COST-BENEFIT ANALYSES OF ALTERNATIVE LIGHT DUTY TRANSPORTATION OPTIONS FOR THE 21ST CENTURY

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1. Introduction

New fuels and alternative vehicles will be required to substantially cut our dependence on foreign oil and reduce our transportation sector carbon footprint. Biofuels such as biodiesel and ethanol, especially if made from cellulosic feedstocks, are promising. Natural gas might reduce oil consumption and make modest reductions in greenhouse gas emissions, but only as a temporary transition fuel. Hydrogen and electricity could eventually become key zero-carbon transportation fuels.

In terms of alternative vehicles, gasoline-powered hybrid electric vehicles (HEVs) are already making an impact in the light duty vehicle fleet, and plug-in hybrid electric vehicles (PHEVs) that derive some of their energy from the electrical grid may soon enter the marketplace. The combination of biofuels and PHEVs will reduce oil consumption, and--depending on the types of fuels used to generate electricity in any region of the country--may help to appreciably reduce greenhouse gas emissions. Ultimately all-electric vehicles powered either by fuel cells or by batteries could make a major contribution to achieving our long-term societal goals.

This report reviews prior simulations of light duty vehicle options, focusing primarily on the comparison between battery-powered and fuel cell-powered all-electric vehicles that we believe will be required in the future. We then explore the societal costs and benefits of the major alternative vehicle options over the 21st century.

2. Previous Studies

The 2008 National Research Council (NRC) report on alternative transportation technologies compared advanced gasoline internal combustion vehicles with gasoline HEVs, biofuels and hydrogen-powered fuel cell electric vehicles (FCEVs) [1]. The NRC first considered each fuel or technology acting alone. They showed that biofuels by themselves or advanced gasoline cars by themselves would each reduce GHG emissions and oil consumption compared to business as usual, but both emissions and oil use would begin rising again after 2030 as increased vehicle miles traveled wiped out the advantage of biofuels or advanced engine technologies. The NRC report showed that hydrogen-powered fuel cell electric vehicles (FCEVs), acting alone, would set GHG emissions and oil consumption on a downward trajectory through 2050 (the last year analyzed). So if society opted for only one pathway, then FCEVs would be the most beneficial in the long run.

By far the best outcome, however, would rely on a portfolio of fuels and technologies. The NRC concluded that biofuels, HEVs, advanced gasoline engines *and* hydrogen-powered FCEVs, acting together, will be required to eliminate nearly all oil consumption from cars and to cut GHGs to 80% below 1990 levels by 2050….we need all of the above.

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Our previous computer simulations showed similar results [2]. We concluded that all-electric vehicles in combination with biofuels, HEVs and PHEVs will most likely be required to meet our energy security and climate change reduction goals. As shown in Figure 1, hybrid electric vehicles (HEV's) and plug-in hybrid electric vehicles (PHEV's) both reduce greenhouse gas (GHG) emissions, but neither of these vehicles that still use internal combustion engines will be sufficient alone to cut GHGs to 80% below 1990 levels, the goal set by the climate change community, even if biofuels such as cellulosic ethanol are used in place of gasoline to power the internal combustion engines on the PHEVs[1]. Either battery EVs or (preferably) fuel cell EVs must be added to the mix to reach our GHG targets.

