Fuel-Cell Vehicles: Solution or Shell Game?

Stephen S. Eaves
Eaves Devices, Inc., Charlestown, RI
stepheneaves@eavesdevices.com

And

James E. Eaves
University of California, Davis[*]
eaves@primal.ucdavis.edu

The Bush administration's "Freedom Car" initiative aims to establish the Fuel-Cell Vehicle (FCV) as a replacement for the internal combustion engine. However, the administration seems to have taken this stance in the absence of an explicit study confirming that FCVs are superior to the only other zero-emission vehicle (ZEV) alternative, the Battery Electric Vehicle (BEV). Based on an automobile model that is characteristic of the largest segment of light-duty vehicles, results are presented from widely cited government studies of FCV and BEV technology to show that the BEV is far more favorable than the FCV in terms of performance, cost, and energy efficiency. The differences are particularly dramatic when we assume that energy is derived from renewable resources. Our results suggest, that for this important class of vehicles, BEVs would be more likely than FCVs to meet consumer demands. This is striking, in light of the fact that the Bush Administration has chosen to direct federal support away from BEV development.

Introduction

Over 40% of our foreign oil dependency is due to the fuel used by light-duty vehicles. These are the machines that take millions of Americans to work or play each day. Although the vast majority of Americans agree that foreign oil dependency, global warming and air pollution are pressing issues, they apparently do not translate these concerns to any significant change in personal life style; our vehicles are at their lowest average fuel economy level in over 20 years, due largely to an insatiable appetite for Sports Utility Vehicles (SUVs) and light trucks. California, having cities with the highest level of air pollution in the country, has been the natural defender of clean air laws for automobiles, and to the frustration of auto companies and the federal government, has historically supported clean-air measures that exceed federal legislation. The most widely known California initiative is referred to as the Zero Emissions Vehicle (ZEV) program. Starting this year, the legislation mandates that Automakers must be able to claim ZEV credits for a small percentage of total vehicle sales. The percentage ramps up to 11% in 2009 and to 18% by 2018 [1]. Failure to comply with the requirements of the mandate results in stiff financial penalties [2]. Further, Massachusetts, New York, and Vermont have copycat bills that will require automakers to sell ZEVs if California does.

Only two ZEVs have emerged as potential replacements of the internal combustion engine, the BEV and the FCV [3]. Until recently, it appeared that BEVs would be the most practical technology to satisfy California's deadlines. Thousands of BEVs are already registered in California, and hundreds of charging stations have been constructed. However, with the approach of the 2003 deadline, automakers have increasingly lobbied to delay or modify the legislation. Most recently, automakers have argued that although they may be able to satisfy the 2003 deadline by selling BEVs, the vehicles will not be broadly adopted by consumers in the long run. Josephine Cooper, president of the Alliance of Automobile Manufactures, representing 13 major automakers, stated, "Our companies have explored the path of battery electric vehicles. However, electric cars with broad consumer appeal are an idea whose time has come and gone, much like eight-track tapes, Betamax and New Coke." The same companies contend that FCVs can satisfy consumer's performance-quality demands but they need more time to develop the technology [4]. Following suit, the federal government has also shifted its emphasis towards the promotion of FCVs. Assistant Secretary of Energy, David Garman, explained to attendees at the Detroit Auto that the Bush administration aims to "promote the development of hydrogen as a primary fuel for cars and trucks…" Later in his testimony to congress Garman stated that the Department of Energy (DOE) would cut funding for BEV technology [5] quoting inadequate single charge range and performance as the primary reasons.

