Proceedings of the 2000 DOE Hydrogen Program Review
NREL/CP-570-28890

ANALYSIS OF RESIDENTIAL FUEL CELL SYSTEMS & PNGV FUEL CELL VEHICLES

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Abstract

Directed Technologies, Inc. has completed two analysis projects for the hydrogen program office during the past year: an assessment of battery augmentation for residential fuel cell systems, and an analysis of the effects of applying PNGV (Partnership for a New Generation of Vehicles) body parameters to both fuel cell vehicles and to hybrid electric vehicles. We have also started the first activities in a three-year competitively bid grant to compare in detail hydrogen with methanol and gasoline as fuels for fuel cell vehicles.

The results of adding a battery to a residential fuel cell system were negligible. A storage battery provides the peak power to the home, permitting a much smaller and less expensive fuel cell system. However, the cost savings due to a smaller fuel cell system were nearly offset by the added costs of the battery system, resulting in very little change in our results from last year: in order to bring a 10% real, after-tax return on investment, a company would still have to charge a single family residence about 40 ¢/kWh, well above the average residential rate near 8 ¢/kWh.

In the transportation sector, using PNGV body parameters (drag coefficient, cross sectional area, rolling resistance, and weight) for passenger vehicles instead of current body parameters uniformly improved the performance of all vehicles in terms of increased fuel economy and decreased greenhouse gas emissions. This analysis shows that only a direct hydrogen FCV will meet the PNGV fuel economy goals of 80 mpgge on realistic driving cycles. Converting from current to PNGV body parameters also reduces the differential cost of a fuel cell vehicle compared to an internal combustion engine vehicle by $450 – with conventional vehicle bodies, the fuel cell vehicle would cost about $2,100 more, while a PNGV fuel cell vehicle would cost only $1,650 more than a conventional car.

Executive Summary for PNGV Transportation Analysis

Directed Technologies, Inc. has previously compared the fuel economies, costs, and environmental impacts of various alternative fueled vehicles including three types of fuel cell vehicles (direct hydrogen, methanol and gasoline) and nine different types of hybrid electric vehicles (Thomas -1998a, 1998b, 1998c). All of these previous analyses used an AIV (aluminum intensive vehicle) Sable as the basic glider. The power source of the AIV Sable was varied, keeping the characteristics of the vehicle fixed. However, the Partnership for a New Generation of Vehicles (PNGV) is developing a new class of vehicle with the goal of a three times increase in fuel economy. We were therefore tasked to evaluate the same group of alternative power train systems with the proposed PNGV glider instead of the AIV Sable glider characteristics. The PNGV glider will have less weight, less aerodynamic drag and less rolling resistance than the AIV Sable, which itself is approximately 300 kg lighter than a conventional Sable or Taurus five-passenger vehicle.

This analysis has demonstrated that converting to a lighter and more aerodynamic vehicle body does not significantly alter the *relative* merits of the fuel cell and hybrid electric vehicles relative to conventional passenger vehicles. The fuel economies of all vehicles (including ICEVs) improves more or less uniformly by almost 30%, but the relative improvements in performance of the alternative fueled vehicles compared to a more conventional internal combustion engine vehicle (ICEV) remain nearly constant. For example, the fuel economy of a direct hydrogen FCV on the 1.25 times accelerated EPA combined 55/45 city/highway driving schedule[1] is about 2.19 times higher than the corresponding ICEV with the AIV Sable. This fuel economy advantage increases only slightly to 2.23 times higher when both vehicles use a PNGV glider.

From another perspective, the fuel economy of a direct hydrogen FCV improves by a factor of 1.29 (from 65.8 mpgge[2] with the AIV Sable up to 85.2 mpgge with the PNGV glider), while the conventional gasoline-powered ICEV improves by a factor of 1.27 (from 30.1 mpg to 38.2 mpg by converting to a PNGV glider). Both of these calculations assume no improvement in the efficiency of the power source -- the ICE and the fuel cell efficiencies are fixed -- only the vehicle glider characteristics change.

While the fractional change in fuel economy is only slightly better with the FCV compared to the ICEV, the absolute fuel economies illustrate that fuel cell technology is required to reach the 80 mpg fuel economy goal of the PNGV, as shown in Figure 1. Both the pure FCV that has no battery or other peak power augmentation device and the battery-augmented direct hydrogen

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[1]Directed Technologies, Inc. uses the U.S. Environmental Protection Agency (EPA) combined driving schedule (55% city and 45% highway) with each speed increased by a factor of 1.25 for all comparative analyses. This 1.25 times acceleration factor more closely resembles American driver habits as discussed below.

[2]Fuel economy is measured in miles per gallon of gasoline-equivalent (mpgge) on a lower heating value (LHV) basis. That is, the LHV energy content of hydrogen necessary to propel a 65.8 mpgge-FCV over 65.8 miles of the specified driving cycle would be equal to the lower heating value of one gallon of gasoline.

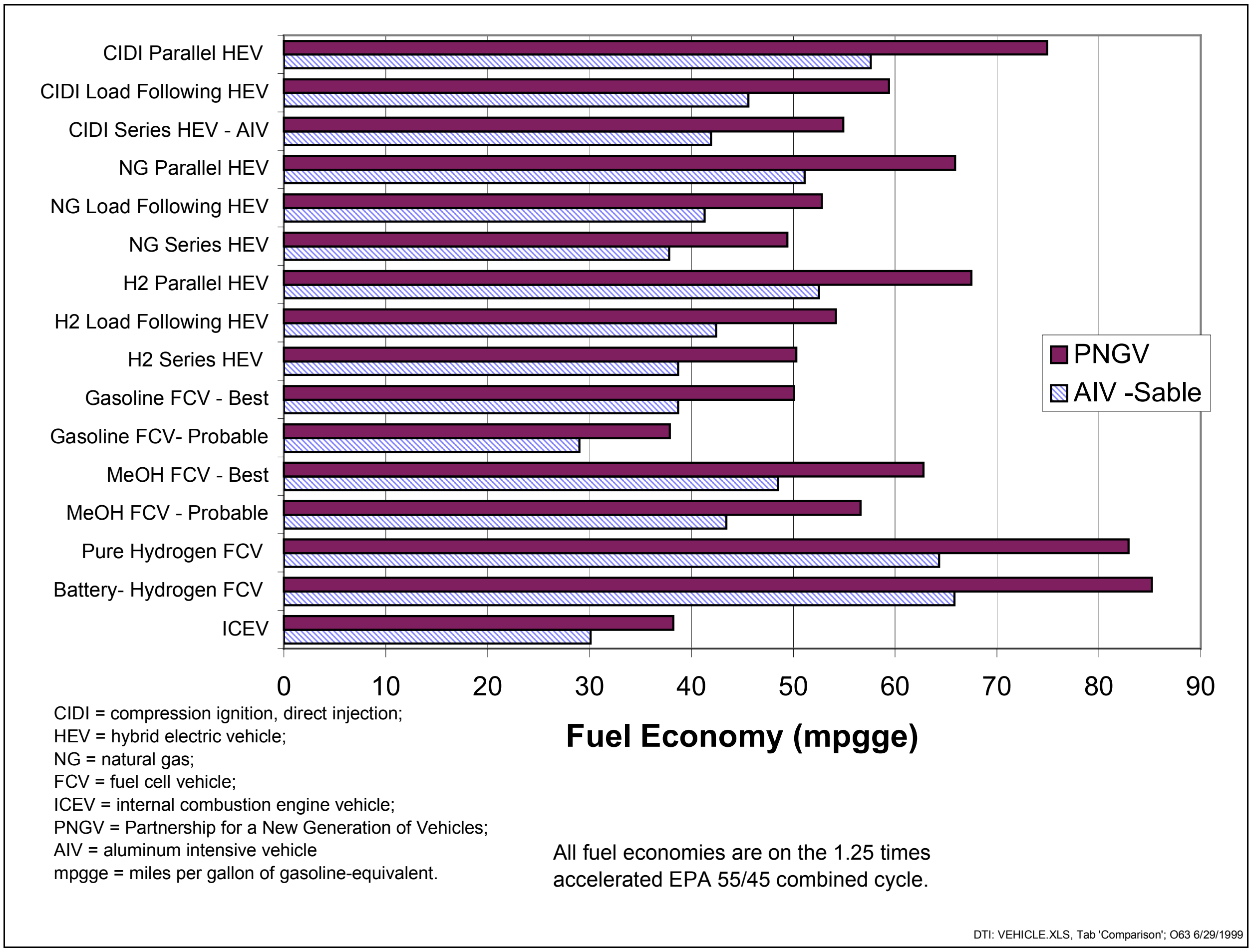

Figure 1. Estimated Fuel Economy for Various Fuel Cell and Hybrid Electric Vehicles on the 1.25 Times Accelerated EPA Combined Driving Cycle

FCV would achieve over 82 mpgge on the 1.25 times accelerated combined driving cycle. The diesel-powered compression ignition direct injection (CIDI) vehicle in the parallel hybrid mode would reach almost 75 mpgge, close to the PNGV goal. All series hybrid electric vehicles (in either the thermostat on/off mode or the load following mode) and all fuel cell vehicles powered by either gasoline and methanol in the probable cases would achieve less than 60 mpgge.

Both the hydrogen and the diesel parallel hybrid vehicles could achieve the 80 mpgge goal on the standard EPA 55/45 combined schedule without the 1.25 acceleration factor, as shown in Figure 2. However, this driving schedule does not reflect the speed and acceleration rate profiles of typical American drivers. These vehicles would meet the 80 mppge goal on paper only. In any case, even with the unrealistic EPA combined cycle, the FCVs with onboard reformers would not meet the 80 mpgge goal, although the best-case methanol FCV would come very close at 79.8 mpgge. On this unrealistic driving cycle[3], the direct hydrogen FCVs would achieve over 105 mpgge.

[3] Although the EPA combined driving cycle is unrealistic, it is the standard often used to compare vehicle performance.