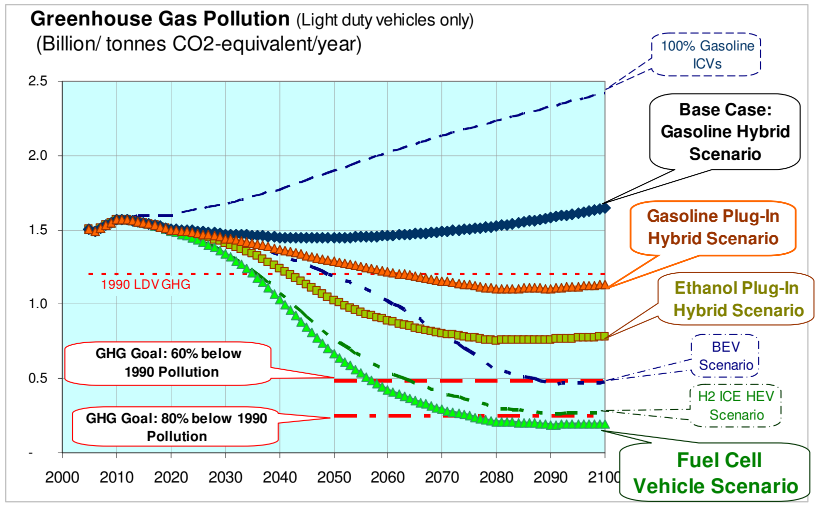

Figure 1. Projected greenhouse gases for different alternative vehicle scenarios over the 21st century for the US light duty vehicle fleet, assuming that both the electrical grid and hydrogen production reduce their carbon footprints over time. The fuel cell electric vehicle and battery electric vehicle scenarios include gasoline ICEVs, HEVs and ethanol PHEVs in the mix (BEV= battery electric vehicle; H2 ICE HEV = hydrogen internal combustion engine hybrid electric vehicle)

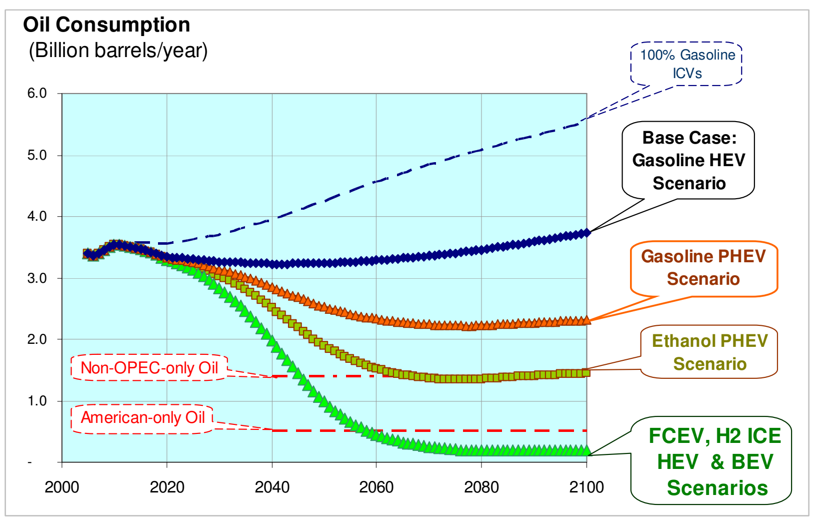

Figure 2. US light duty vehicle oil consumption for the various scenarios over the 21st century

Similarly, Figure 2 shows that HEV's and PHEV's powered by biofuels will be unlikely to reduce oil consumption in the US to levels that would allow us to produce most of our petroleum from American sources if needed in a future crisis. To achieve oil "quasi-independence," to cut GHGs to 80% below 1990 levels, and to remove most urban air pollution from cars and trucks, we will eventually have to eliminate the internal combustion engine from many if not most light duty

[1] We assume a limit of 80 billion gallons of cellulosic ethanol per year, which limits PHEVs to ~75% of the market by the end of the century. The 2008 NRC study assumed a maximum of 60 B gallons/year [1] and the Sandia National Laboratory/General Motors study concluded that 90 billion gallons/year was possible [3]. All GHG estimates are calculated with the Argonne National Laboratory GREET model [4].

vehicles. We will have to transition to *all-electric vehicles* over the next few decades to meet our societal goals, in conjunction with HEVs, biofuels and PHEVs in the near term.

We have only two choices to power all-electric vehicles: fuel cells or batteries. Both generate electricity to drive electric motors, eliminating the pollution and in-efficiencies of the venerable internal combustion engine. Fuel cells derive their energy from hydrogen stored on the vehicle, while batteries obtain their energy exclusively from the electrical power grid. Both hydrogen and electricity can be made from low- or zero-carbon sources including renewable energy (solar, wind & biomass), nuclear energy and coal with carbon capture and storage. Both hydrogen and electricity are zero carbon fuels that will permit all-electric vehicles to meet the stringent California zero emission vehicle (ZEV) standards, eliminating virtually all controllable[2] urban air pollution from light duty motor vehicles.