However, the fact that Freedom Car imposes no firmly set development milestones on automakers has prompted some environmentalists to dismiss the Automakers' and the Bush Administration's promotion of FCVs as simply a shell-game, designed to placate the public and the California legislature by offering a ZEV alternative to BEVs that will not impact automakers' bottom line for a decade, at the very least[6]. For example, despite promises of vastly improved performance and affordability, actual results from FCVs have not shown considerable improvement over what was demonstrated by electric vehicles years ago with less modern batteries. The Honda FCX, recently presented as one of the first commercially available fuel-cell vehicles [7], has a peak power of 80 HP (considerably less pick-up than a Geo Metro when the vehicle's weight is considered) and a 220 mile range under ideal conditions. Honda's chief engineer for fuel-cells commented that the vehicle currently costs approximately $1 million to produce, but they believe that they can reduce the cost of the vehicle to $100,000 in high production volume after ten years. Comparatively, Solectria Corporation in 1997, using battery technology that had less than ½ the energy density as what is available today in a laptop computer, drove 216 miles from Boston to New York City on a single charge, under normal driving conditions [8]. At the time, Solectria quoted the cost of the car in prototype quantities to be $100,000.

Ironically, the Solectria demonstration was not widely publicized due to a simultaneous media blitz for fuel-cells by the major automakers.

The fact that BEV technology from six years ago can compete with today's best fuel-cell vehicles begs the question of this paper: has the government and former proponents of BEVs "jumped ship" prematurely to embrace a less viable ZEV technology?

Rather than base our comparison of the two technologies on manufacturers claims alone, this paper utilizes widely cited government studies to show that a BEV equipped with state-of-the-art batteries is more favorable than an FCV in terms of performance, cost, and energy efficiency. Most importantly, the differences are particularly dramatic when we assume that energy is derived from renewable resources such as solar, wind, geothermal or hydroelectric power. In president Bush's recent proclamation that Fuel-cell vehicles are an answer to our dependence on foreign oil, he followed the standard spin developed by the automakers, and neglected to mention that hydrogen is merely an energy storage medium not a source; the industry plans to obtain hydrogen by processing fossil fuels [14].

Comparison of BEVs and FCVs

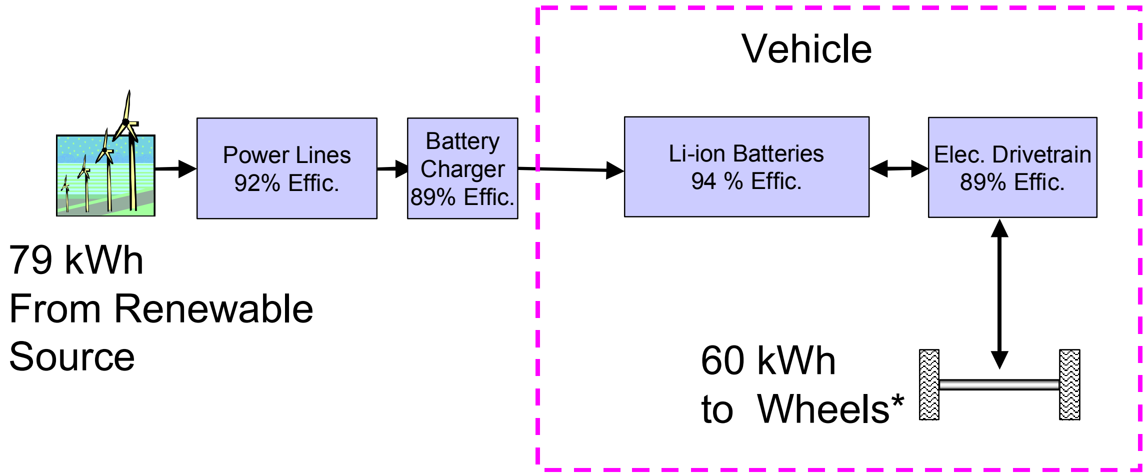
In this analysis, we compare the two technologies based on a vehicle model that is capable of delivering 100 kW of peak power, and 60 kWh total energy to the wheels [9]. This translates into a vehicle that is capable of delivering 135 horsepower and driving approximately 300 miles. The vehicle characteristics are comparable to a small to midsize car, such as a Honda Civic, representing the largest segment of the light-duty vehicle class [10]. Given this range-performance constraint, we first compare the relative efficiency of the "well-to-wheel pathways" of the two technologies. This allows us to calculate the energy a power plant must produce in order to deliver a unit of energy to the wheels of a FCV and a BEV. Next, we compute the volume, weight, and ownership costs associated with each vehicle [11]. We make these calculations first assuming that hydrogen for the FCVs and the electricity for the BEVs is generated using non-fossil fuel sources. Then we relax this assumption and consider the case where hydrogen is reformed from natural gas and the electricity for BEVs is generated using a mix of fossil fuel and non-fossil fuel sources, such as wind and hydroelectric, as is the norm today.