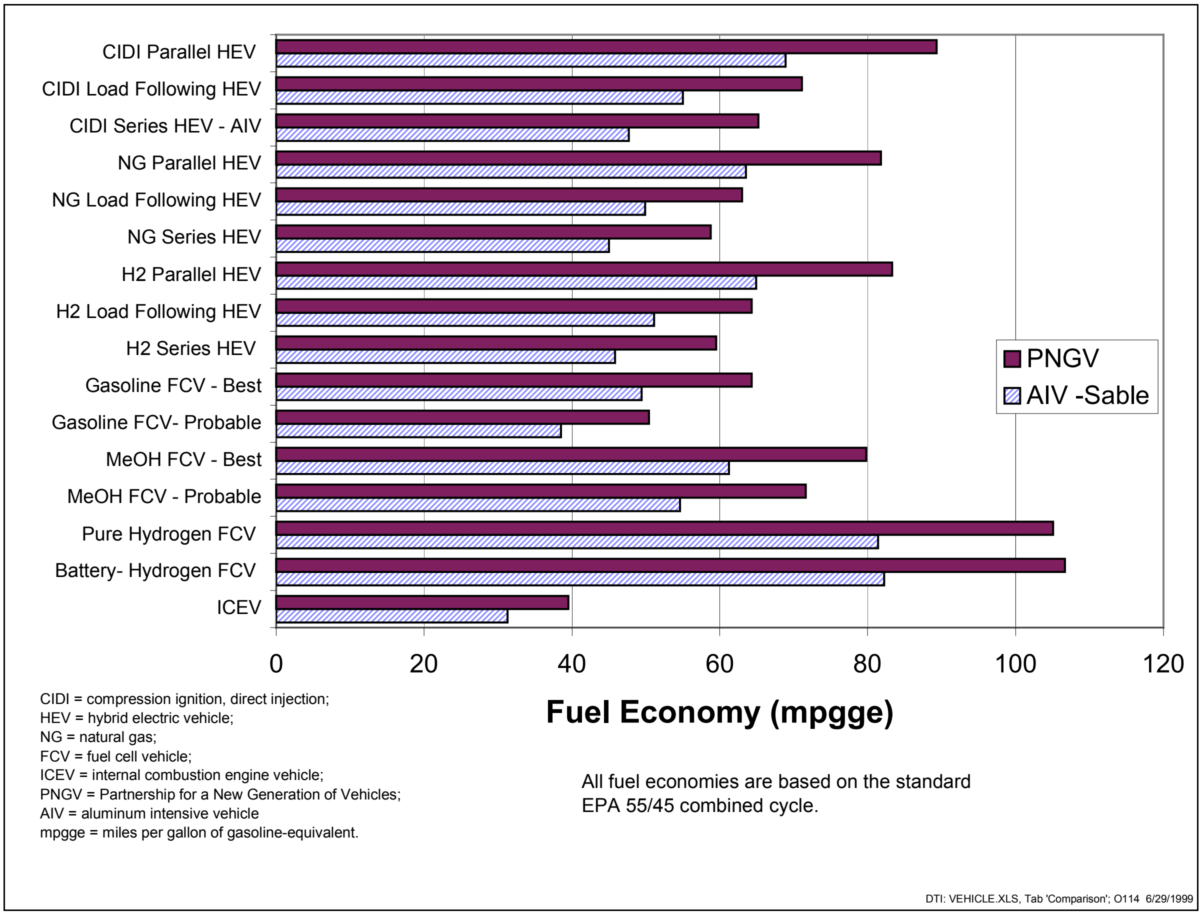

Figure 2. Estimated Fuel Economy for Various Fuel Cell and Hybrid Electric Vehicles on the Standard EPA Combined Driving Cycle

The environmental benefits of the alternative vehicles are generally proportional to fuel economy. Hence switching from the AIV Sable to the PNGV glider will also improve environmental benefits (both local emissions of criteria pollutants and greenhouse gas emissions) by the fuel economy factors -- an improvement of 1.29 for the FCV and an improvement of 1.27 for the ICEV. However, the diesel parallel hybrid vehicle has a net greenhouse gas advantage over the direct hydrogen FCV when the hydrogen is derived from natural gas by conventional steam methane reforming, as shown in Figure 3.

In addition, the natural gas parallel hybrid produces less greenhouse gas emissions than a hydrogen parallel hybrid, since more natural gas is consumed in making hydrogen than is used to directly fuel a hybrid vehicle. Thus there is no incentive from a climate change perspective in making a hydrogen hybrid vehicle -- storing natural gas directly on the vehicle not only reduces the volume of gas storage required, but also reduces net greenhouse gas emissions. The hydrogen hybrid vehicle would have an advantage in terms of local criteria pollutant emissions, as discussed in previous DTI reports (Thomas-1998a).

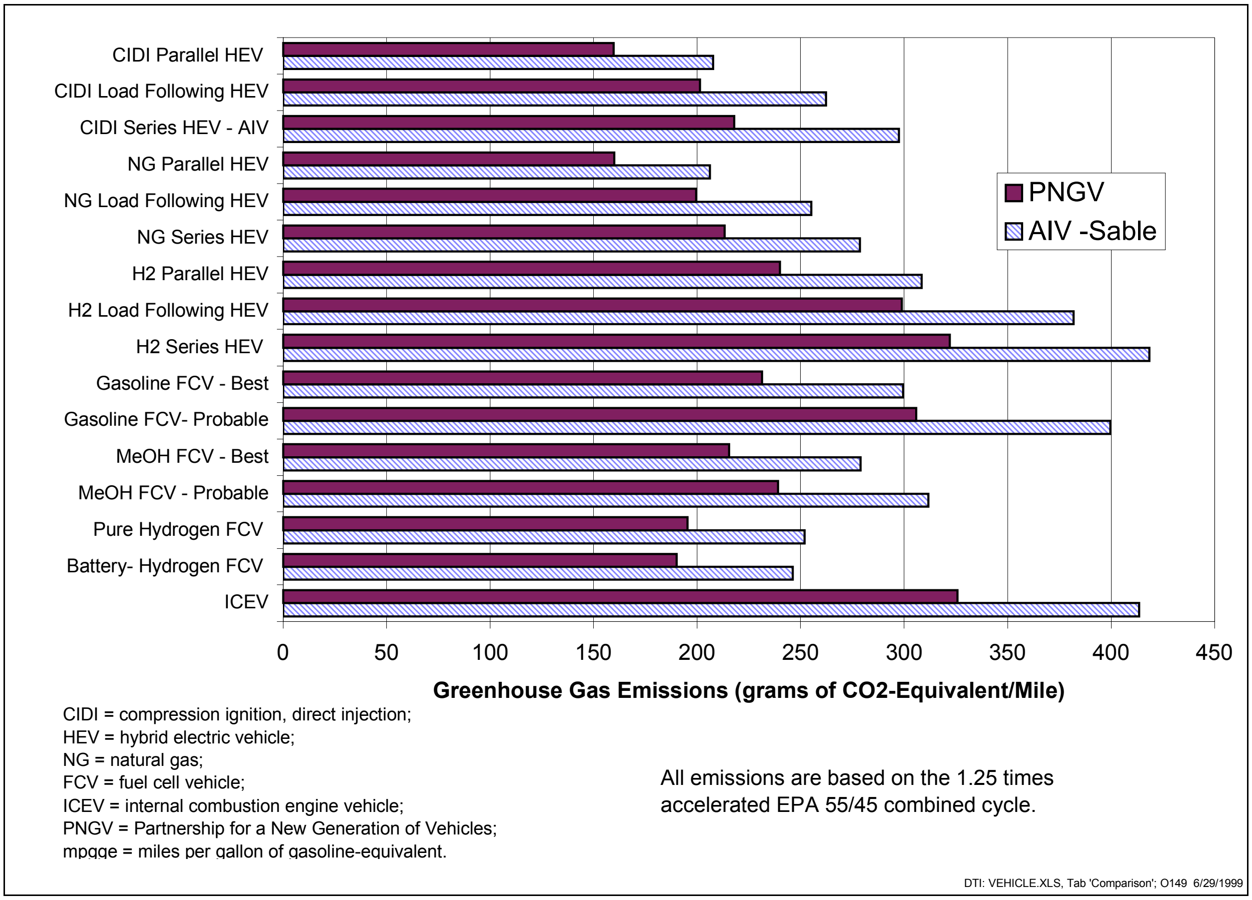

Figure 3.Estimated Greenhouse Gas Emissions from Alternative Vehicles

We conclude that switching from the AIV Sable glider to the PNGV glider for a five-passenger vehicle will improve fuel economy by about 30% and will decrease greenhouse gas and local emissions by about 23% for almost all vehicles. The relative advantage of a direct hydrogen fuel cell vehicle over the ICEV with the same vehicle glider will increase only one or two percent with the lighter, more aerodynamic bodies. Therefore most of the relative conclusions with respect to fuel cell vehicles compared to conventional vehicles and to hybrid electric vehicles from previous DTI reports are equally valid as vehicle gliders improve in the future. Only direct hydrogen fuel cell vehicles will achieve the PNGV goal of 80 mpgge fuel economy over realistic driving schedules, although parallel hybrid electric vehicles could achieve 80 mpgge fueled by hydrogen, natural gas or diesel fuel operating on the rather anemic EPA combined driving schedule.

Executive Summary for Battery Augmented Fuel Cell Systems

Directed Technologies, Inc. has previously estimated the cost of electricity from stationary proton exchange membrane (PEM) fuel cell systems, including the cogeneration of hydrogen from the natural gas fuel processor needed to run the stationary fuel cell system (Thomas - 1999). That analysis demonstrated that selling both hydrogen and electricity improved the economics of larger building fuel cell systems in the 50 kWe size range. In some circumstances, selling only electricity would not be competitive with current commercial electricity prices. But producing and storing hydrogen during the off-peak hours when no electricity was needed for later sales to commercial users of hydrogen or to owners of direct hydrogen fuel cell vehicles would make the project economic -- electricity could be sold below the commercial price of electricity and the hydrogen could be sold to owners of fuel cell vehicles at a cost below the cost per mile of gasoline in a conventional vehicle. In effect the high value product (hydrogen for transportation) could be used to offset the cost of electricity for fuel cell systems larger than 50 kWe.

However, these favorable economics for larger stationary fuel cell systems do not hold for smaller residential systems, absent a fundamental reduction in small scale fuel cell or reformer cost. Using the detailed fuel cell cost analysis conducted by Directed Technologies, Inc., we concluded that even very large-scale mass production would not make stationary fuel cell systems competitive with current residential electricity rates. And yet several commercial ventures are attracting investment in the development of residential fuel cell systems. Most of these proposed ventures reportedly cut costs by using battery storage for peak power generation. That is, a typical residence in the United States might require an average power of only one kilowatt. But this home might require 3 to 5 kW of peak power during a hot August afternoon to run the air conditioner. Initially, providing that rare peak power by storing energy in batteries may cost less than building a fuel cell system to handle the peak load. We therefore added peak power battery augmentation to the stationary fuel cell systems analysis conducted previously.

The results of this analysis were all negative -- adding a peaking battery storage system would slightly increase the cost of electricity necessary to make the required return on investment. For a typical residence in California, for example, the fuel cell owner would have to charge 43.3 cents/kWh to make a 10% real, after-tax return on investment with a 4.3 peak kWe[4] fuel cell system without battery, assuming that 10,000 such fuel cell systems were built. Adding the battery storage system and reducing the fuel cell power to 1.2 kWe would actually increase the required electricity price from 43.3 to 44.1 cents/kWh to make the 10% return on investment.

