare the two electricity pathways with each other and the two biomass pathways with each other than to compare the electricity with the biomass pathways.) See DeLuchi (1992) and Ogden and DeLuchi (1992) for details.

[b] The estimate of the efficiency of the powertrain accounts energy recovered from regenerative braking over the entire drive cycle. The recharging and battery efficiency does not include the use of any energy to heat a high-temperature battery.

Table 6. Percentage change in gm/km emissions from alternative-fuel light-duty vehicles, relative to gasoline vehicles, year-2000[a]

Feedstock/Fuel/Vehicle	Criteria Pollutants[b] NMOC	CO	NO_x	SO_x	PM	Greenhouse Gases[c]
U.S. power mix/BPEV[d]	−95	−99	−56	+321	+153	−37
NG/compressed hydrogen/FCEV	−100	−100	100	−100[e]	−100	−65
Biomass/compressed hydrogen/FCEV	−100	−100	−100	−100[e]	−100	−84
Biomass/methanol/FCEV[f]	−90	−99	−99	−100[e]	−100	−89
Solar/compressed hydrogen/FCEV[g]	−100	−100	−100	−100[e]	−100	−94
Solar/compressed hydrogen/ICEV	−95	−99	−?[h]	−100[e]	lower	−89
Solar power/BPEV	−100	−100	100	−100	−100	−100
Baseline emissions on gasoline, g/km	0.48	3.81	0.28	0.035	0.01	282.5

[a] The percentage changes shown are with respect to the baseline g/km emissions shown at the bottom of this table, except in the case of BPEVs (see note below).

[b] From Sperling and DeLuchi (1992), DeLuchi (1992), and Wang *et al.* (1990). We assume that all vehicles would use advanced engines and drivetrains, would be optimized to run on the particular fuel shown and would meet the in-use emissions standards mandated by the 1990 amendments to the U.S. Clean Air Act. These estimates are only approximations; actual emissions from any vehicle will depend on the particular characteristics of the engine and emission control systems and on the composition of the fuel, and could differ substantially from our estimates.

NMOCs = nonmethane organic compounds (total emissions of organic compounds less emissions of methane, which is almost nonreactive and hence usually does not contribute to ozone formation). CO = carbon monoxide. NO_x = nitrogen oxides. SO_x = sulfur oxides. PM = particulate matter.

[c] From unpublished runs of an updated version of the model documented in DeLuchi (1991). In these runs all the vehicles were modeled to have the same energy consumption as in the cost analysis presented in this paper. The percentage changes refer to the sum of emissions of CO_2, CH_4, N_2O, CO, NO_x and NMOCs from the entire fuel-production and use cycle (excluding the manufacture of vehicles and equipment), per km of travel. Emissions of gases other than CO_2 have been converted to an "equivalent" amount of CO_2.

[d] The estimates for the BPEV using the national power mix are the "Year-2010 minimum-impact" (minimum-emissions-reduction scenario) of Wang *et al.* (1990), which compares emissions from power plants with emissions from ICEVs (exhaust and evaporative) plus emissions from petroleum refineries.

[e] SO_x emissions are proportional to the sulfur content of the fuel. We assume that methanol and hydrogen would contain virtually no sulfur.

[f] A methanol/fuel-cell vehicle would have no tailpipe emissions of NMOCs, but the storage, distribution and transfer of methanol would produce a small amount of evaporative emissions of methanol (DeLuchi, 1991). The methanol reformer would produce tiny amounts of CO and NO_x (Patil, 1992).

[g] In this scenario, we assume that hydrogen would be produced from water using solar power, but that the hydrogen compressor at the refueling station would run off electricity generated from the projected national mix of power sources in the U.S. in the year 2000 (EIA, 1991). If the hydrogen compressor used solar power, there would be no fuel-cycle emissions of greenhouse gases (100% reduction compared to gasoline).

[h] It is widely believed that hydrogen vehicles could be designed to have very low NO_x emissions, but we are not aware of any recent vehicle-test data (from the official EPA emissions test) that show g/km NO_x emissions much lower than those from a year-2000 gasoline ICEV.

share and hence ultimately could provide greater total air-quality benefits.

5.2. Greenhouse gases

The use of solar electricity to recharge BPEVs, or to make and compress hydrogen for FCEVs, would eliminate not only emissions of urban air pollutants but all fuel-cycle emissions of greenhouse gases as well (Table 6).[4] In fact, solar-powered BPEVs or FCEVs are the lowest-greenhouse-gas-emitting personal-transportation options available. If solar power were used to make but not compress the hydrogen, and instead the U.S. average power mix were used for compression (to 550 bar for vehicle storage tanks), the reduction in greenhouse-gas emissions (relative to the gasoline fuel cycle) would be between 90% and 95%, versus 100% in the case where solar power is used for compression (Table 6).