A substantial cost of the widespread adoption of FCV would be the construction and maintenance of a hydrogen infrastructure. However, in our non-fossil fuel analysis, we do not consider any of these costs associated with the adoption of the FCV. A renewable hydrogen infrastructure would consist of a network of electrolysis plants, supported by an intra-national pipeline, which, in turn, would supply a myriad of hydrogen refueling stations. The cost of hydrogen production from electrolysis is already well characterized from existing installations, but accurately projecting the downstream costs of a massive transportation and distribution infrastructure is much more difficult. The practical implication of only considering the production costs is that our estimates of refueling cost for FCVs will be significantly lower than they would be in reality. For instance, the cost of building the hydrogen refueling stations alone is estimated between $100 billion and $600 billion [31]. On the other hand, a BEV infrastructure would be largely based on the current power grid, making its construction vastly less costly [12].

Energy Efficiency Comparison

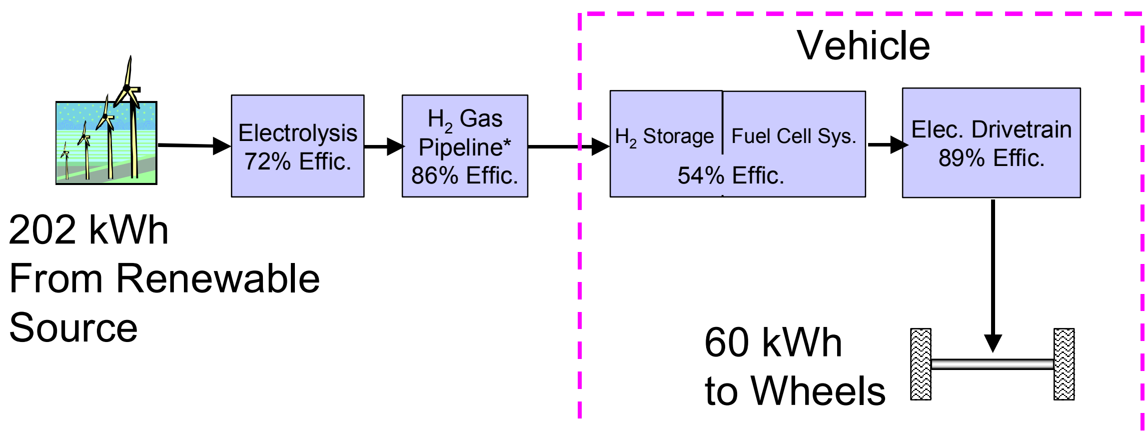
A vehicle's "well-to-wheel pathway" is the pathway between the original source of energy (e.g. a wind farm) and the wheels of the car. The pathway's components are the energy conversion, distribution, and storage stages required to transport and convert the energy that eventually moves the automobile. Thus, analyzing the efficiency of each vehicle's 'well-to-wheel pathway' allows us to determine the total energy consumption of each vehicle.

Figure 1 and Figure 2, below, illustrate the pathways for BEVs and FCVs respectively. The first stage of both pathways is the generation of electricity. Since presumably we are concerned with the long-run development of a sustainable transportation infrastructure, we first assume that the electricity is generated by a non-fossil fuel resource like hydroelectric, solar, wind, geothermal, or a combination. All of these sources are used to generate energy in the form of electricity. The only established method to convert electricity to hydrogen is through a process known as electrolysis, which electrically separates water into its components of hydrogen and oxygen.