The actual capital costs for the battery-augmented system would be slightly lower than the pure fuel cell system for small production quantities, but nearly equal once production quantities reached the 10,000 unit level. We are projecting relatively high fixed costs for these small fuel cell systems -- reducing the peak power from 4.3 kWe to 1.2 kWe only reduces the initial capital costs from $4,696 to $4,019 for the fuel cell system, and from $5,639 to $5,184 for the steam methane reformer system. These cost reductions are barely adequate to cover the estimated cost of $664 for a 6.7 kWh battery storage system, all at the 10,000 unit production volume. In addition, the battery system requires higher maintenance and has shorter lifetime (4 years assumed here compared to 10 years for the fuel cell system), producing a larger capital recovery factor for the battery storage system. Finally, extra natural gas is required for the battery system to cover the round-trip losses in storing energy in the battery. As a result of these factors, we conclude that the cost of electricity that must be charged to bring a 10% return on investment would be higher for the battery-augmented system even in the low (100 unit) production volume compared to a higher peak power pure fuel cell system.

[4]This fuel cell system would generate 4.33 kW of DC electricity, enough to supply 3.4 kW AC peak to the home in addition to providing the electricity to run the natural gas fuel processor.

Based on our analyses, we conclude that some combination of three factors must be exploited to make a fuel cell system for private residences economically viable:

* Lower fuel cell or steam methane reformer mass production costs

* Producing larger fuel cell systems to service 20 to 50 or more private residences

* Serving individual utilities with higher than average electricity rates, or regions within a utility district with unusually high transmission and distribution costs, or within states like Alaska that have unusually high electricity rates and low natural gas prices.

It appears from our analysis that all three factors could be required to make fuel cells attractive for residential customers initially.

1.0 Introduction to the PNGV Transportation Analysis

In previous DTI vehicle simulations for the Hydrogen Program Office, we have fixed the vehicle glider, choosing the AIV Sable as a surrogate for advanced vehicles with respect to weight reduction. The AIV Sable is similar to a five-passenger vehicle weighing about 300 kg less than its conventional counterparts, the Ford Taurus and Mercury Sable. For each alternative fueled vehicle, we effectively stripped out the conventional power train and replaced it with either a fuel cell system and electric drive motor, or a hybrid electric drive system using an ICE to provide the main motive power. Some concern was expressed that as vehicle systems became more advanced, incorporating other features being developed by the PNGV partnership between government and the U.S. automakers, the previous conclusions based on the AIV Sable might not hold. We have therefore repeated all calculations of vehicle weight, fuel economy and emissions assuming the glider characteristics of a future PNGV-like vehicle.

1.1 Glider Characteristics

The PNGV program has set three major goals, the last of which is to increase fuel economy of passenger vehicles by "up to" a factor of three. This goal can be achieved by various combinations of higher efficiency power trains, reduced weight, reduced aerodynamic drag and reduced rolling resistance. Possible combinations include 45% thermal efficiency for the main power source such as a hydrogen fuel cell system, a 20 to 40% weight reduction, 20% lower drag and 20% lower rolling resistance. Table 1 illustrates our choice of vehicle glider parameters compared to the AIV-Sable parameters used previously. Although the 23.8% weight reduction is on the low side, the AIV Sable is already about 300 kg lighter than the conventional Sable. Thus the total weight reduction from today's mass produced vehicle is closer to 40%.

Table 1. Vehicle Glider Parameters for the AIV Sable and a PNGV-Like Vehicle

	AIV Sable	PNGV	% Change
Drag Coefficient	0.33	0.27	18.2
Cross Sectional Area (m^2)	2.127	2.08	2.2
Rolling Resistance	0.0092	0.0072	21.7
Glider Weight[5] (kg)	852	649	23.8
Direct Hydrogen FCV Curb Weight (kg) [including battery peak power augmentation]	1,155	896	22.4

[5]Glider as used here includes all vehicle components except the main power source (ICE or fuel cell system), fuel tank, fuel, exhaust system, transmission, electric motor, inverter & motor controller and peak power battery (if any).

1.2 Fuel Cell Electric Vehicles

We have analyzed three types of fuel cell vehicles (FCV): direct hydrogen FCVs, methanol FCVs and gasoline FCVs. The last two require an onboard fuel processor to convert the liquid fuel to hydrogen for the PEM fuel cell. Since no organization has yet built, tested and published performance results for a mature onboard fuel processor, we have assumed a "probable case" and a "best case" set of parameters for both processors. The parameters assumed for these two cases are summarized in Table 2. The fuel cell power capacity (on pure hydrogen) is increased by the factor shown in the first row to compensate for lower peak power operating on the gas reformate from the fuel processors. The methanol reformer reformate would have at best 80 to 85% hydrogen, and the gasoline reformer would have at best 35% to 40% hydrogen. These dilute hydrogen streams would then have to be exhausted from the anode cavity of the fuel cell. Otherwise the other gases in the reformate stream [CO_2, N_2 (in the case of partial oxidation reformers), H_2O, CH_4, etc.] would accumulate in the anode, smothering and shutting down the cells. As a result, some hydrogen must necessarily pass through the anode unreacted. This unused hydrogen can be burned to raise steam for the methanol reformer, but it might be difficult to utilize this heat in the case of an exothermic gasoline partial oxidation or autothermal reactor (ATR) system. For details on how these parameters were chosen, see Thomas-1998a.

Table 2. Fuel Processor Parameters for "Best Case" and "Probable Case"

	Methanol Fuel Processor		Gasoline Fuel Processor	
	Best Case	Probable Case	Best Case	Probable Case
Fuel Cell Size Increase w/r to H_2 Fuel Cell	1.10	1.12	1.21	1.36
Fuel Cell Efficiency Curve	LANL Theory	LANL Exper.	LANL Theory	LANL Exper.
Hydrogen Utilization	90%	83.3%	90%	83.3%
Fuel Processor Efficiency (LHV)	84.5%	80%	75%	70%
Anode Exhaust Gas Heat Recovery	75%	75%	70%	0
Reformer Weight (kg)[6]	46	60	55	100

The direct hydrogen FCV stores hydrogen at 34.5 MPa (5,000 psi) in carbon-fiber wrapped composite tanks. These tanks are extraordinarily strong, and have been shown to survive rear-end collisions at up to 50 mph without losing pressure. DTI has previously analyzed the weight, volume and cost various hydrogen storage systems, and has concluded that the 34.5 MPa compressed gas tanks are the best choice for passenger vehicle applications (James-1996, 1997b, 1999).

[6]This is the initial weight (before weight compounding) for a fuel processor to supply 40 kW peak power from a fuel cell system. Actual processor weights are increased in the program to provide the higher power to accelerate the slightly heavier vehicle.

1.3 Hybrid Electric Vehicles

We have also analyzed nine types of hybrid electric vehicles. Each of these vehicles uses a small internal combustion engine to provide steady-state power, combined with an electric motor or motors to provide traction to the wheels. In series operation, the ICE is connected to a generator which provides electrical power to charge a battery or to power the drive motor. All traction power comes from this motor. In a parallel hybrid, both the ICE and the electric motor are connected to the wheels through a transmission.

Two types of series HEVs were analyzed: a thermostat series hybrid where the ICE is turned on and off in response to battery state of charge, and a load-following series hybrid where the ICE power is varied over a limited range to track the vehicle power demands, with the battery providing extra power for acceleration and limited hill climbing. In addition, we analyzed one parallel hybrid vehicle configuration. The operating algorithms for both the load-following series hybrids and the parallel hybrids were devised by DTI. These algorithms were not vigorously optimized, and may not represent the highest possible fuel economy.

For each of the three HEVs (thermostat series, load-following series, and parallel), we also evaluated three different fuel options: hydrogen, natural gas and diesel fuel. We assumed that the ICE would be optimized for each fuel. We assumed a peak efficiency of 38% (on a lower heating value basis) for a natural gas ICE and 40% for a hydrogen ICE. In the case of diesel fuel, we assumed 43% peak efficiency for a compression ignition, direct injection engine such as those demonstrated in mass production by Volkswagen.

1.4 Vehicle Weight Estimates

We calculate the weight of each alternative vehicle based on a weight compounding formula derived earlier (See Appendix G of Thomas -1998a). The weights of all power train components are adjusted to provide equal vehicle performance, including equal acceleration. If extra weight is required for any function such as a fuel processor, for example, then the size (and weight) of other power train components must also be increased to accelerate the extra fuel processor weight. This added incremental weight in turn requires still further increases in other components in an iterative process. However, this iteration can be solved in closed form for both added power train weight components and for non- power train components. The amount of fuel stored on each vehicle is also adjusted to produce a range of 308 miles on the 1.25 times accelerated combined driving cycle, or about 380 miles for the FCV on the standard EPA combined driving cycle. As a result all vehicles considered in this report have identical performance in terms of range and acceleration.

The resulting vehicle test weights are summarized in Figure 4, along with the other vehicle characteristics. The test weight is equal to the vehicle curb weight plus 136 kg in all cases.