The use of FCEVs of fuels derived from biomass also would provide a very large reduction in emissions of greenhouse gases, relative to gasoline, although no as large the reduction provided by the all-solar/FCEV cycle (Table 6). For example, the use of biomass-derived methanol in FCEVs would produce only slightly more greenhouse gases than would the use of solar-electrolytic hydrogen compressed using the U.S. power mix projected for the year 2000. There are two reasons why the use of biomass-derived fuels in FCEVs would provide large reductions in emissions, relative to gasoline. First, any CO_2 released from the production and use of a biofuel would not count as a net emission to the atmosphere, because the carbon in the CO_2 would have

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[4] There still would be greenhouse-gas emissions from making and assembling materials for vehicles and solar energy facilities. However, DeLuchi (1991) has estimated that the emissions from the manufacture and assembly of materials for energy facilities probably would be insignificant. This means that vehicle manufacture and assembly would be the only significant source of emissions from an all-solar BPEV or hydrogen-FCEV fuel cycle.

come originally from CO_2 in the atmosphere, via photosynthesis. Second, the vehicles themselves would emit very little (in the case of methanol FCEVs) or zero (in the case of hydrogen FCEVs) non-CO_2 greenhouse gases. However, the use of biomass would not reduce greenhouse-gas emissions as much as would the all-solar cycles because of emissions from planting, fertilizing, harvesting, transporting and gasifying biomass (DeLuchi, 1991).

In the very near term, hydrogen will continue to be made from natural gas. The use of natural-gas-derived hydrogen in an FCEV would provide a large reduction in emissions of greenhouse gases compared to the use of gasoline, because of the high efficiency of the FCEV, the elimination of emissions of greenhouse-gases other than CO_2 and the low carbon-to-hydrogen ratio of natural gas. However, some greenhouse-gas emissions would result from the production and transmission of natural gas, the reforming of natural gas to hydrogen and the use of electricity to compress hydrogen.

6. SAFETY: A MISUNDERSTOOD ISSUE?

In spite of its considerable environmental benefits, hydrogen will not be used widely until policy makers and the public are convinced that it is no more dangerous than the petroleum fuels they are accustomed to. Although hydrogen has a reputation as a particularly dangerous fuel, the limited experience with hydrogen, and analyses of its physical and chemical properties, indicate that it is in some ways more dangerous than gasoline, but in other ways safer.

Hydrogen is more hazardous than gasoline in several ways. First, it is invisible and odorless, and therefore requires odorants and colorants to enable detection. Second, because hydrogen flames are very hot yet radiate very little heat and are invisible, they are harder to locate and thus harder to extinguish or to avoid. Third, hydrogen can ignite within a rather large range of hydrogen/air densities, from 4% to 74% by volume. Compared to methanol or gasoline, it needs very little energy to ignite. (However, all three fuels have such low ignition energies that similar precautions must be taken when handling them.)

But hydrogen also has several safety advantages over gasoline. First, hydrogen must reach a concentration of 18% to 59% in air before it will detonate (as exposed to merely ignite), whereas gasoline can detonate at concentrations as low as 1% to 3% in air. Second, because of its very low molecular weight, hydrogen, if leaked, disperses exceedingly fast – unlike gasoline, which puddles and remains a fire hazard for much, much longer. Third, hydrogen fires burn quite rapidly and are relatively short-lived compared to gasoline fires involving the same amount of energy.

Researchers have judged hydrogen storage systems to be relatively safe (Strickland, 1978; Bockris, 1980; Huston, 1984; Peschka, 1986). Carbon-wrapped aluminum containers, which in the base case we have assumed would be used in hydrogen FCEVs, would have to undergo extensive safety testing before they could be certified.[5] Presently, the USDOT requires that commercial cylinders withstand gunfire without fragmenting, a bonfire without exploding and several pressure cycling and thermal cycling tests. Additional testing by manufacturers has demonstrated that CNG (compressed natural gas) cylinders can withstand extraordinary abuse (Structural Composite Industries, 1986). According to Young (1990), composite pressure vessels, unlike gasoline tanks, generally do not fail catastrophically.

For the reasons cited above, the U.S. National Bureau of Standards (Hord, 1978), the Stanford Research Institute (in Hoffmann, 1981) and the German "Alternative Fuels for Road Transport" program (Quadflieg, 1986), have concluded that the hazards of hydrogen are different from, but no necessarily greater than, those presented by current petroleum fuels. We believe that eventually the public will accept this conclusion as well. As Appleby (1992) points out, "if the public and vehicle manufacturers can be persuaded that natural gas is acceptable, then hydrogen should also be acceptable using identical pressurized storage equipment" (p. 229).

7. A LIFE-CYCLE COST ANALYSIS

Hydrogen fuel and hydrogen vehicles probably will be costly. Even assuming substantial cost reductions over the next 10 to 20 years, renewable hydrogen is likely to cost considerably more than gasoline per gJ (Ogden and DeLuchi, 1992), and hydrogen storage systems are likely to cost orders of magnitude more than gasoline tanks (Table 4). In the case of hydrogen ICEVs, the higher fuel price and vehicle price result in a *life-cycle* cost substantially higher than that of gasoline vehicles (DeLuchi, 1989; Table 7 here). But we will show that this conclusion might not apply to hydrogen-powered *fuel-cell vehicles*, which would be much more efficient than ICEVs (and hence have a lower fuel cost per km), and would use a relatively long-lived and low-maintenance electric powertrain. In this section, we examine the economics of FCEVs by making a detailed and comprehensive life-cycle cost comparison between gasoline ICEVs, hydrogen FCEVs and BPEVs.