3. Batteries vs. Fuel Cells

In the following sections, we compare hydrogen-powered fuel cell electric vehicles (FCEV's) with battery-powered electric vehicles (BEV's) in terms of weight, volume, greenhouse gases, fueling time and cost.

3.1. Weight

Figure 3 compares the useful specific energy (energy per unit weight) of existing deep discharge lead-acid (Pb-A) batteries, nickel metal hydride (NiMH), Lithium-Ion and the US ABC (Advanced Battery Consortium) goal with the specific energy of a PEM fuel cell system plus compressed hydrogen storage tanks. Two hydrogen pressures are shown: 35 MPa (350 bar or 5,000 psi) and 70 MPa (700 bar or 10,000 psi) with fiber-wrapped composite tanks[3]. The energy used to calculate these specific energies is the actual *useful* energy delivered to the vehicle motor controller, not the total stored energy.

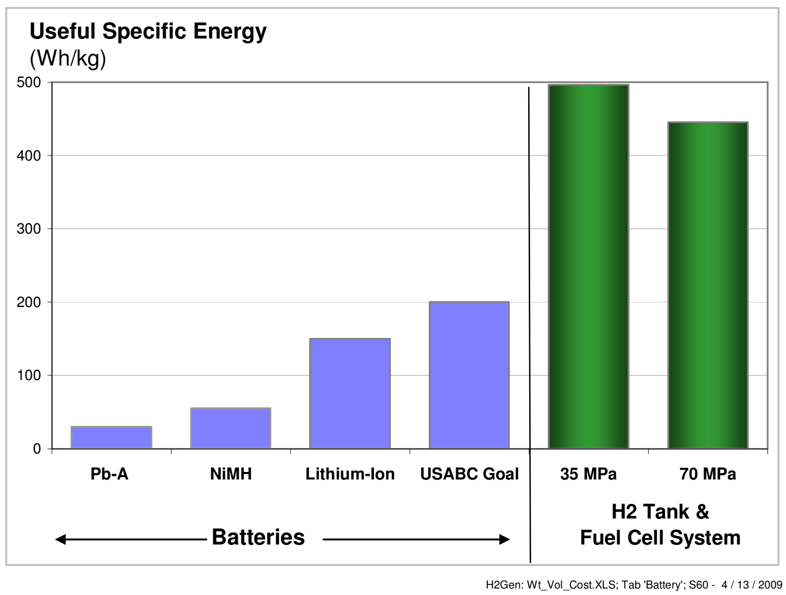

Figure 3. The useful specific energy of hydrogen and fuel cell systems compared to the useful specific energy of various battery systems

[2] All-electric cars still generate particulate matter (PM) from tire and brake wear, but no tailpipe emissions.
[3] Based on fuel cell power of 60 kW, FC system specific power of 0.69 kW/kg[5], FC system power density of 0.67 kW/liter [5], 51.8% FC system efficiency averaged over the EPA 1.5 times accelerated combined driving cycle, 4.5 kg of useable onboard hydrogen storage for 350 miles range, 2.25 safety factor on the hydrogen tank, and a 1.7 times weight multiplier to account for current tank construction that is 70% heavier than the minimum possible. With these data hydrogen is 5.9% of the weight of the 35 MPa tanks and 4.7% of the weight of the 70 MPa tanks.

For hydrogen, we calculate only the electrical energy out of the fuel cell system, which is approximately 52% of the lower heating value of the hydrogen actually stored in the compressed gas tanks, averaged over an aggressive vehicle driving cycle. The weight in the specific energy calculation includes the hydrogen tanks, the fuel cell stack plus all auxiliary fuel cell system components such as humidification, air blowers and control electronics. Similarly, for batteries we include only the energy delivered to the motor in the specific energy calculation, not the total stored battery energy. For example, a battery might store 200 Wh/kg of energy, but if the state of charge (SOC) can only be varied between 30% and 90% to avoid battery degradation over time, then the useful specific energy might only be 120 Wh/kg[4]. The weight used to calculate specific energy includes all battery system components such as thermal management systems, the battery charger and associated electronic controls.