*The BEV regeneration capability reduces the 60kWh requirement by 6kWh while achieving the same range

Figure 1 – "Well to Wheel" Energy Pathway for Battery Electric Vehicle



* "Pipeline" includes losses from compression, expansion, storage and distribution

Figure 2 – "Well to Wheel" Energy Pathway for Fuel Cell Vehicle

For BEVs, the electricity is delivered over power lines to a battery charger. The battery charger then charges a Lithium-ion battery that stores the energy on-board the vehicle to power the vehicle's drivetrain. In addition to one storage and two distribution stages, the BEV pathway consists of two conversion stages (the conversion of, say, wind to electricity in stage 1 and the conversion of electricity to mechanical energy in stage 2). The figure shows that the entire pathway is 76% efficient; approximately 79 kWh of energy must be generated in order to deliver the necessary 60 kWh of electricity to the wheels of the car.

The FCV's 'well-to-wheel pathway' illustrated in Figure 2 is believed by experts to be the most likely scenario, with some exceptions that are addressed below [14]. In this case, the energy from the electric plant is used for the electrolysis process that separates hydrogen gas from water. The hydrogen gas is then compressed and distributed to fueling stations where it can be pumped into and stored aboard individual fuel-cell vehicles. The onboard hydrogen gas is then combined with oxygen from the atmosphere to produce the electricity that powers the vehicle's drivetrain. In addition to one distribution and one storage stage, the FCV pathway consists of four conversion stages (the conversion of, say, wind to electricity in stage 1, the conversion of electricity to hydrogen in stage 2, the conversion of hydrogen back to electricity in stage 3, and finally, the conversion of electricity to mechanical energy in stage 4). Due largely to the fact that there are two additional conversion stages relative to the BEV and the fact that the onboard conversion stage is only 54% efficient [15], the FCV pathway is only approximately 30% efficient. The result is that the pathway requires the production of 202 kWh of electricity at the plant, to deliver the necessary 60 kWh to the vehicle or 2.6 times the requirements of the BEV pathway [16]. Obviously, this means that there will need to by that many times more wind farms or solar panels to power the fuel-cell vehicles versus BEVs.

Some may argue that on-board fossil fuel reforming or liquid hydrogen storage would provide more efficient pathways than the one illustrated in Figure 2. However, attempts at these alternative methods have proven uncompetitive compared to a system based on compressed hydrogen gas. As a consequence, the pathway illustrated in Figure 2 is considered by DOE and industrial experts to be the most feasible [14].

However, the DOE's support for the distribution pipeline of Figure 2 is based on the assumption of using fossil fuels as the source of hydrogen, contrary to our present assumption. In the case of renewable energy, it would be more cost effective to transport the electricity over power lines and perform the electrolysis at local "gas stations", thus eliminating the need for the expensive and less efficient hydrogen pipeline [17]. Elimination of the hydrogen pipeline stage significantly increases the overall efficiency of the pathway, however, 188 kWh is still necessary to deliver 60 kWh to the wheels, or 2.4 times the energy required to power a BEV.

The inefficiency of the FCV pathway combined with the high capital and maintenance costs of the distribution system results in significant differences in the refueling cost between a FCV and BEV, particularly if the source is renewable. For example, Pedro and Putsche [31] estimate that using wind energy, hydrogen production costs alone will amount to $20.76 per tank to drive our FCV 300 miles. This compares to $4.28 "per tank" to drive the BEV 300 miles [18].

Comparison of Weight, Volume and Cost

Maintaining the same performance assumptions, we next compare the projected relative weight, volume, and unit costs of each vehicles propulsion system. The results are reported in Table 1 and Table 2. When interpreting the tables, it is important to note that the limiting factor in FCV performance is the amount of power that can be delivered, which affects vehicle acceleration and hill climbing. For BEVs, it is the amount of energy that can be delivered which affects total vehicle range. The result is that scaling factors for weight, volume, and cost for the FCV are based on how many Watts (of power) that can be delivered per unit of weight, volume or cost. For the BEV it is the amount of Watt·hours (of energy) that can be delivered per unit of weight, volume or cost.