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[5] Today, there are some barriers to the use of very-high-pressure storage of hydrogen on a vehicle. For example, the U.S. Department of Transportation (USDOT) presently limits gas storage on board vehicles to no more than 3000 psia. This rule, however, is not based on technical assessments of the safety of advanced-technology, ultra-high-pressure systems; rather, it is due to USDOT wishing to be conservative as it gains experience with a new technology, and, we presume, to the lack of interest in ultra-high pressure storage.

Table 7a. Summary of cost results, FCEVs and BPEVs[a]

	Gasoline ICEV 640-km range	FCEV 400-km range	FCEV 250-km range	BPEV 400-km range
Fuel retail price ($/gallon-equivalent)[b]	1.18	2.97	3.04	2.57
Full retail price of vehicle ($)[c]	17,302	25,446	23,183	28,247
Maintenance cost ($/year)	516	434	434	388
Life-cycle cost (cents/km)	21.45	21.33	20.94	22.96
Break-even gasoline price ($/gallon)	n.a.	1.43	1.27	2.11

[a] Based on the analysis outlined in this paper and detailed in DeLuchi (1992). n.a. = not applicable.

[b] Dollars per gasoline-equivalent gallon is calculated as the $/million-Btu (HHV) price of the fuel to the motorist, excluding federal, state and local taxes ($0.31/gallon in the U.S.), multiplied by 0.125 million Btu/gallon-gasoline. Note that this gasoline equivalence is defined in terms of energy delivered to the vehicle, and hence does not account for the efficiency with which the vehicle uses that energy. The hydrogen production and distribution costs are from Ogden and DeLuchi (1992); in the base case we assume $18 per gJ of hydrogen delivered to the refueling station. We estimated that a high-pressure refueling station will cost $4.50/gJ (DeLuchi, 1992).

[c] Including sales tax, dealer costs and shipping costs.

7.1. Methods

We compare these vehicles using two summary cost parameters: the total cents-per-km life-cycle cost, and the break-even price of gasoline. The total life-cycle cost, expressed here in U.S. cents (1990$) per km of travel, is the sum of all yearly operating costs and all annualized initial costs, divided by the average distance traveled per year. Initial costs include the vehicle shell, chassis and interior, the drivetrain, the fuel storage system and, in the case of FCEVs and BPEVs, the traction battery, the fuel cell and the peak-power device. Operating costs include fuel and/or electricity, insurance, maintenance, registration fees, accessories, replacement tires, parking and tolls. In this analysis, most of these initial and operating costs are a function of many other parameters. Details of the analysis are given in DeLuchi (1992).

The other summary cost statistic used in this analysis is the break-even gasoline price. The break-even price of gasoline is that retail price of gasoline, in $/gallon, including current total average fuel taxes in the U.S. ($0.31/gallon), which equates the total cost-per-km of the gasoline vehicle (insurance cost, maintenance cost, tire cost, amortized initial cost, fuel cost . . . everything) with the total cost-per-km of the hydrogen vehicle.

We assume that all vehicles and their major components, such as fuel cells, hydrogen storage tanks and batteries, are mass-produced at high enough volumes (typically, at least 10,000 units per year) to capture most economies of scale. Our estimate of the cost of producing solar hydrogen is based on the analyses presented in Ogden and DeLuchi (1992). Although hydrogen produced electrolytically from wind or solar power would at present cost much more than most other transportation fuels, costs are projected to drop considerably over the next 10 to 20 years, to perhaps $18/gJ (delivered to the refueling station) by the early part of the next century. Hydrogen produced from biomass would be even cheaper—as little as $6/gJ at the plant gate (Larson and Katofsky, 1992). We consider biomass-derived hydrogen in the scenario analyses.

Generally, our assumptions for FCEVs and BPEVs are optimistic but plausible. They assume continued improvement in all the key technologies but no *major* technological innovations. For most of the important cost parameters for BPEVs and FCEVs, we can cite at least one estimate that is more favorable to BPEVs or FCEVs than is ours (see DeLuchi, 1992). Our cost assumptions for hydrogen ICEVs are perhaps even more optimistic than our estimates for FCEVs: in virtually every case, they are

Table 7b. Summary of cost results, hydrogen ICEVs[a]

	Hydride 400-km range	Liquid hydrogen 400-km range	Compressed hydrogen 400-km range
Fuel retail price ($/gallon-equivalent)	2.86	4.22	2.97
Full retail price of vehicle ($)	26,118	18,719	24,467
Maintenance cost ($/year)	464	464	464
Life-cycle cost (cents/km)	28.67	25.96	26.67
Break-even gasoline price ($/gallon)	4.28	3.36	3.61

[a] The results for the hydrogen ICEVs are from an updated but unpublished version of the analysis described in DeLuchi (1989). See also notes to Table 7a.

at the low end of an estimated cost range (DeLuchi, 1992). We chose relatively optimistic base cases because pessimistic cases would not be very interesting: obviously, if fuel-cell vehicle technology does not develop and costs do not decline, then fuel-cell vehicles will not be economical. (This is demonstrated clearly in our scenario analyses.) We think it is more useful to show the conditions under which a technology might succeed than to say that if technologies do not develop as hoped then they will fail.