Figure 3 illustrates that compressed hydrogen and fuel cells can provide electricity to a vehicle traction motor with 8 to 9 times more energy per unit weight than current NiMH batteries used in most gasoline HEVs, and two to three times more than advanced Lithium-ion batteries and the US ABC goal. As a result, battery EVs must be heavier than FCEVs for a given range, as shown in Figure 4 based on a full-function five-passenger sedan[5].

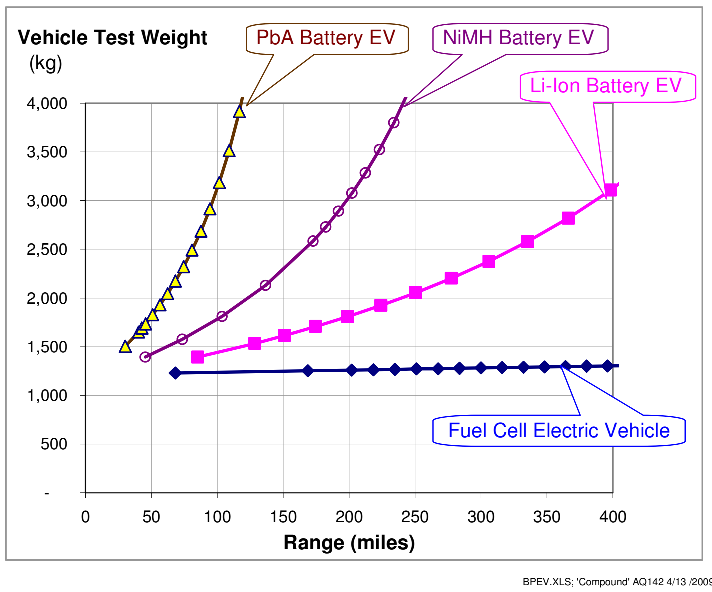

Figure 4. Estimated battery electric vehicle and fuel cell electric vehicle test weights as a function of vehicle range

As shown in Figure 4, little extra weight is required to increase the range of the fuel cell EV since hydrogen plus slightly larger tanks to extend the range are very light, while the battery EV weight escalates dramatically with range, since each extra mile requires the addition of heavy battery plates. The growth in weight with vehicle range is also the result of weight compounding, where each extra kilogram of battery weight to increase range requires extra structural weight, heavier brakes, a larger traction motor, and in turn more batteries to accelerate this extra mass in an insidious feedback process.

3.2. Storage Volume

Some analysts are concerned about the volume required for compressed gas hydrogen tanks. They do take up more space than a gasoline tank, but compressed hydrogen tanks plus the entire fuel cell system together take up *less* space than batteries per unit of useful energy

[4] Internal battery resistance will also reduce energy delivered to the motor as a result of I^2R losses, particularly at high current discharges when high power is required for vehicle acceleration.
[5] Based on a FCEV with 350 miles range with a test weight of 1280 kg, cross sectional area of 2.13 m^2, drag coefficient of 0.33 and rolling resistance of 0.0092.

delivered to the motor. The basic energy density (energy per unit volume) of the hydrogen fuel cell system in watt-hours per liter is compared with those of batteries in Figure 5.

The hydrogen fuel cell system has an inherent energy density advantage. This advantage is amplified on a vehicle because fuel cell EVs due not suffer from weight compounding to the degree of battery EVs as described previously.

The total volume required for the hydrogen tanks and fuel cell system is compared with battery packs in Figure 6, again as a function of range. The space to store lead acid batteries would preclude a full five-passenger vehicle with a range of more than 100 miles, while a NiMH EV would be limited in practice to less than 150 to 200 miles range.[6]

An EV with an advanced Li-Ion battery could in principle achieve 250 to 300 miles range, but these batteries would take up 500 to 700 liters of space (equivalent to a 130 to 180 gallon gasoline tank!). The fuel cell plus hydrogen storage tanks for 350 miles range would take up less than half this space, and, if the DOE hydrogen storage goals are achieved, then the hydrogen tanks plus the entire fuel cell system would occupy only 180 liters (50 gallons) volume for 350 miles range.