Table 1: Estimated weight, on-board space, and mass-production cost requirements of the FCV propulsion system

Component	Weight	Volume	Cost	Reference
Fuel-Cell	617 kg	1182 liters	$23,033	ADL(2001)
3.2 kg storage tank	51 kg	215 liters	$2,288	Padro and Putsch(1999)
Drivetrain	53 kg	68 liters	$3,826	AC Propulsion, Inc.(2001), Solectria Corp (2001)
Total	**721 kg**	**1465 liters**	**$29,147**	

Table 2: Estimated weight, on-board space, and mass-production cost requirements of a BEV propulsion systems

Component	Weight	Volume	Cost	Reference
Li-ion Battery	451 kg	401 liters	$16,125	Gaines and Cuenca(2000)
Drivetrain	53 kg	68 liters	$3,826	Cuenca and Gains (1999)
Total	**504 kg**	**469 liters**	**$19,951**	

Weight Comparison

According to the DOE report on the status of fuel-cells conducted by Arthur D. Little [19], a modern fuel cell is presently capable of delivering 182 Watts of power per kg of fuel-cell. Including the required FCV drivetrain components and their losses [20,21] and weight of the storage tank [22], a fuel-cell propulsion system capable of meeting the assumed range-performance constraint must weigh approximately 721 kg. According to the National Renewable Energy Laboratory (NREL) working group report on advanced battery readiness [23], a Lithium-ion battery is capable of delivering 143 Watts·hours of energy per kg of battery. Considering an equivalent drivetrain to the one assumed for the FCV, the battery system must weigh 504 kg to satisfy our range-performance constraint [24].

Volume Comparison

The fuel-cell is reported in the Aurthur D. Little study to deliver 95 Watts per liter of fuel-cell, which combined with the volume of the hydrogen storage tank, and the volume of the electric drivetrain components produces a total volume of 1465 liters [25]. A Lithium-ion battery delivers 161 Watt·hours per liter of battery [26]. When combined with the electric drivetrain volume, this results in a total volume of 469 liters.

Cost Comparison

Finally, The Aurthur D. Little study reports a cost of $205 per kW for a 100kW fuel-cell [27]. Adding in the cost of the electric motor, control electronics and hydrogen-storage tank results in a total cost for the fuel-cell propulsion system of $29,147 [28]. As for the BEV, the total cost for a Lithium-ion battery is estimated as $250/kWh [29]. Considering the electric drivetrain, this implies a total cost of $19,951.

Energy Use with Fossil Fuels

Most experts are imagining that for many years, fossil fuels will be the main source of the hydrogen or the electricity that powers zero emission vehicles. In light of this, one should consider the near term case where the electricity for BEVs is generated using a mix of fossil fuel and non-fossil fuel sources and the FCVs are fueled using hydrogen reformed from natural gas, as is the norm today. This scenario makes FCVs more competitive, but as is shown below, the overall findings reported in this paper are not reversed.

A 2001 study conducted for the California Air Resources Board [30] found that when electricity for BEVs is generated using a mix of fossil fuel and non-fossil fuel and hydrogen is created from natural gas, a BEV pathway is about 8% more efficient than a FCV pathway. The study also concluded that the BEV pathway would generate lower greenhouse gas emissions. Although the efficiency comparison of the two vehicles is much closer than for the non-fossil fuel case, if the substantial cost of building and maintaining the hydrogen infrastructure necessary to support the FCV is considered, then the BEV would clearly be more attractive than the FCV. Further, if renewable energy sources will eventually replace fossil fuels, then the hydrogen pipeline will at best be inefficient, and at worst be obsolete. This is because hydrogen producers would find it more economical to make hydrogen locally by using renewable electricity to hydrolyze water, rather than purchasing hydrogen transported via pipeline. Since the nation's electricity is already generated using an array of fossil and non-fossil fuel resources, the optimal design of the BEV infrastructure would not change in the conversion to a non-fossil fuel economy.

Lastly, when the non-fossil fuel assumption is relaxed, the refueling cost of a BEV is still far less than that of the FCV. Pedro and Putsch estimate the retail cost of hydrogen from fossil fuel to be $2.42 per kg [31]. Given the 3.2 kg of hydrogen necessary to meet our range-performance constraint, this results fill-up cost of $7.77 for the FCV.