7.2. Interpreting the results of the cost of the analysis

The cost results presented here are scenarios, not predictions or projections. There is far too much uncertainty to be making projections: although we have documented or explained all the important assumptions (DeLuchi, 1992) and believe that our analytical method is detailed and sound, we cannot avoid speculating about some of the cost parameters. Therefore, the reader should not view our base-case cost analysis as our attempt at a definitive cost projection, but rather as a scenario analysis—an "if-then" statement"—or as a parametric analysis. For example, as shown below, our base-case assumptions for FCEVs result in life-cycle cost comparable to the life-cycle cost of gasoline ICEVs at the projected price of oil in the year 2000. But this does not mean that we are confidently predicting the economic success of fuel-cell vehicles. Rather, it means either: (a) that if our assumptions are correct, then solar-hydrogen FCEVs will be economically competitive with gasoline ICEVs or (b) that one way to make fuel-cell vehicles economically competitive is to realize the set of cost specifications used here. (Of course, as discussed below, there are many other combinations of assumptions that produce a life-cycle cost equal to or lower than the base-case life-cycle cost, as well as many sets of assumptions that produce a higher life-cycle cost.)

7.3. Results of the base-case analyses

The base-case cost analyses are summarized in Tables 7 and 8. There are four noteworthy results. First, hydrogen FCEVs probably will have a lower life-cycle cost per km than hydrogen ICEVs. Second, hydrogen FCEVs probably will have a lower life-cycle cost than BPEVs, except perhaps if BPEVs have a very short range. Third, with the base-case cost parameters used here, hydrogen FCEVs will be competitive with gasoline vehicles at gasoline prices of less than $1.50/gallon (including taxes). Fourth, life-cycle competitiveness with gasoline ICEVs does *not* depend on large reductions in the cost of the fuel cell itself. Each of these results is discussed in more detail next.

The lower life-cycle cost of hydrogen FCEVs, compared to hydrogen ICEVs (even with very optimistic cost assumptions for the hydrogen ICEVs), is due to several factors: the much higher net efficiency of the fuel-cell electric-drive system (about 46% for the fuel cell, including auxiliaries, and 88% for the drivetrain, giving an overall system efficiency of 40%; see Table 5) compared to the IC engine and transmission (about 14% in combined city and highway driving, in use); the lower average-annual maintenance costs (Table 7); and, most importantly, the longer life of the electric drivetrain. The higher efficiency of the fuel cell not only reduces fuel costs but also reduces the amount of fuel that must be carried to provide a given range, which reduces the cost of the fuel storage system. This reduction in the cost of fuel storage is significant in the case of hydrogen, because hydrogen storage is expensive per unit of fuel carried. The longer life of the drivetrain is important because it substantially reduces the amortized cost-per-km of buying a vehicle. These advantages, plus the significantly lower cost of the electric drivetrain, more than compensate for the extra cost of the fuel-cell-plus-battery system in the FCEV. Therefore, if these cost results prove accurate, then it clearly will be more economical to use hydrogen in FCEVs than in ICEVs.

The lower projected lifecycle cost of hydrogen FCEVs, compared to BPEVs, is due entirely to the great cost of the battery required for a 400-km or even a 250-km range. Although the BPEV would have slightly lower maintenance costs and fuel (electricity) costs than would the FCEV, and would not have a fuel-cell or hydrogen-storage system, these savings would be swamped by the cost of a 400-km battery—well over $10,000 at the retail level. (Note that most battery-cost estimates in the literature are of manufacturing cost, not retail cost. The retail cost is roughly twice the manufacturing cost.) Moreover, the great weight and cost of the battery would increase the cost of insurance, tires, and registration, and would necessitate a larger, more expensive powertrain to match the performance of the FCEV (Tables 4 and 8). Of course, if the battery were much smaller and the range of the BPEV much less, the life-cycle cost would be less. Our analysis indicates that a BPEV with a 160-km (100-mile) range would have approximately the same life-cycle cost as an FCEV with a 400-km (250-miles) range. Based on this, we believe that BPEVs with a long driving range probably would never compete economically with FCEVs with the same driving range, but that BPEVs with small, low-cost batteries could compete with FCEVs with a short range. This suggests that battery researchers should concentrate at least as much on reducing the cost of batteries as on improving performance.