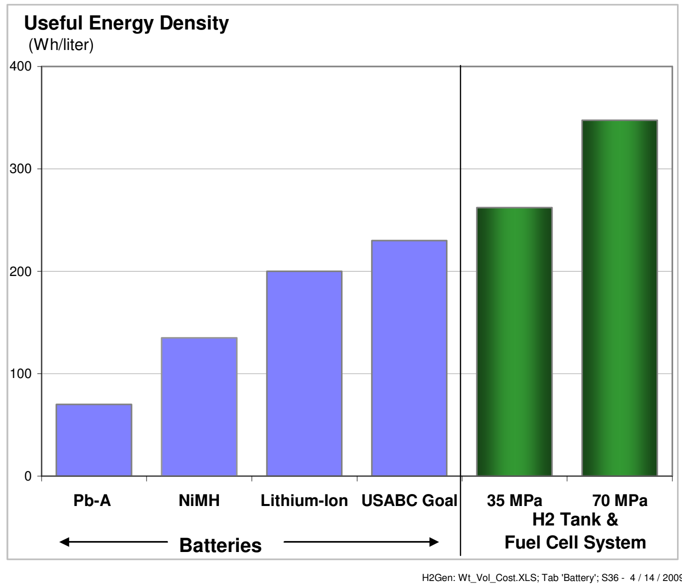

Figure 5. Useful energy densities of hydrogen tanks and fuel cell systems compared to the useful energy densities of various battery systems

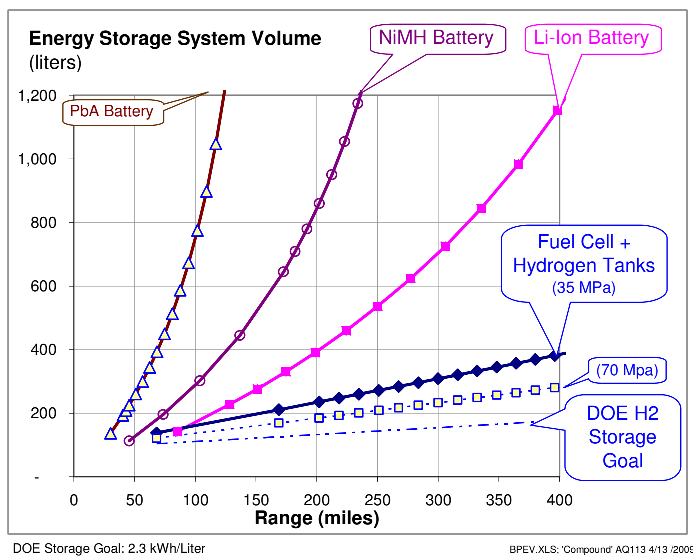

Figure 6. Calculated volume of hydrogen storage plus the fuel cell system compared to space required for batteries on the vehicle as a function of range

[6] The battery EV range could be extended by reducing its weight, aerodynamic drag and rolling resistance as in the now defunct GM Impact/EV-1. But the FCEV range would also be increased with such an aerodynamic and light vehicle. Thus the relative comparisons between FCEVs and BEVs in these charts would still be valid.