Vehicle Characteristics									
Vehicle Body	Fuel	Engine	Peak Engine Efficiency	Comment	Battery Peak Power?	Test Weight (kg)	Drag Coeff.	Cross Sect. Area	Rolling Resistance
AIV Sable	Gasoline	ICE	29.6		No	1304	0.33	2.127	0.0092
AIV Sable	Hydrogen	Fuel Cell			Yes	1291	0.33	2.127	0.0092
AIV Sable	Hydrogen	Fuel Cell			No	1283	0.33	2.127	0.0092
AIV Sable	MeOH	Fuel Cell		Probable	Yes	1414	0.33	2.127	0.0092
AIV Sable	MeOH	Fuel Cell		Best	Yes	1390	0.33	2.127	0.0092
AIV Sable	Gasoline	Fuel Cell		Probable	Yes	1475	0.33	2.127	0.0092
AIV Sable	Gasoline	Fuel Cell		Best	Yes	1387	0.33	2.127	0.0092
PNGV	Gasoline	ICE	29.6		No	1042	0.27	2.08	0.0072
PNGV	Hydrogen	Fuel Cell			Yes	1032	0.27	2.08	0.0072
PNGV	Hydrogen	Fuel Cell			No	1023	0.27	2.08	0.0072
PNGV	MeOH	Fuel Cell		Probable	Yes	1119	0.27	2.08	0.0072
PNGV	MeOH	Fuel Cell		Best	Yes	1110	0.27	2.08	0.0072
PNGV	Gasoline	Fuel Cell		Probable	Yes	1172	0.27	2.08	0.0072
PNGV	Gasoline	Fuel Cell		Best	Yes	1099	0.27	2.08	0.0072
Hybrid Electric Vehicles (HEV) -- Thermal Engine Plus Battery for Peak Power									
AIV Sable	Hydrogen	ICE	40	Series HEV	Yes	1507	0.33	2.127	0.0092
AIV Sable	Hydrogen	ICE	40	Load Follow	Yes	1366	0.33	2.127	0.0092
AIV Sable	Hydrogen	ICE	40	Parallel HEV	Yes	1253	0.33	2.127	0.0092
AIV Sable	Natural Gas	ICE	38	Series HEV	Yes	1435	0.33	2.127	0.0092
AIV Sable	Natural Gas	ICE	38	Load Follow	Yes	1308	0.33	2.127	0.0092
AIV Sable	Natural Gas	ICE	38	Parallel HEV	Yes	1200	0.33	2.127	0.0092
AIV Sable	Diesel	CIDI	43	Series HEV	Yes	1472	0.33	2.127	0.0092
AIV Sable	Diesel	CIDI	43	Load Follow	Yes	1361	0.33	2.127	0.0092
AIV Sable	Diesel	CIDI	43	Parallel HEV	Yes	1245	0.33	2.127	0.0092
PNGV	Hydrogen	ICE	40	Series HEV	Yes	1229	0.27	2.08	0.0072
PNGV	Hydrogen	ICE	40	Load Follow	Yes	1117	0.27	2.08	0.0072
PNGV	Hydrogen	ICE	40	Parallel HEV	Yes	1016	0.27	2.08	0.0072
PNGV	Natural Gas	ICE	38	Series HEV	Yes	1158	0.27	2.08	0.0072
PNGV	Natural Gas	ICE	38	Load Follow	Yes	1057	0.27	2.08	0.0072
PNGV	Natural Gas	ICE	38	Parallel HEV	Yes	969	0.27	2.08	0.0072
PNGV	Diesel	CIDI	43	Series HEV	Yes	1185	0.27	2.08	0.0072
PNGV	Diesel	CIDI	43	Load Follow	Yes	1082	0.27	2.08	0.0072
PNGV	Diesel	CIDI	43	Parallel HEV	Yes	990	0.27	2.08	0.0072

Figure 4. Alternative Vehicle Characteristics

1.5 Fuel Economy and Drive Cycles

The fuel economy of a FCV depends much more on the drive cycle than that of a conventional vehicle. The ICE has variable efficiency that depends on both torque and engine speed. Efficiency peaks at moderate engine speed and output torque, and falls off significantly at low engine speed and low torque, and less so at higher speeds and torques. As a result, with more aggressive driving, the average fuel economy over a drive cycle does not always vary significantly with an ICEV. For example, at very low speeds, increasing speed may push the ICE closer to its high efficiency "sweet spot," thereby improving fuel economy over the low speed portion of the driving cycle, which helps to offset the drop in fuel economy associated with an increase in high speed driving. The efficiency of a fuel cell, however, declines monotonically above a very low power level. Hence more aggressive driving will always lead to lower fuel economy for the FCV. Therefore the relative advantage of the FCV fuel economy compared to the ICEV fuel economy will generally drop if both vehicles are driven more aggressively.

The most common drive schedule used to compare passenger vehicles in the United States is the EPA's federal urban driving schedule (FUDS), and the federal highway driving schedule (FHDS). Fuel economy is also estimated over a combination of these two cycles, typically 55% urban and 45% highway. However, these cycles are notoriously anemic. For example, the average highway speed in only 48.6 mph with a top speed of 60 mph, or far below typical American highway conditions. The average FUDS speed is 19.5 mph with a peak of 56.7 mph, which may be reasonable under some circumstances. However, the automobile companies have all developed their own proprietary customer driving schedules to test out their new cars. These schedules are all more aggressive than the EPA schedules. In addition, the EPA has generated a new drive cycle, called the US06 which is even more aggressive than some auto company drive cycles.

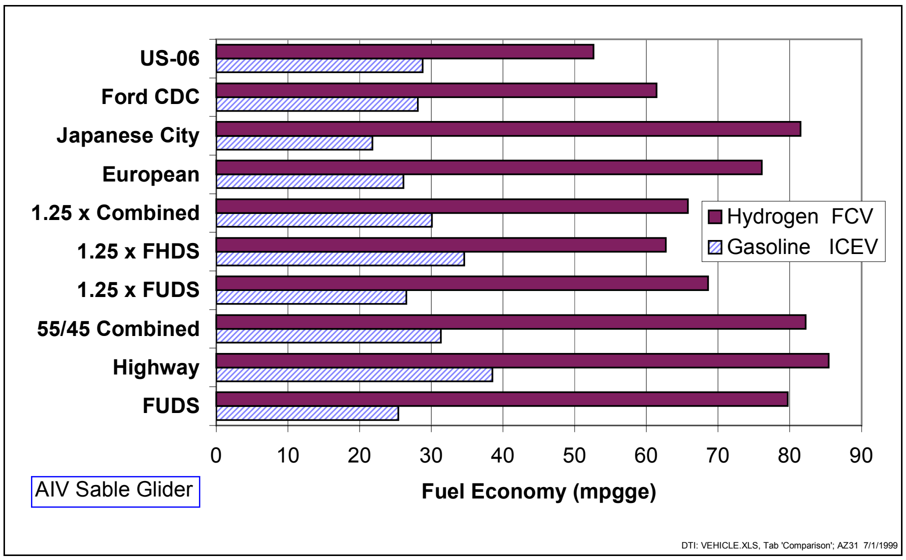

Figure 5. Fuel Economy for a Direct Hydrogen Fuel Cell Vehicle and a Conventional Gasoline Internal Combustion Engine Vehicle

The fuel economies predicted by the DTI simulation code are shown in Figure 5 for both a direct hydrogen FCV and a conventional ICEV, both based on the AIV-Sable glider. In addition to the EPA schedules with and without the 1.25 times speed multiplier, we show the fuel economies for the European and Japanese cycles, and the Ford Customer Driving Cycle. The ratios of the fuel economies for these driving cycles are shown in Figure 6 for both the AIV-Sable and for the PNGV glider. These driving cycles are displayed in more or less decreasing order of aggressiveness -- the US06 is the most aggressive cycle, while the Japanese City cycle is very anemic. The sluggish Japanese driving schedule provides over 3.5 times better fuel economy for the FCV compared to the ICEV, while the US06 produces only a 1.8 to one advantage. Note also that the 1.25 times accelerated combined cycle provides almost the same improvement factor, 2.2 to one, as the Ford Customer Driving Cycle, while the standard EPA combined cycle would predict a 2.6 to one advantage in fuel economy for the FCV over the ICEV. DTI has therefore chosen the 2.2 to one improvement factor in all of our comparisons as being more realistic for typical American drivers.

The effects of changing from the AIV-Sable glider to the PNGV glider are also shown in Figure 6. In all cases, the PNGV glider improves the relative performance of the FCV relative to the ICEV by about 2 to 3 percent. The actual fuel economies for both FCVs and for HEVs are shown in Figures 1 and 2 in the Executive Summary.

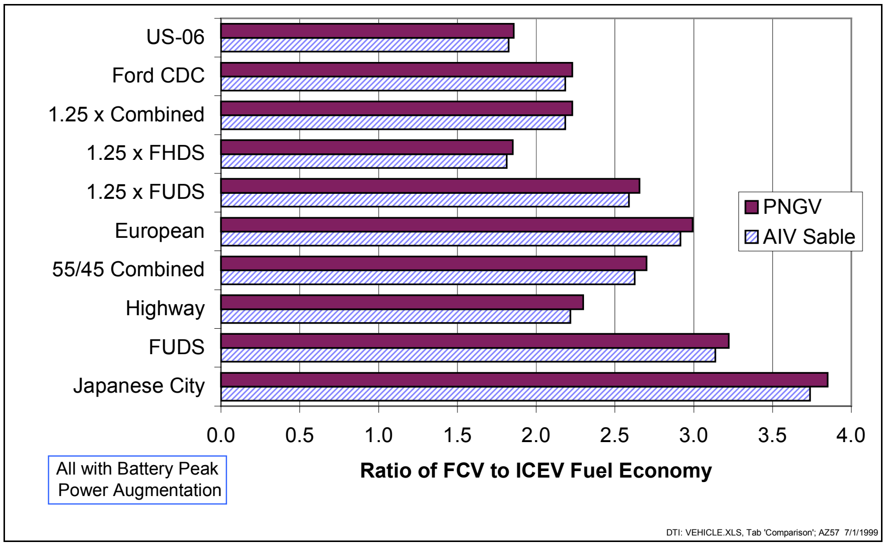

Figure 6. Ratio of FCV Fuel Economy to ICEV Fuel Economy

1.6 Mass Production Cost of Alternative Vehicles

DTI has previously estimated the cost of fuel cell vehicles for the Ford Motor Company and the U.S. Department of Energy (James-1997, Lomax-1997), using detailed, bottom-up cost analysis for material, process and assembly procedures assuming automotive scale production (500,000 units per year). We have also estimated costs for HEVs (Thomas-1998a, 1998b, 1998c) based on scaling from existing ICE and battery system costs, but have not applied detailed mass production cost estimation methodology to HEV components.

All previous cost estimates were based on the power trains necessary to propel the AIV-Sable glider. We have modified these estimates based on the PNGV glider, which requires less power and less fuel to meet our specifications of 380 miles range on the EPA combined cycle and acceleration of 0 to 60 mph in 10 seconds. While costs do not scale linearly with reduced power, they do decrease to some degree as peak power requirements decline for the lighter, more aerodynamic PNGV glider. In addition, more of the power train cost scales with power demand for fuel cell systems than for ICEs. Much of the cost of a six-cylinder engine is due to the engine block, pistons, rings, valves, etc. Increasing or decreasing the size of an engine over the limited range considered here does not change the number of components. The peak power of the fuel cell for a given current density and operating voltage depends linearly on the number of cells in the stack. Hence the total fuel cell system cost is more linearly dependent on peak power.

We have assumed a six-cylinder engine for the conventional passenger vehicles and a lower peak power four-cylinder engine for the hybrid electric vehicles. We assume a fixed cost dependent on the number of cylinders plus a variable cost dependent on the peak power required. The four cylinder engine cost is given by:

$$C_4 = \$720 + 5.14 \times P \qquad (1)$$

where P = the peak engine power. The cost of a six-cylinder engine is then:

$$C_6 = \$1080 + 5.14 \times P \qquad (2)$$

For a 40-kW four-cylinder engine, the total cost would then be $925 in mass production, with 78% of the cost fixed. For a 100-kW six-cylinder engine for the conventional car, the mass production cost would then be $1,600, with 32% of the cost dependent on output power.