The prospect that hydrogen-FCEVs could be economically competitive with gasoline-fired ICEVs, despite the high initial cost of the FCEVs and the higher cost of solar-electrolytic hydrogen (Table 7), is due to three factors. First, the electric powertrain (excluding the battery and fuel cell) would cost much less than the ICE system it replaced (DeLuchi, 1992). Second, the FCEV would be nearly three times as efficient as the ICEV (Table 3). This would lower

Table 8. Life-cycle cost of gasoline ICEVs, BPEVs and FCEVs, 400-km range (cents/km)[a]

Gasoline (baseline)	BPEV	FCEV	Cost Item
0.00	1.52	0.20	Purchased electricity, incl. recharging station[b]
11.17	7.59	7.18	Vehicle, excl. battery, f.c. and H_2 system[c]
0.00	7.08	2.15	Battery, incl. tray and auxiliaries
2.82	0.00	1.96	Fuel, excluding retail taxes
0.00	0.00	0.81	Fuel storage system
0.00	0.00	2.23	Fuel cell system, including reformer
2.53	3.23	3.09	Insurance[d]
3.21	1.98	1.17	Maintenance, repairs, oil and tires[e]
0.36	0.21	0.19	Vehicle registration and inspection fees[f]
1.35	1.35	1.35	Parking, tolls, fuel taxes, accessories[g]
21.45	22.96	21.33	Total cost per km
	2.11	1.43	Break-even gasoline price ($/gal)

[a] Calculated from the input data and formulae shown in DeLuchi (1992). n.a. = not applicable.

[b] In the base case, this includes electricity bought to heat the battery when the vehicle is idle, as well as electricity bought to recharge the battery. In the scenario analyses, we consider a case in which hydrogen (via the fuel cell) is used to heat and recharge the battery in the FCEV (to the extent that regenerative braking does not). It is costly to use hydrogen for these purposes, but it does liberate the vehicle from plug-in recharging.

[c] The amortized initial cost of the EVs (excluding the battery, the fuel cell and the fuel storage system, which are treated separately) is less than the amortized initial cost of the ICEV, because the EVs have both a lower initial cost (excluding the components listed above) and a longer life.

[d] The insurance cost per km is calculated as a function of the km driven per year, the value of the vehicle, the amount of the deductible and the number of years that insurance against collision damage is carried. Because the complete EVs (i.e., with the battery, fuel cell and fuel storage system) of this analysis are more expensive than the ICEV and might be driven more km per year, they have a higher insurance cost per km.

[e] EVs are expected to have lower maintenance and repair costs than ICEVs, and no oil cost (DeLuchi, 1992). The tire-cost-per-km is calculated as a function of the frequency of tire replacement, which in turn is a function of the weight of the vehicle.

[g] We assume that the cost per km would be the same for all vehicle types.

[f] We assume that the vehicle registration fee is a function of vehicle weight, as it is now in most states. We also assume that EVs will be charged less for vehicle inspections, since they do not have pollution control equipment.

[g] We assume that all these costs, including federal and state fuel taxes, will be the same for all vehicles, on a per-km basis.

the cost of fuel, so much so that the cost-per-km of hydrogen in an FCEV actually would be lower than the cost-per-km of gasoline in an ICEV (Table 8), given the base-case fuel prices (Table 7) of this analysis. Third, the electric drivetrain probably would have lower maintenance costs and last much longer than the ICE drivetrain. If the longer life of the electric drivetrain translated into a longer vehicle life, the amortized cost per km of vehicle ownership would be dramatically reduced. The longer life and lower cost of the electric drivetrain would compensate for many of the cost disadvantages of the FCEV (Table 8). However, even though our assumption of a longer vehicle life is supported by experience in England, where electric fleet vehicles last longer—in some cases, several times longer—than their ICEV fleet counterparts, it still is unproven as regards all household and commercial vehicles. We therefore test different assumptions about vehicle life in the scenario analyses.

In order to get a rough idea of the economics of FCEVs, analysts often compare the cost of hydrogen or methanol fuel with the cost of gasoline, and the initial cost of a fuel-cell system with the cost of an engine (e.g. Appleby, 1992). These comparisons can be interesting, but because they omit several important variables, they usually do not tell the whole story. As demonstrated here, the advantages of FCEVs—longer life, lower maintenance costs and higher efficiency than with ICEVs—can compensate for the higher $/gJ cost of hydrogen and the higher $/kW cost of the complete fuel-cell, hydrogen-storage and electric-drive system (compared to the cost of an ICE system). In fact, our analysis indicates that achieving a very low cost for hydrogen fuel and the fuel-cell system is by itself neither necessary nor sufficient to make the life-cycle cost of an FCEV competitive with that of gasoline ICEV. For example, in our base-case analysis, the fuel cell and auxiliaries alone (excluding the electric drivetrain) cost over $150/kW at the vehicle-retail level, whereas the retail-level cost of the entire ICE powertrain (all the parts removed from the ICEV) is about \$55/kW — yet on a life-cycle-cost basis, the hydrogen FCEV competes economically with the gasoline ICEV. This is partly because of the life-cycle-cost advantages mentioned above, and partly because in this analysis the peak power of the EV is less than the peak power of the ICEV, and the fuel cell itself supplies only part of the peak power — a battery, with a lower power cost supplies the rest. Thus, we believe it is unnecessarily stringent, and perhaps misleading, to set cost targets for fuel cells or fuel-cell components based only on a comparison with the cost of an engine. The economics of FCEVs should be evaluated on a systems life-cycle basis.

We do recognize that the cost disadvantages of FCEVs (the high initial cost and the high fuel cost) might be more prominent in the eyes of consumers than the cost advantages (long life, high efficiency and low maintenance costs), at least initially. Thus, FCEVs might have a reasonable life-cycle cost but seem relatively expensive to many consumers. We believe that this gap between perception and reality can and to some extent will be closed in two ways.