Accounting for efficiency losses between a BEV's battery and its wheels, 64.5kWh of energy must be delivered to the BEV to assure that 60 kWh is delivered to its wheels. Considering a 0.89 charger efficiency and a 0.94 battery efficiency, this implies that 77 kWh of energy must be purchased from the utility company. Since BEVs will typically be charged at night, an off-peak cost of $0.06/kWh is applied for the electricity generated from a mix of fossil and non-fossil fuels. This implies a "fill-up" cost of $4.63 for the BEV, which is 70% lower than that of the FCV.

Conclusion

This analysis uses results from widely cited government studies of FCVs and BEVs to explicitly compare the performance of the two technologies. The analysis is based on an automobile model (similar to a Honda Civic) that is representative of the largest segment of the automobile market. A comparison is important since our nation has made a recent change in policy for widespread adoption of fuel-cell vehicles, while all but abandoning its efforts on battery electric vehicles. Since the BEV and FCV are the only two zero-emission candidates, elementary risk analysis would require overwhelming evidence indicating that FCV's are vastly superior to BEVs in order to justify investing in only one of the technologies. We were unable to find such overwhelming evidence in government studies, and our conclusions are confirmed by published data on introductory vehicles. The results show that in a future economy based on renewable energy, the FCV requires production of between 2.4 and 2.6 times more energy than the BEV. The FCV propulsion system weighs 43% more, consumes three times more space onboard the vehicle for the same power output, and costs approximately 46% more than the BEV system. Further, the refueling cost of a FCV is nearly three times greater, even if we do not consider the substantial cost of building and maintaining the hydrogen infrastructure on which the FCV would depend. Finally, when we relax the renewable energy assumption, the BEV is still more efficient, cleaner, and vastly less expensive in terms of refueling and infrastructure investment. As indicated above, at the very least, this indicates that the development effort on battery electric vehicles should continue, particularly if the objective is to maximize the use of renewable energy resources.

REFERENCES AND NOTES

[1] " Proposed 2003 Amendments to the California Zero Emission Vehicle Regulation" Published by the California Air Resources Board, (March 5, 2003), www.arb.ca.gov/regact/zev2003/modifications.pdf

[2] "Zero Emission Vehicle Program Changes Fact Sheet", Published by the California Air Resources Board, (Dec. 10, 2001), http://www.arb.ca.gov/msprog/zevprog/factsheets/evfacts.pdf

[3] We do not consider Hybrid FCVs, which combine a fuel cell with batteries, since the benefits if these vehicles are yet to be characterized by the DOE. A recent study by Ford Motor Company concluded that the increased complexity of a Fuel Cell Hybrid would probably not justify the benefits: "Direct-Hydrogen-Fueled Proton-Exchange-Membrane Fuel Cell System for Transportation Applications" Final Technical Report, Prepared by Ford Motor Company and Directed Technologies for U.S. Department of Energy, (December 4, 2000).

[4] "Final Statement of Reasons for Rulemaking Including Summary of Comments and Agency Response", State of California Air Resources Board, (2002).

[5] "DOE Official Testifies Before House on HEVs", *Electric Vehicle Online Today*, (March 7, 2002).

[6] Mark Schrope, "New-Generation Cars Become Old hat as US Changes Course", Nature 415, 248, (2002).

[7] "Fuel Cells: Japans Automakers are Flooring it", *Business Week*, Pages 50,51, (December 23, 2002).

[8] "Ovonic NiMH batteries power EV from Boston to New York on a Single Charge", http://www.ovonic.com/news_events/5_2_press_releases/19971024.htm, (October 24,1997).

[9] The BEV has the ability to capture approximately 10% of the energy sent to the wheels back to the battery pack during deceleration, this is commonly known as regeneration. Characteristics of a General Motors EV1 as tested by CARB were used in the analysis. See "Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost, and Availability", Prepared for the State of California Air Resources Board, (June 2000).