The total estimated cost for a PEM fuel cell system is given by:

$$C_{FC} = \$1{,}132 + P \times \left(3.27 + \left[\frac{3.46 + 29.66 \times Lp}{P_d} \right] \right) \qquad (3)$$

where L_p = the total platinum catalyst loading (mg/cm^2), and
P_d = the fuel cell power density (W/cm^2), assuming that platinum costs $400/troy ounce ($12.86/gram).

This cost includes the fuel cell stack itself, as well as all the auxiliary equipment such as humidification, air compressor, radiator, piping, and controls. Based on projected fuel cell performance of one W/cm^2 power density using 0.25 mg/cm^2 platinum catalyst loading (including both the anode and cathode), the fuel cell system cost becomes:

$$C_{FC} = \$1{,}132 + P \times 14.15 \qquad (2)$$

An 80-kW fuel cell system for a pure FCV (no peak power augmentation) would then cost $2264, , with half the cost being power-dependent, versus only 32% for the six-cylinder ICE. For a FCV with peak power augmentation, both the fuel cell system and the battery scale down in size and cost for smaller PNGV power trains. As a result, the differential cost between a conventional ICE power train and the fuel cell power train diminishes for a PNGV power train with lower peak power demands as shown in Figure 7. The first two columns show the cost differential between the AIV Sable FC and the PNGV FC power train and the ICEV power train. The last column shows the difference between the AIV Sable and the PNGV incremental cost. Thus moving from the AIV Sable glider to the PNGV glider would reduce the power train

	AIV Sable Delta Over ICEV	PNGV Delta Over ICEV	Delta
Battery - Hydrogen FCV	$2,302	$1,832	$470
Pure Hydrogen FCV	$2,102	$1,650	$452
MeOH FCV – Probable	$2,752	$2,308	$444
MeOH FCV – Best	$2,096	$1,734	$362
Gasoline FCV – Probable	$4,356	$3,699	$657
Gasoline FCV – Best	$2,717	$2,281	$436
H2 Series HEV	$3,851	$2,997	$854
H2 Load Following HEV	$2,879	$2,263	$616
H2 Parallel HEV	$1,827	$1,479	$348
NG Series HEV	$2,363	$1,866	$497
NG Load Following HEV	$1,563	$1,247	$316
NG Parallel HEV	$1,110	$702	$408
CIDI Series HEV – AIV	$2,647	$2,165	$482
CIDI Load Following HEV	$1,837	$1,532	$305
CIDI Parallel HEV	$1,067	$972	$95

DTI: VEHICLE.XLS, Tab 'Comparison'; D86 7/2/1999

Figure 7. Cost Differential Between Alternative Vehicle Power Train and Conventional ICE Power Train (Adjusted for weight compounding, except no glider cost increase is included for glider weight increase.)

differential by $470 for the direct hydrogen FCV with battery peak power augmentation, and by $452 for the pure FCV, etc. These data are also plotted in Figure 8.

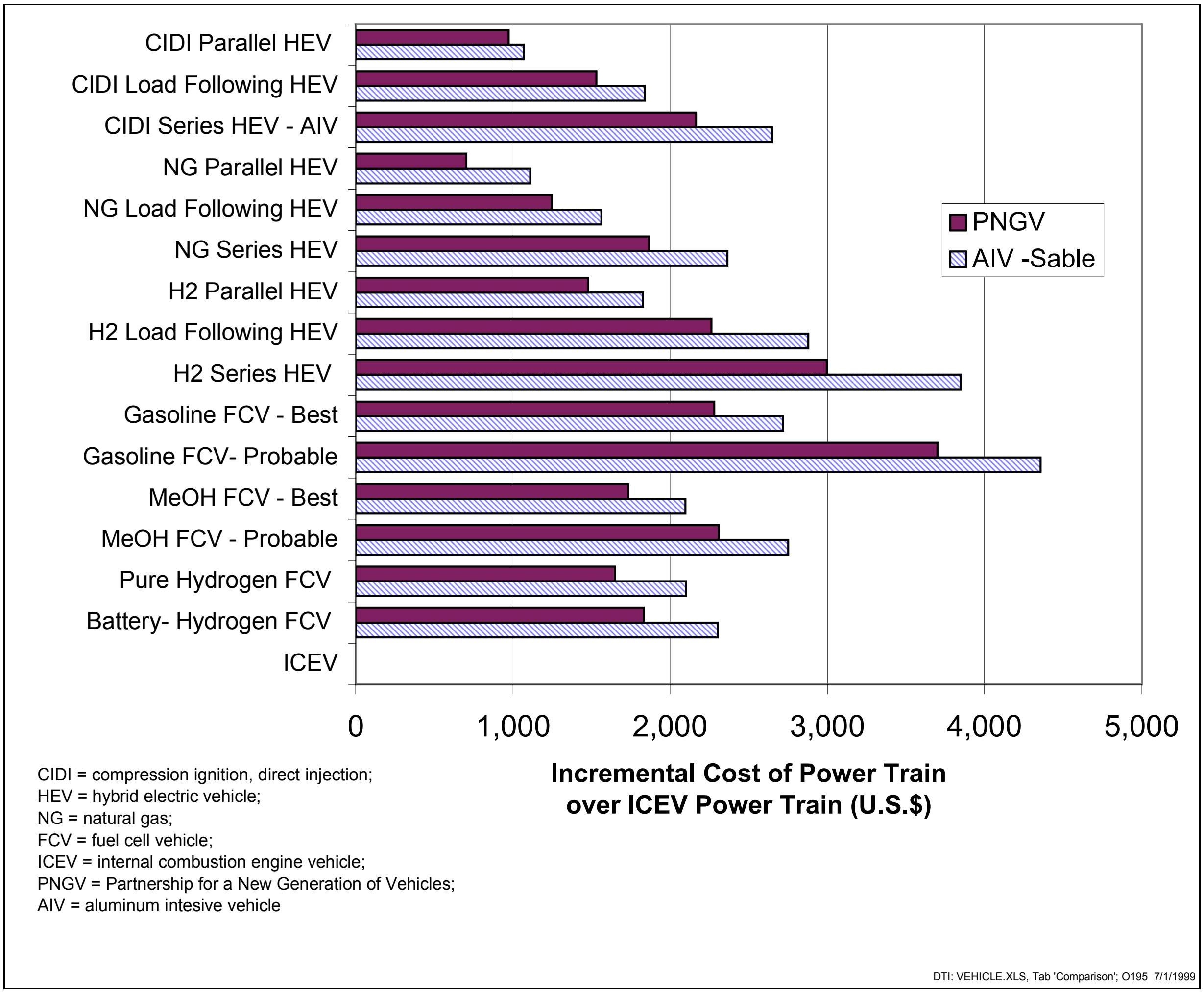

Figure 8. Incremental Cost of the Power Train for Alternative Vehicles Above the Cost of a Conventional ICE Power Train.

Component cost breakdowns are shown in Tables 3 and 4 for representative fuel cell vehicles assuming an AIV Sable glider (Table 3) and a PNGV glider (Table 4). Similar cost breakdowns are shown in Table 5 for the thermostat (on/off battery charging) series hybrid electric vehicle on the AIV Sable glider, and in Table 6 for the PNGV glider.

Table 3. Alternative Vehicle Component Cost Breakdown for Fuel Cell Vehicles with AIV Sable Glider

	ICEV		Hydrogen FCV		Hydrogen FCV with Battery Power Augmentation		Probable Methanol FCV with Battery		Probable Gasoline FCV with Battery	
Vehicle Weight (kg)	1,304		1,283		1,291		1,414		1,475	
	Power (kW)	Cost ($)	Power (kW)	Cost ($)	Power (kW)	Cost ($)	Power (kW)	Cost ($)	Power (kW)	Cost ($)
Fuel Cell System			74.1	$2,180	38	$1,670	45.1	$2,006	56.5	$2,410
ICE System	100	$1,600								
Transmission/Gear Box		$700		$200		$200		$200		$200
Fuel Tank		$125		$1,096		$1,073		$157		$128
Generator										
Fuel Processor							45.1	$950	56.5	$2,129
Motor/Inverter/ Controller			81.5	$901	82.1	$906	88.1	$943	91.7	$966
Battery					40.3	$728	43.2	$771	45.0	$798
Controller & misc.				$150		$150		$150		$150
Total		$2,425		$4,527		$4,727		$5,177		$6,781

Table 4. Alternative Vehicle Component Cost Breakdown for Fuel Cell Vehicles with PNGV Glider

	ICEV		Hydrogen FCV		Hydrogen FCV with Battery Power Augmentation		Probable Methanol FCV With Battery		Probable Gasoline FCV with Battery	
Vehicle Weight (kg)	1,042		1,023		1,032		1,119		1,172	
	Power (kW)	Cost ($)	*Power (kW)*	Cost ($)	*Power (kW)*	Cost ($)	*Power (kW)*	Cost ($)	*Power (kW)*	Cost ($)
Fuel Cell System			*59.1*	$1,968	*29.8*	$1,554	*35.7*	$1,823	*45.0*	$2,149
ICE System	*80*	$1,491								
Transmission/Gear Box		$700		$200		$200		$200		$200
Fuel Tank		$125		$877		$856		$131		$109
Generator										
Fuel Processor							*35.7*	$856	*45.0*	$1,897
Motor/Inverter/ Controller			*65*	$771	*65.6*	$776	*71.1*	$811	*74.5*	$832
Battery					*32.8*	$612	*35.6*	$653	*37.3*	$677
Controller & misc.				$150		$150		$150		$150
Total		$2,316		$3,966		$4,148		$4,624		$6,014

Table 5. Alternative Vehicle Component Cost Breakdown for Thermostat Series Hybrid Electric Vehicles with AIV Sable Gliders
(ICEV and Pure Hydrogen FCV shown for reference)

	ICEV		Hydrogen FCV		Natural Gas Thermostat HEV		Hydrogen Thermostat HEV		Diesel CIDI Thermostat HEV	
Vehicle Weight (kg)	1,304		1,283		1,435		1,507		1,472	
	Power (kW)	Cost ($)	Power (kW)	Cost ($)	Power (kW)	Cost ($)	Power (kW)	Cost ($)	Power (kW)	Cost ($)
Fuel Cell System			74.1	$2,180						
ICE System	100	$1,600			44.7	$950	46.5	$959	45.6	$1,432
Transmission/Gear Box		$700		$200		$200		$200		$200
Fuel Tank		$125		$1,096		$385		$1,741		$125
Generator					44.7	$612	46.5	$626	45.6	$619
Fuel Processor										
Motor/Inverter/ Controller			81.5	$901	90.8	$975	95.4	$1,011	93.2	$993
Battery					90.8	$1,517	95.4	$1,589	93.2	$1,554
Controller & misc.				$150		$150		$150		$150
Total		$2,425		$4,527		$4,789		$6,276		$5,073