First, education and experience will make consumers understand, believe in and ultimately value the longer life and lower maintenance costs of FCEVs (assuming, of course, that these benefits are real). Experience with diesel vehicles supports this hypothesis (Kurani and Sperling, 1989; see also Turrentine, *et al.*, 1991, on perceptions of the maintenance costs of EVs). If buyers do not now think much about vehicle life and maintenance, it probably is because the differences in these attributes among vehicles are minor and unreliable. However, even now, most consumers do not think solely in terms of initial cost, because most take out a loan to buy a vehicle and hence face a monthly payment rather than an initial cost.[6] It is not difficult to imagine that prospective car buyers already used to considering monthly vehicle payments would begin to weigh more explicitly the operating costs and resale value of the vehicle if there were significant and certain differences in these attributes between EVs and ICEVs.

Second, government can subsidize or even mandate FCEVs, or penalize ICEVs, in recognition of the environmental benefits of FCEVs, and to help overcome initial consumer wariness.

7.4. Scenario analyses

7.4.1. EVs versus gasoline ICEVs. We must emphasize that many of the important cost parameters are very uncertain. Although as mentioned above we do not assume any major technological breakthroughs, and generally have *not* used the lowest estimates available for major components, we do assume that the key battery, fuel cell and hydrogen storage technologies will be developed successfully, and that mass production will greatly reduce costs to levels that are being targeted or estimated by industry analysts and others. As shown in Table 9, if we have been too favorable in our estimation of any one of several important cost parameters — the cost of the fuel cell, the cost of the battery, the cost of the electric drivetrain, the lifetime of the battery, the lifetime of the BPEV or FCEV, the ratio of the retail price to manufacturing cost, the production cost of hydrogen, the efficiency of the electric powertrain relative to the ICE powertrain, the cost and characteristics of the hydrogen storage system (scenarios 3, 4, 10–15 and 18) — then the break-even gasoline price for the FCEV and BPEV would increase substantially, in many cases by over \$0.30/gallon. The assumed driving distance, maximum performance and driving cycle of the FCEV and BPEV also are quite important: a high-power, long-range FCEV or BPEV used mainly in highway driving would have a much higher life-cycle cost than the vehicle assumed for our base-case analysis (scenarios 1, 2, 6 and 19). Assumptions about financial parameters — e.g. The interest rate, and the percent of people taking out a loan to buy the vehicle — (scenarios 8 and 9) are less important but not trivial. But most importantly, any combination of two to four of the high-end scenarios of Table 9 would result in a much higher vehicle life-cycle cost than in the base case and would make the FCEV economically unattractive (e.g. scenarios 20 through 22). The BPEV already is somewhat unattractive in the 400-km case.)

On the other hand, our base-case scenario is not the only one in which FCEVs are competitive with gasoline ICEVs. In fact, as shown in the low-end scenarios of Table 9, there are many other favorable scenarios. For example, if hydrogen were produced from biomass instead of from solar power, the production cost would be much lower, and the break-even gasoline price would be significantly lower (scenario 14). Or, the lifetime of the BPEV or FCEV might exceed the lifetime of the ICEV by more than 33%; in this case the break-even gasoline price would be reduced considerably for both the BPEV and the FCEV. If the ratio of the retail price to the manufacturing cost was 1.5 : 1 instead of 1.77 : 1, then the break-even price for both FCEVs and BPEVs would be much lower than in the base case, and hydrogen FCEVs would be competitive with gasoline ICEVs at well under \$1/gallon of gasoline. If the fuel cell, battery or electric drivetrain cost less than we have estimated or assumed, or if the vehicle had less power and a shorter range, or if the EV drivetrain was more efficient, then the break-even gasoline price for both the BPEV and the FCEV again would be much lower than in the base case. The successful development of H-Power's iron oxidation/reduction

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[6] Our cost analysis assumes both that more people would take out loans to buy cars in the FCEV world than in the ICEV world, and that the interest rate on loans in the FCEV world would be higher than in the ICEV [no-FCEVs] world, due to the increased demand for credit. In both worlds, the interest rate on loans is substantially higher than the interest rate consumers effectively face when paying cash for a vehicle. See DeLuchi (1992).

Table 9. Scenario analyses: sensitivity of the break-even gasoline price to important cost parameters