[10] "Light-Duty Automotive Technology and Fuel Economy Trends 1975-2001", conducted by the U.S. Environmental Protection Agency, (Sept. 2001).

[11] Some may argue that onboard reforming of methanol is a more likely means of powering a FCV, since this liquid fuel would have transportation and distribution systems similar to gasoline. However, experts are strongly divided on this point. First, since methanol is a neuro-toxin, safety issues are a serious concern. Second, building a FCV with an onboard fuel-processor- reformer nearly doubles the weight, size, and cost estimates calculated above, making the system too impractical to warrant inclusion in this study.

[12] Studies on EV charging infrastructure in California found that a large number of electric vehicle will not severely tax the existing power grid. In fact, the load leveling effect of the vehicles would be beneficial, see "Electric Vehicle and Energy use Fact Sheet" published by California Air Resources Board, (January 2002).

[13] National Renewable Energy Laboratory, "Advanced Battery Readiness Ad Hoc Working Group Meeting Report", (March 2000).

[14] "Interviews with 44 Global Experts on the Future of Transportation and Fuel Cell Infrastructure and a Fuel Cell Primer", M.J. Bradley, Northeast Advanced Vehicle Consortium under contract to Defense Advanced Research Projects Agency, Agreement No. NAVC1099-PG030044, (2000).

[15] The actual efficiency would most likely be significantly lower since there are "parasitic" losses from fans, pumps etc. However, since the ADL study did not separately account for parasitic losses in the fuel cell stack and fuel processor, they were conservatively not considered in this study.

[16] "Well-to-Wheels Energy use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems", General Motors,Argonne National Laboratory,BPAmoco,Exxon Mobile and Shell, (2001).

[17] "A Fuel Cycle Energy Conversion Efficiency Analysis", Status Report Prepared for the CA Energy Commission and the Air Resource Board, (2000).

[18] The cost per tank is based on the Padro and Putsche (1999) estimate of $6.49 per kg to produce the 3.2 kg of hydrogen necessary to power the FCV for 300 miles and $.055 cents per kWh to provide the 77.9 kWh required to power the BEV for 300 miles.

[19] Arthur D. Little Inc., "Cost Analysis of Fuel Cell System for Transportation", Report to Department of Energy, Ref. No. 49739, SFAA No. DESC02-98EE50526, (2001).

[20] AC150 GEN-2 EV Power System Specification Document, AC Propulsion Inc., San Dimas, CA, (2001).

[21] DMC0645 AC Motor Controller Specification, Solectria Corp., Woburn, MA, Document, (2001).

[22] To store 3.2 kg of hydrogen the tank must be 215 liters (30).

[23] "Advanced Battery Readiness Ad Hoc Working Group Meeting Report", (National Renewable Energy Laboratory 2000).

[24] Accounting for the drivetrain efficiency, and 10% regeneration, 64.5 kWh must be stored in the battery to deliver 60kWh to the wheels.

[25] The electric drive train volume with a 66% packing factor occupies 68 liters for both the FCV and BEV, See AC150 GEN-2 EV Power System Specification Document, (19,20).

[26] Lithium-ion batteries provide approximately 230 Wh/l; a 43% packing factor reduced this to 161Wh/l.

[27] The study reports on a 55kW fuel cell, but also indicates that the fuel cell cost scales well with power.

[28] The electric drivetrain components are $3,826 for the BEV and FCV (R. Cuenca, L. Gaines, A. Vyas,"Evaluation of Electric Vehicle Production and Operating Costs", Center for Transportation Research, Argonne National Laboratory, 1999).

[29] L. Gaines, R. Cuenca,"Costs of Lithium Ion Batteries", Center for Transportation Research, Argonne National Laboratory, (2000).

[30] "A Fuel Cycle Energy Conversion Efficiency Analysis", Status Report Prepared for the CA Energy Commission and the Air Resource Board, (2000).

[31] C.E.G Padro', V. Putsche,"Survey of Economics of Hydrogen Technologies", National Renewable Energy Laboratory Study NREL/TP-570-27079, (1999).