Table 6. Alternative Vehicle Component Cost Breakdown for Thermostat Series Hybrid Electric Vehicles with PNGV Glider
(ICEV and Pure Hydrogen FCV shown for reference)

	ICEV		Hydrogen FCV		Natural Gas Thermostat HEV		Hydrogen Thermostat HEV		Diesel CIDI Thermostat HEV	
Vehicle Weight (kg)	1,042		1,023		1,158		1,229		1,185	
	Power (kW)	Cost ($)	*Power (kW)*	Cost ($)	*Power (kW)*	Cost ($)	*Power (kW)*	Cost ($)	*Power (kW)*	Cost ($)
Fuel Cell System			*59.1*	$1,968						
ICE System	*80*	$1,491			*35*	$900	*36.4*	$907	*35.8*	$1,356
Transmission/Gear Box		$700		$200		$200		$200		$200
Fuel Tank		$125		$877		$339		$1,367		$125
Generator					*35*	$535	*36.4*	$546	*35.8*	$542
Fuel Processor										
Motor/Inverter/ Controller			*65*	$771	*72.3*	$829	*76.0*	$858	*74.5*	$846
Battery					*72.3*	$1,229	*76.0*	$1,285	*74.5*	$1,262
Controller & misc.				$150		$150		$150		$150
Total		$2,316		$3,966		$4,182		$5,313		$4,481

1.7 PNGV Transportation Conclusions

Based on this assessment, we conclude that converting from the AIV Sable glider assumed in previous studies to the PNGV type of glider would have minimum effect on the *relative merits* of fuel cell and hybrid electric vehicles compared to the conventional ICEV. However, the *absolute values* of fuel economy, emissions and cost would be superior for the PNGV vehicles. But the ICEV performance will improve almost as much as the fuel cell and hybrid vehicles with a lighter, more aerodynamic vehicle glider. Specifically, we conclude for the main figures-of-merit for these vehicles as follows:

<u>Fuel Economy</u>: In absolute terms the PNGV body parameters are essential to meet the PNGV goal of over 80 mpgge on realistic customer drive cycles. Only the direct hydrogen fuel cell vehicle can meet the 80 mpgge goal on the 1.25 times accelerated EPA 55/45 combined cycle, which more closely represents actual American driving habits. The direct hydrogen fuel economy improves from 65.8 mpgge on the 1.25 times accelerated combined cycle with the AIV Sable glider up to 85.2 mpgge with the PNGV glider. The next best vehicle in terms of fuel economy, the diesel CIDI engine in the parallel hybrid vehicle, increases from 57.6 mpgge to 74.9 mpg on the same drive cycle, close to the PNGV goal.

In relative terms, however, the PNGV glider improves the fuel economy of the FCV by about 29%, but the ICEV fuel economy also improves by 27% (from 30.1 to 38.2 mpg). So the net gain for the FCV relative to the ICEV is very small.

Greenhouse Gas Emissions: In absolute terms, greenhouse gases are reduced for each vehicle by their relative fuel economy improvements -- about 29% reduction for the FCV (from 246 grams of CO_2-equivalent per mile down to 190 g/mile). The HEVs also would have a 20% to 30% reduction in greenhouse gas emissions. The lowest emitters would be the natural gas parallel hybrids and the diesel CIDI parallel hybrids at 160 g/mile with the PNGV glider, down from 206 g/mile for the AIV Sable.

The relative improvements are marginal, however, since the ICEV greenhouse gas emissions would also be reduced by about 27%, from 414 g/mile of CO_2-equivalent with the AIV Sable glider down to 326 g/mile. Thus the direct hydrogen FCV would move from a net greenhouse gas advantage of 40.5% reductions compared to the ICEV for the AIV Sable, to a 41.7% reduction if both vehicles were based on the PNGV glider.

Local Air Pollution: The local emissions of criteria pollutants (VOCs, CO, NOx) would also show a 27 to 30% reduction for all vehicles. The direct hydrogen FCV has no local emissions, but these vehicles could create emissions within the local urban airshed if, for example, the hydrogen were produced locally at small steam methane reformer appliances. In this case the FCV local emissions attributed to these reformers would also decrease by 29%.

Incremental Cost: In absolute terms, the PNGV body parameters would reduce the cost of the direct hydrogen FCV power train by about $579, from an estimated mass production cost of $4,727 down to $4,148. Relative to the ICEV power train, the cost savings would be almost as great, since the ICE power train does not scale down as fast with reduced peak power demand as the fuel cell power train. The relative cost difference between the fuel cell power train and the ICEV power train would decrease by $470, from $2,302 cost differential for the AIV Sable down to $1,832 for the PNGV glider.

In summary, converting from the AIV Sable to the PNGV glider is essential for the direct hydrogen fuel cell vehicle to meet the 80 mpgge fuel economy goal of the PNGV on realistic driving cycles. This improve glider would also reduce the cost differential of the power train relative to the ICEV by $470, but otherwise has marginal (2 to 3%) impact on the relative performance of the fuel cell vehicle compared to either conventional ICEVs or to hybrid electric vehicles.

2.0 Introduction to Battery-Augmented Stationary Fuel Cell Systems

Stationary fuel cell systems can provide electricity at or near the end-user's facility, avoiding the cost of transmission and distribution that can account for up to half of the cost of delivered electrical power. For utilities faced with major investments to expand their transmission and distribution networks to portions of their service territory, placing fuel cell power generators on their customer's property could be a financially viable option. Other power generation sources such as gas turbines can provide local power, but efficiencies of gas turbines decline in smaller sizes, and fuel cells offer substantial advantage in terms of reduced air emissions and reduced noise.

Several companies are now reportedly developing stationary PEM fuel cell systems with fuel processors to convert natural gas, propane or methanol to hydrogen. These companies have stated that they can be competitive in the residential marketplace, offering the vision of homeowners generating their own electricity from natural gas, propane or methanol, independent of the electrical power grid. Some attributes of these residential fuel cell systems reported primarily in press releases are summarized in Table 7. It is not clear whether the quoted prices are goals or whether the companies involved have actually identified and thoroughly analyzed mass production costs for actual fuel cell system designs.

DTI has previously shown that stationary fuel cell systems are only head-to-head competitive in sizes above 50 kWe, as shown in Figure 9 based on average California electric utility and natural gas commercial rates, assuming that 10,000 systems are produced. The lower line in Figure 9 illustrates that selling only electricity from these systems would not be economic, generating a negative return on investment. Adding heat co-generation provides a positive return on investment for systems larger than 50-kWe, but the total system would only provide 10% real, after-tax return on investment if hydrogen were also produced during off-peak hours for use in fuel cell vehicles or other industrial hydrogen applications.

Table 7. Proposed Residential PEM Fuel Cell Systems

Company	Parent Companies or Business Partners	Fuel	Projected FC System Costs
Northwest Power Systems (Bend, Oregon)	DeNora PEM Fuel Cells (Italy), Methanex (Canada), Statoil (Norway)	Methanol	\$7,500 to \$10,000[7]
Plug Power LLC (Lantham, N.Y.) / GE Fuel Cell Systems	Mechanical Technology, Inc (MTI), DTE Energy Company, GE Power Systems	Natural Gas	\$7,500 to \$10,000 (\$3,500 in mass production) (Wolk -1999)
American Power Corporation (Boston)	Analytic Power	Natural Gas or Propane	<\$5,000 (Wolk - 1999)
Avista Labs	Black & Veatch		
H-Power Corp. (Bellville, N.J.)			
NuPower			

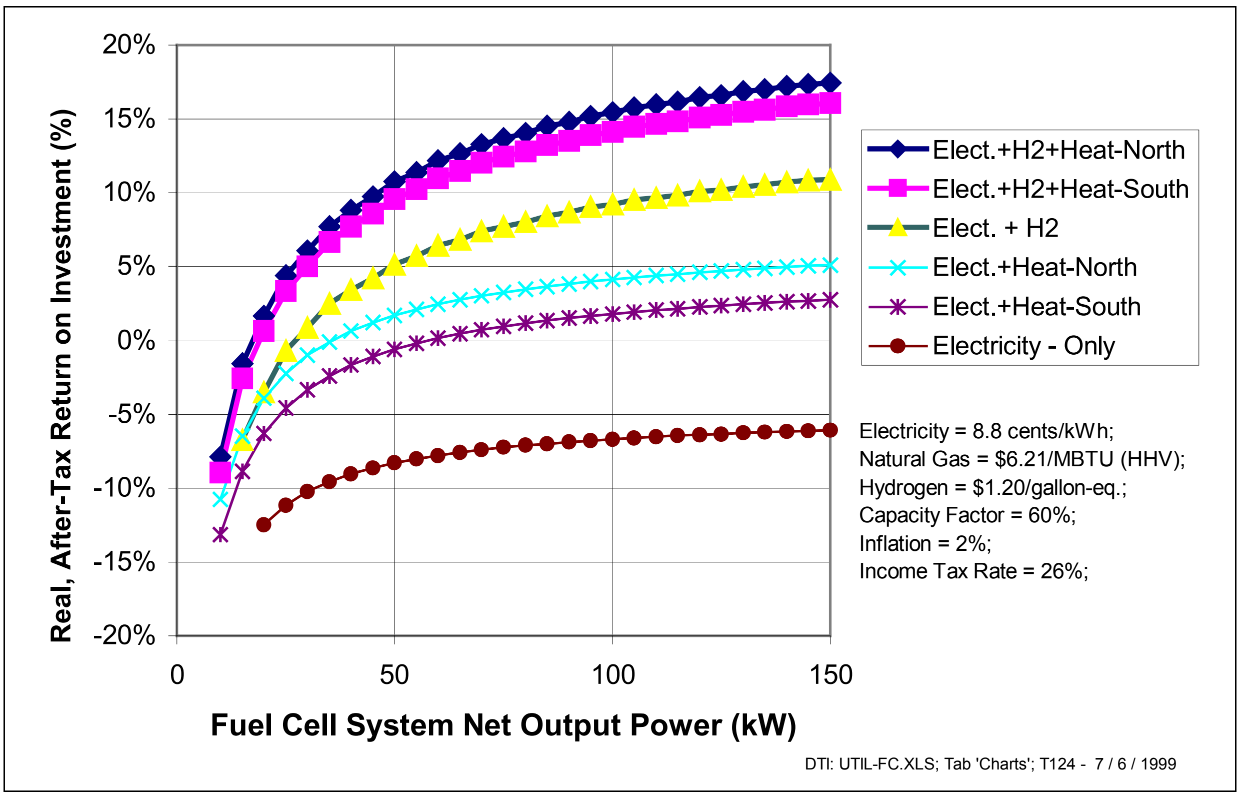

Figure 9. Return on Investment for a Commercial Fuel Cell System in California

[7]Cost based on Northwest Power Systems press release of February 17, 1998, stating that a 5-kW residential system would cost between \$1,500 to \$2,000/kW.