Scenario examined (low end–high end) [base case][a]	Break-even gasoline price (1990$/gallon)	
	BPEVs	FCEVs
0) Base case results (400-km range)	2.11	1.43
1) Miles of city driving divided by total driving miles (1.00–0.00) [0.68]	1.91–2.81	1.24–2.12
2) Km of driving range per tank or battery charge (160–560) [400][b]	1.48–2.98	1.50–1.67
3) In-use once-through electric-drivetrain efficiency (0.76–0 62) [0.69][c]	1.61–2.77	1.04–1.87
4) Life VMT of EV divided by life VMT of ICEV (1.66–1.00) [1.33][d]	1.67–3.18	0.82–2.72
5) Life miles to scrappage, baseline gasoline ICEV (100k–140k) [120k][e]	1.76–2.46	1.17–1.65
6) Ratio of EV to gasoline ICEV max. acceleration (0.60–1.00) [0.80]	1.60–2.69	1.05–1.84
7) Horsepower of baseline gasoline-vehicle engine (120–170) [145][f]	1.72–2.55	1.14–1.72
8) How the vehicle is payed for (0% of buyers take out loan—80% take out loan, no downpayment) [70% take out loan with 11% downpayment]	1.67–2.24	1.18–1.53
9) Foregone real before-tax interest rate on cash (2.5%–15%) [3.6%]	2.08–2.39	1.41–1.68
10) Ratio of retail price (excl. taxes) to OEM cost (1.50–2.30) [1.77][g]	1.40–3.58	0 88–2.56
11) OEM $/kW cost of electric drivetrain, excl. battery (($400 + $16/kW)-($625 + $25/kW)) [$500 + $20/kW]	1.88–2.41	1.23–1.69
12) Fuel-cell cost, retail level, incl. tax ($100/kW–$250/kW) [$180/kW][h]	n.a.	0.92–1.89
13) Battery manufacturing cost (($400 + 72/kWh + $5.20/Kw) – ($600 + $108/kWh + $7.80/kW)) [$500 + $90/kWh + $6.50/kW]	1.41–2.84	1.22–1.65
14) Delivered cost of electricity and hydrogen ($0.04/kWh–$0.13/kWh and $7/gJ–$33/gJ) [$0.07/kWh and $18/gJ][i]	1.85–2.64	1.00–2.05
15) Hydrogen storage (Iron redox—FeTi hydride) [Compressed gas][j]	n.a.	1.02–1.98
16) Battery heat loss (no heat loss—heating energy comes from battery or fuel cell) [loss of 4.0 W/kWh made up by electricity from outlet][k]	2.05–4.72	1.42–1.90
17) Battery heating & recharging in FCEV (from the fuel cell) [wall outlet]	n.a.	1.77
18) Battery cycle life, to 80% depth of discharge (1100–500) [800]	1.43–3.62	1.23–1.89
19) Scenarios 2 and 6 combined	1.05–3.72	1.06–2.12
20) Scenarios 2, 4, and 6 combined	0.66–4.99	0.55–3.51
21) Scenarios 3 and 14 combined	1.38–3.38	0.69–2.56
22) Scenarios 10, 11, 12 and 13 combined	0.63–4.66	0.21–3.34

[a] In each scenario, only the parameters named change from their base-case values, except that the sizing tradeoff between the battery and the fuel cell is reoptimized where necessary (these instances are noted below), and any variables linked to the parameter of interest (e.g., vehicle weight) change automatically. Each scenario shows the effect of substituting low and high values (shown in parentheses) for the parameter of interest. The "low-end" value is the value that results in the low-end break-even gasoline price, not necessarily the numerically lower value. The "high-end" value is the value that results in the high-end break-even gasoline price. The base-case values of the parameters are shown in brackets and are documented in DeLuchi (1992). OEM = original equipment manufacturer. "EV" refers to both the BPEV and the FCEV. n.a. = not applicable. VMT = vehicle miles traveled.

[b] The fuel cell and the battery are resized in these scenarios. The 160-km range FCEV has a higher life-cycle cost than the 250- and the 400-km range FCEVs because the peak-power battery in the 160-km FCEV must be replaced more frequently than the batteries in the longer-range FCEVs.

[c] The electric drive includes the motor, electronics package (controller and inverter) and transmission. "Once-through" means that regenerative braking is not included in this metric (it is accounted for in the final cost results, however). "In-use" means that an adjustment is made for the difference between the efficiency measured over a test cycle and the efficiency achieved in the real world. The fuel-cell and battery are resized in this scenario.

[d] The life of the fuel cell is assumed to be equal to the life of the FCEV, but the life of the battery is assumed to be 800 cycles regardless of the life of the vehicle.

[e] The relative lifetime of the BPEV and the FCEV remain the same (1.33 times that of the ICEV).

[f] Only the horsepower of the baseline gasoline vehicle changes in the scenario. The weight and cost of the baseline vehicle, and the relative high-end acceleration of the BPEV and FCEV (80% of that of the ICEV) remain the same.

[g] We define the OEM (original equipment manufacturer) or manufacturing cost of the vehicle as the direct variable cost, which is equal to the cost of materials and parts plus the cost of assembly labor (including benefits) plus the operating cost of the assembly plant. The retail price is equal to the manufacturing cost plus the cost of research and development, design engineering, major equipment and facilities, advertising, testing and certification, executives, shipping, retailing and so on.

[h] If there were a peak-power device with the same cost as the Li/S battery assumed here, but with higher power density (perhaps an advanced ultracapacitor), then in the low-end fuel-cell cost scenario, one could reduce the power of the fuel cell and increase the power of the battery and thereby lower the break-even price to $0.80/gallon.

[i] Hydrogen produced by gasification of biomass could be delivered to the refueling station for as little as $7/gJ (Larson and Katofsky, 1992). On the other hand, solar-electrolytic hydrogen could cost over $30/gJ delivered (Ogden and DeLuchi, 1992). Utilities might charge customers as little as $0.04/kWh for off-peak battery recharging, but as much as $0.13/kWh or more for the use of peak power.