However, the typical residence in the United States uses only one kilowatt average power, with peak power levels near 3.4 kWe, including some surges to the 8 kW range, which would place the residential fuel cell system in the negative return region of Figure 9 even with hydrogen and heat co-generation. This poor result stems primarily from our analysis of fuel cell system costs in small sizes. Based on our evaluation, many of the fuel cell and fuel processor costs are fixed, independent of power output. As the systems become smaller, the cost per kilowatt increases as shown in Figure 10. A total system (including fuel processor and inverter/controller) that might cost under $1,500/kWe for a 20 kWe fuel cell system would cost over $5,000/kWe for a 2-kWe system. This pessimistic cost projection for residential systems might be due to our approach of scaling down from existing conceptual system designs. Other innovative fuel cell system designs for these very small systems might be more economic.

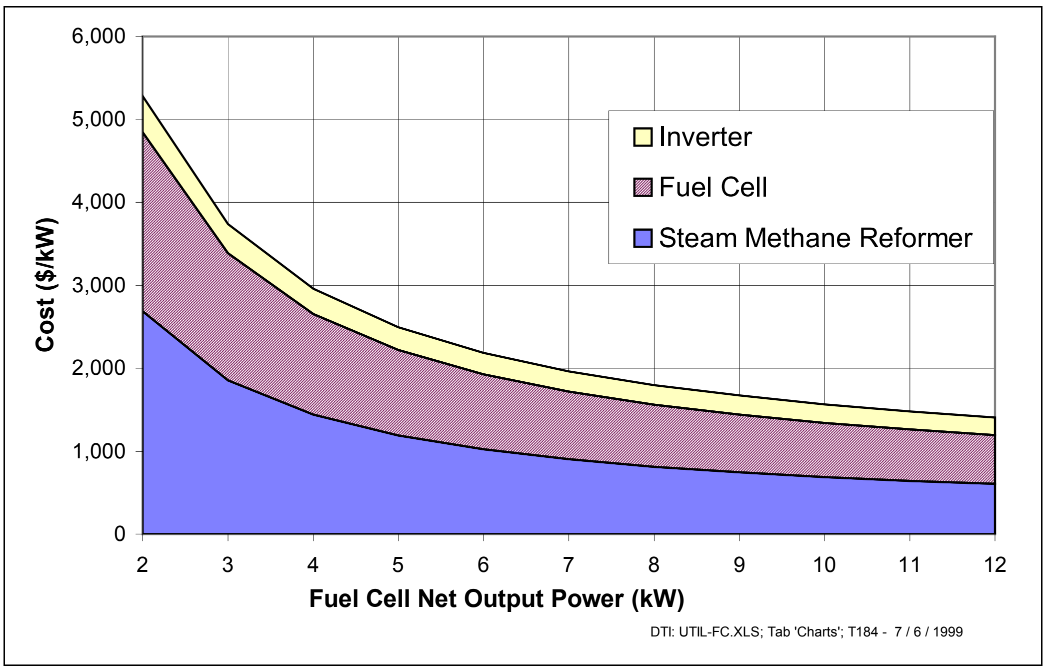

Figure 10. Estimated Capital Costs for a Residential Fuel Cell System (10,000 Production Level)

These previous estimates from DTI all assumed that the fuel cell provided the peak power requirements of the home or business. However, the capacity factor for residences is quite low, typically falling in the 25% range. The average power requirement is only one quarter of the peak power draw. Initially, when fuel cell systems cost is high, it might be beneficial to install lower power fuel cell systems in conjunction with a battery storage system to provide the rare peak power needed by the home. We have therefore added the battery storage option to our stationary fuel cell system model.

2.1 Fuel Cell System Description

The block diagram for the stationary fuel cell system is shown in Figure 11. The three main components (steam methane reformer, fuel cell system and inverter/controller) have been described in previous DTI reports (Thomas-1999). For this analysis, we have added deep discharge lead acid batteries to store electricity during the off-peak hours, along with the necessary charging, monitoring and control circuits. We assume here that the fuel cell and fuel processor both operate at a steady rate determined by the average annual power draw for the residence.[8] For example, the average peak power for single family homes in the US is about 3.4 kWe, with a capacity factor of 27%, or an average power load of 0.92 kWe. We assume that the fuel cell system delivers a continuous load of 0.92 kWe of AC power to the home. When the demand is less than 0.92 kWe, then the excess is used to charge the battery bank. When the demand exceeds 0.92 kWe, then the battery supplies the peak power required. The exact load profile will vary from home to home, but we assume a very simple load profile here for costing purposes: we arbitrarily assume that the peak power of 3.4 kWe is required for two hours every day, and the load is reduced below the average of 0.92 during the other 22 hours to bring the average to 0.92 kWe. This choice requires a battery storage capacity of 6.7 kWh, which is close to the 6 kWh value projected by EPRI for a residential fuel cell system with peak power battery augmentation (EPRI-1995). The capital cost, operation and maintenance (O&M) costs, efficiencies and expected lifetimes of the various components are summarized in Table 8.

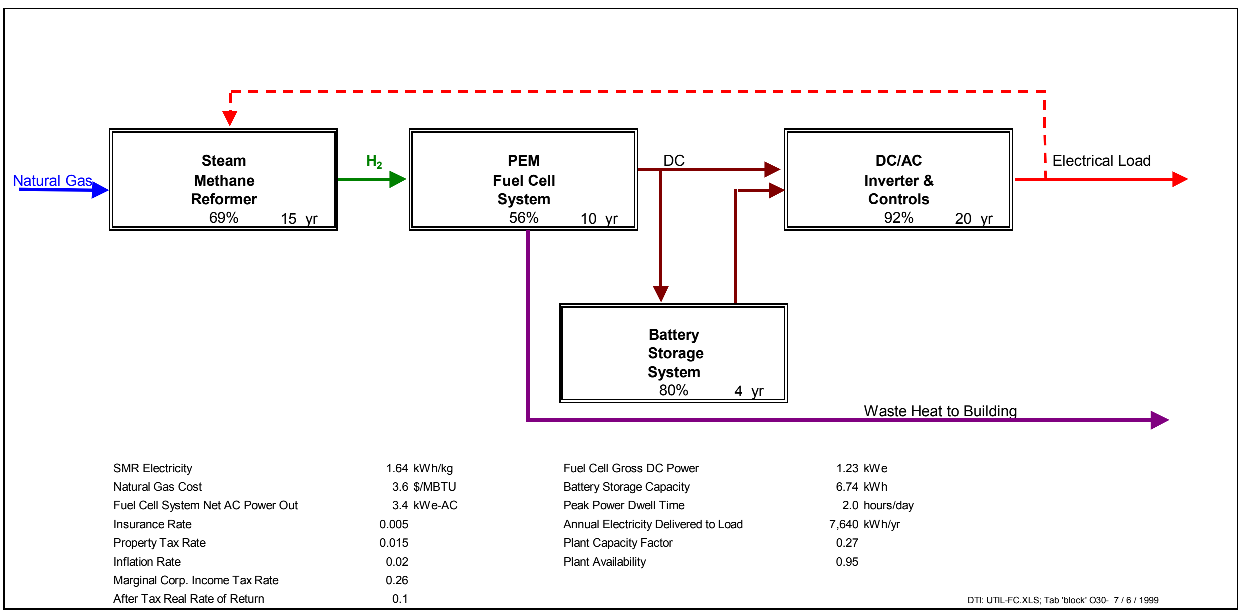

Figure 11. Block Diagram for a Stationary Fuel Cell System with Battery Storage

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[8]In practice, the fuel cell system power output would be set to the average power load over the day, which would increase during the summer air conditioning season, and decrease in spring and fall. We assume constant annual output here for convenience.

Table 8. Assumed Component Parameters in DTI Cost Model

	Steam Methane Reformer	Fuel Cell System	DC/AC Inverter & Controls	Battery System	Totals
Capital Cost -100 Qty	$15,261	$5,570	$2,249	$759	$23,839
Capital Cost - 10,000 Qty	$5,184	$4,019	$1,117	$664	$10,984
O&M Cost (% of Capital /year)	.035	.03	.01	.02	
Lifetime (years)	15	10	20	4	
Efficiency (LHV)	.686	.56	.92	.8	
After-Tax Capital Recovery Factor	0.177	0.206	0.166	0.359	

2.2 Cost Projections for Residential Fuel Cell Systems

The estimated capital costs for a fuel cell system to supply a peak power of 3.4 kWe AC to a private home is shown in Figure 12 for 100 production quantities and for 10,000 production quantities. Two cases are shown for each production level: the pure fuel cell system where the fuel cell has a 3.4 kWe peak output power capacity, and a battery-augmented system where the fuel cell has a nominal 1.2 kWe DC gross output power, and the battery supplies the peak power capability. The battery has an energy capacity of 6.7 kWh. The fuel cell supplies energy for both the house load (3.4 kWe AC peak and 0.92 kWe AC average load) and it supplies the AC electricity to run the steam methane reformer, which we estimate requires about 1.65 kWh of electricity per kg of hydrogen produced.

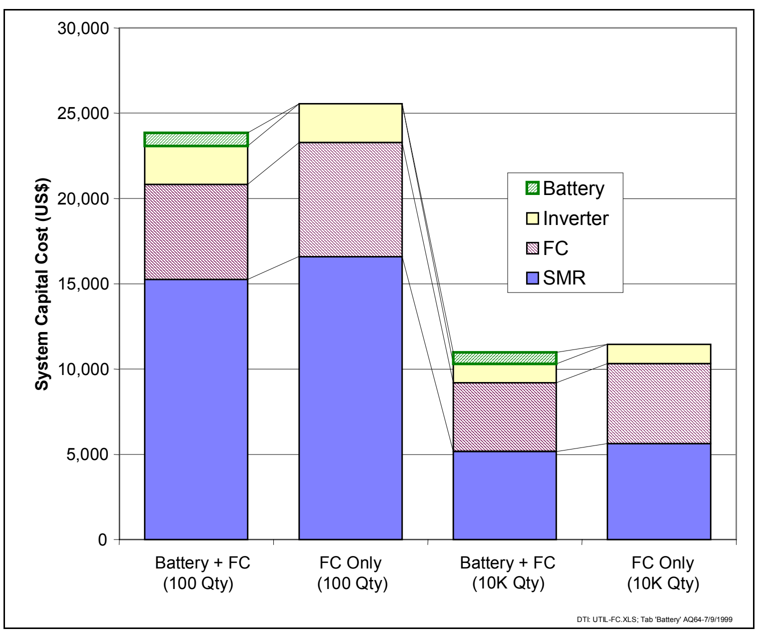
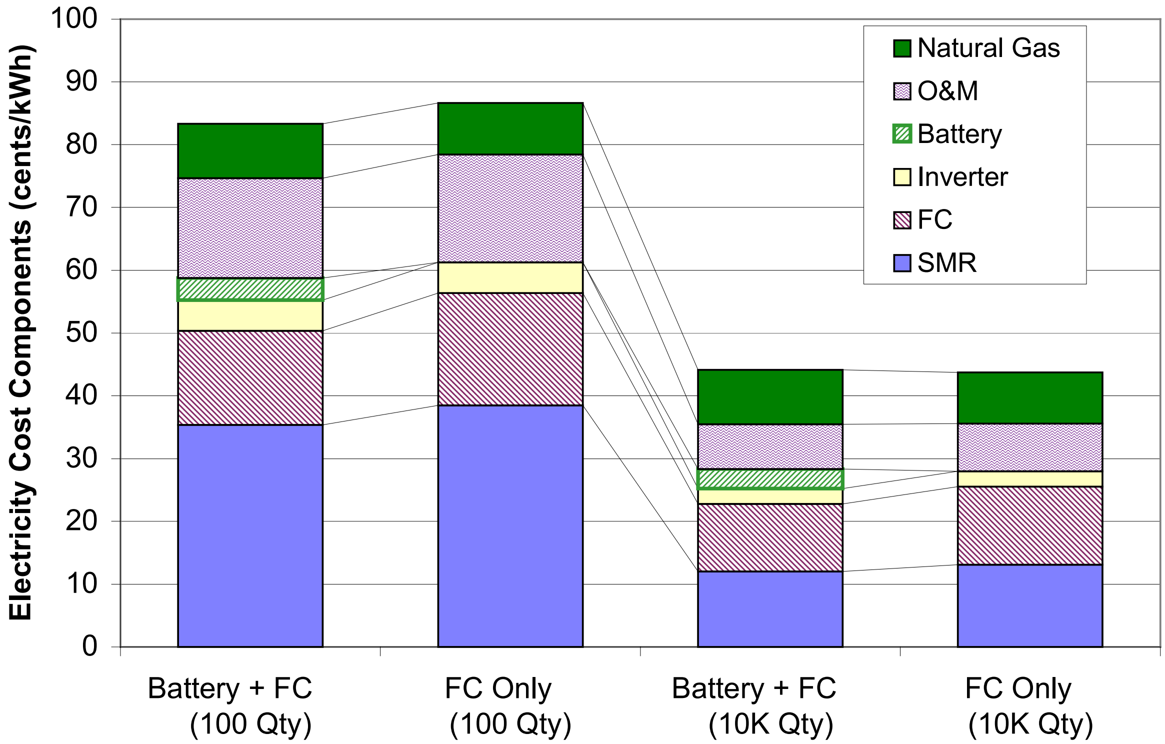


Figure 12. Capital Cost Estimates for a 3.4 kWe Fuel Cell System with Battery Peak Power Augmentation

As shown in Figure 12, adding the battery at an assumed cost of $100/kWh does reduce the total capital costs by about 7% for the 100-quantity production level, and by 4.2% for the 10,000 unit production level. These small reductions in capital cost have very little effect on the price of electricity necessary to provide the desired 10% real, after-tax return on capital, as shown in Figure 13. For the 100 quantity production level, the required price drops slightly with the battery system, from 86 to 83 ¢/kWh. At the 10,000 production level, the required price actually increases slightly, from 43.3 to 44 ¢/kWh. This increase is due to two factors: first the battery system has a very short lifetime (4 years assumed here), so the capital recovery rate is much larger for the battery than for the fuel cell system with an assumed life of 10 years. Second, the quantity of natural gas required increases slightly with the battery system, since the battery in somewhat inefficient (80% round-trip efficiency assumed).



			100 Qty:	10,000 Qty:
California Case	(Residential Rates)	Natrual Gas Reformer Cost:	$15,261	$5,184
Natural Gas Cost:	$6.55 /MBTU	Fuel Cell System Cost:	$5,570	$4,019
Grid Electricity Avoided Cost:	11.20 cents/kWh	Inverter Cost:	$2,249	$1,117
Battery Cost/kWh:	$100 /kWh	Battery Cost:	$759	$664
Battery Energy:	6.74 kWh-DC	Total System Cost:	$23,839	$10,984
Real, After-Tax Return:	10%			

DTI: UTIL-FC.XLS; Tab 'Battery' AZ109-7/9/1999

Figure 13. Electricity Price Required to Yield 10% Real, After-Tax Return on Investment for a Residential Fuel Cell System in California

In any case, the required electricity price in the range of 44 ¢/kWh is four times the average residential utility rate of 11.2 ¢/kWh in California. Adding the battery has negligible effect, and the system remains grossly uneconomic with the assumptions in the DTI cost model.
The situation changes very little in regions with more favorable electricity to natural gas prices such as Alaska. As shown in Figure 14, the lower natural gas costs ($3.65/MBTU vs. $6.55/MBTU in California) reduces the required electricity price by only 4 ¢/kWh. The required price of 40 ¢/kWh is still almost four times the average residential rate of 10.9 ¢/kWh in Alaska.

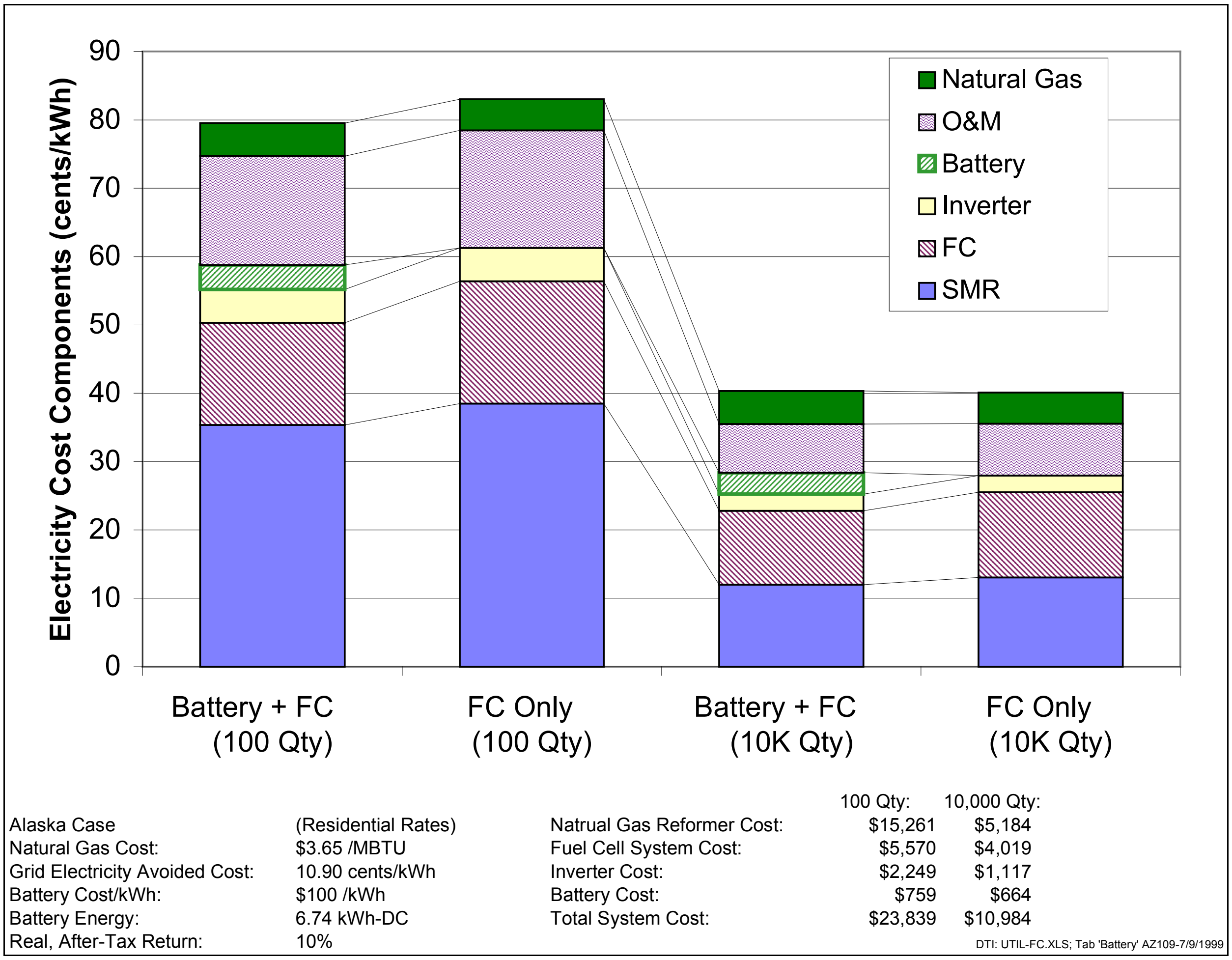


Figure 14. Electricity Price Required to Yield 10% Real, After-Tax Return on Investment for a Residential Fuel Cell System in Alaska

Finally, heat cogeneration has minor effect of the allowable electricity price. We estimate that the natural gas savings in California from using the low grade (80^{o}C) heat from the PEM fuel cell would save at most $90/year. This reduction in natural gas costs would translate into an electricity price lower by only 1.2 ¢/kWh.

2.3 Conclusions on Battery Augmentation

We conclude that adding batteries to a residential fuel cell system to reduce the peak power required from the fuel cell has negligible effect on the electricity price required to bring acceptable return on investment. For a typical single family residence with a one kilowatt average power draw and a 3.4 kWe peak power requirement, the fuel cell system owner would have to charge approximately 40 ¢/kWh to bring a 10% real, after-tax rate of return, which is almost four times the average residential utility rate in the United States. Hence we cannot rationalize a reasonable return on investment for a residential fuel cell system, with or without batteries, given our estimate of $10,000 capital costs at the 10,000 unit production level.

Acknowledgments

We thank the Hydrogen Program Office of the U.S. Department of Energy for supporting these analyses, and for the technical guidance and direction provided by Dr. Sig Gronich. We also thank the Ford Motor Company for providing supporting related fuel cell vehicle analyses.

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