[j] We use the hydrogen-storage cost and performance estimates presented in Table 2. "Iron redox" (the low-cost system) is the iron oxidation/reduction system described by Werth (1992).

[k] If the battery were to provide the energy needed to maintain its own heat (the high-cost end of this scenario), then it would have to contain enough energy to heat itself and provide the original driving range (400-km in the case of the BPEV). This would require a very large and costly battery.

system could lower the cost of hydrogen storage by nearly an order of magnitude and reduce the break-even gasoline price for FCEVs to about $1/gallon. And if several of the favorable cases were combined, the hydrogen FCEV would have a lower life-cycle cost than the gasoline ICEV at any conceivable future gasoline price, and the BPEV with a long driving range would be attractive at gasoline prices of around $1.40/gallon – less, in some cases.[7] (The life-cycle cost of the BPEV is particularly sensitive to changes in parameters that affect the life-cycle cost of the battery. These parameters include the OEM battery cost, the driving range, the ratio of the retail-level price to the OEM cost and the battery life.)

7.4.2. Hydrogen FCEVs versus hydrogen ICEVs. In order for hydrogen ICEVs to have a lower life-cycle cost than hydrogen FCEVs, one must combine very optimistic assumptions for ICEVs (the base case here) with pessimistic assumptions about FCEVs (for example, scenarios 20 and 22 of Table 9 combined). In the vast majority of scenarios, hydrogen FCEVs have a lower life-cycle cost than hydrogen ICEVs.

7.4.3. Summary. Clearly, there is a good deal of uncertainty in this cost analysis. Nevertheless, two conclusions are fairly robust. First, there are *many* scenarios in which hydrogen FCEVs have a lower life-cycle cost than gasoline ICEVs. Second, in *most* scenarios hydrogen FCEVs have a lower life-cycle cost than BPEVs and hydrogen ICEVs. (The second conclusion is robust because there is less uncertainty in comparing hydrogen FCEVs with BPEVs or hydrogen ICEVs than with gasoline ICEVs, because hydrogen FCEVs will be more like BPEVs and hydrogen ICEVs.)

8. SUMMARY AND CONCLUSIONS

If fuel-cell and electric-drive technology develops as we have assumed, then hydrogen FCEVs will have roughly the same life-cycle cost as gasoline ICEVs when gasoline retails for around $1.50/gallon (including taxes). However, hydrogen FCEVs probably would be attractive from society's point of view at lower gasoline prices, because of their significant local and global environmental benefits (compared even to relatively clean year-2000 gasoline ICEVs). Solar-powered BPEVs would be equally as attractive environmentally, but likely would have a higher life-cycle cost than solar-hydrogen FCEVs (unless the BPEVs had a relatively short range) and would take much longer to refuel [recharge]. Solar-hydrogen FCEVs thus could satisfy a much larger market than could BPEVs (Nesbitt, *et al.*, 1992), and hence could do more to improve urban air quality and mitigate global warming. Solar-hydrogen FCEVs could be the all-purpose "zero-emission vehicles" of the future.

Hydrogen FCEVs also would have a lower life-cycle cost than hydrogen ICEVs and slightly lower emissions of criteria pollutants and greenhouse gases (assuming the same fuel feedstock). Thus, we believe that if hydrogen is to be used at all in transportation, it should be used in FCEVs rather than ICEVs. Future hydrogen research programs should be directed with this in mind.

Of course, these conclusions assume the successful development of fuel-cell vehicles. The critical technology in the FCEV is the fuel cell itself. Because the development of the fuel cell has lagged the development of the other components of FCEVs (batteries, electric drivetrains and even hydrogen storage systems), its cost and performance cannot yet be characterized as well. We have assumed that high specific power and high net energy efficiency can be achieved at relatively low total cost. Fuel-cell technology must progress steadily over the next decade in order to realize these assumptions. The peak-power device and the hydrogen storage system in the FCEV also must be developed further to reach the cost and performance levels assumed here.

Although none of these R & D tasks is trivial, there are so many technology and design routes for each task – at least three different kinds of fuel cells potentially suitable for highway vehicles (PEM, alkaline and solid oxide), at least four different ways to supply peak power (several types of batteries, ultracapacitors, flywheels or the fuel cell itself) and many ways to store hydrogen – that we are optimistic that eventually all the components of FCEVs will be developed successfully.

Ultimately, marketability will be the yardstick of success. To begin to understand how consumers will use and react to hydrogen FCEVs, a large number of experimental vehicles should be built and tested. The purpose of these projects should not be to display a purportedly finished technology, but rather to experiment – to provide information from users that can feed back to basic research and development. Hydrogen FCEV technology already is far enough along that this experiment and fed-back strategy could begin today. Within a decade this strategy could provide a reasonably clear picture of the ultimate technical and economic potential of the fuel cell in transportation. With success, hydrogen FCEVs could be an economical clean transport option by the early part of the next century.

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[7] Of course, this economic analysis does not account for the environmental and energy-security benefits of FCEVs and BPEVs. If these benefits were monetized, hydrogen-powered FCEVs probably would be socially cost-effective under a relatively wide range of conditions.

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