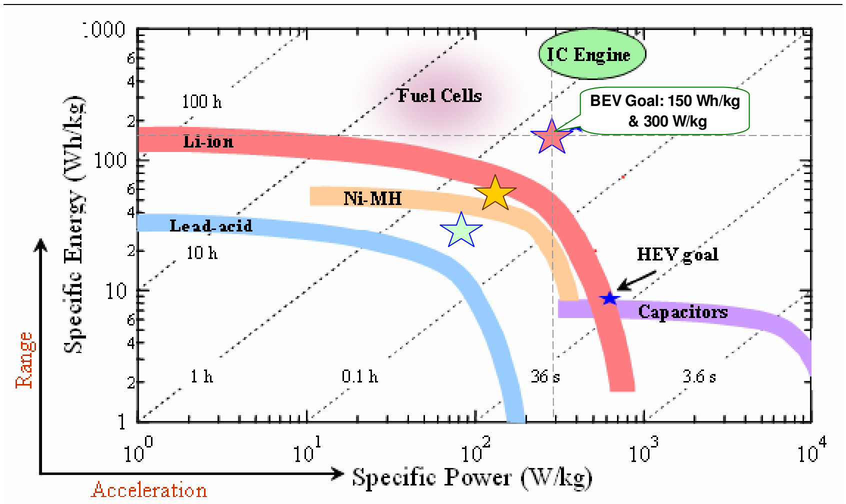

Figure 7. Specific Energy vs. Specific Power for battery technologies from Kromer and Heywood (MIT) [6]; star symbols indicate the battery parameters used in this study that are all more optimistic than current battery performance

The previous charts assume somewhat optimistic battery parameters for both specific energy and specific power. We placed star symbols on Figure 7 taken from Kromer and Heywood of MIT to illustrate the energy and power ratings used in this model[6]. In all cases we have assumed higher specific energy and power levels than existing capability for each battery technology. That is, the stars lie above the broad curves of existing performance for each battery. We have assumed in particular that the Li-ion battery technology achieves the BEV goal of 150 Wh/kg and 300 W/kg, above current Li-ion battery system achievements for *useful* energy divided by total battery system weight or volume. Some Li-ion batteries have demonstrated high specific energy of up to 150 Wh/kg, but only at very low power levels where the battery can be discharged at low power to avoid resistive losses and where the battery state of charge could be varied over a wide range without adversely affecting battery lifetime for applications such as laptop computers or cell phones. Similarly Li-ion batteries with very thin plates have achieved up to 900 W/kg specific power levels (or more), but only at very low energy levels that would be unsuitable for a BEV.

These curves demonstrate that all battery technologies involve a trade-off between energy and power. For hybrid vehicles power is the major driver, since the onboard fuel provides stored energy via the internal combustion engine. An all-electric vehicle requires much more energy storage, which involves sacrificing specific power. In essence, high power requires thin battery electrodes for fast response, while high energy storage requires thick plates.

3.3. Greenhouse Gases

The greenhouse gas (GHG) implications of charging battery EVs with today's power grid are serious[7]. Since on average 52% of our electricity in the US comes from coal, and since the electrical grid efficiency averages only 35%[8], GHGs would be much greater for EVs than for

[7] If both the electricity to charge the car batteries and the hydrogen came from renewable sources, there would be negligible GHG implications. This GHG assessment applies to the next decade or two before renewable or nuclear power (or coal with carbon capture and storage) replaces most of the conventional coal-generated electricity.

[8] Electrical power generating plants convert only 32% to 36% of the energy in coal to electricity, and only 92% of that electricity reaches the end user due to transmission line losses, for a net system efficiency of conversion between 30% to 34%; natural gas conversion rates vary between 26% to 32% for gas turbines, and between 38%

hydrogen-powered FCEVs, assuming that most hydrogen was made by reforming natural gas for the next decade or so.

Increasing the weight of the EV by adding batteries to achieve reasonable range increases fuel consumption as the vehicle becomes heavier, thereby generating more GHGs from the electrical power plant per mile driven. The GHG emissions with today's marginal grid mix are shown in Figure 8. These GHG calculations include all "well-to-wheels" GHGs adjusted for a 100-year atmospheric lifetime, based on the Argonne National Laboratory GREET model[4].

Because longer range EVs are heavier and less efficient for any given battery type, a 5-passenger PbA battery EV that achieved more than 60 to 70 miles range would generate more net GHGs than the gasoline version of the same car. A NiMH battery EV with more than 125 to 150 miles range and a Li-ion battery EV with more than 270 miles range would generate more GHG emissions than a comparable gasoline car. Longer range battery EVs are possible[9], but only by generating more GHGs than gasoline cars of the same size.

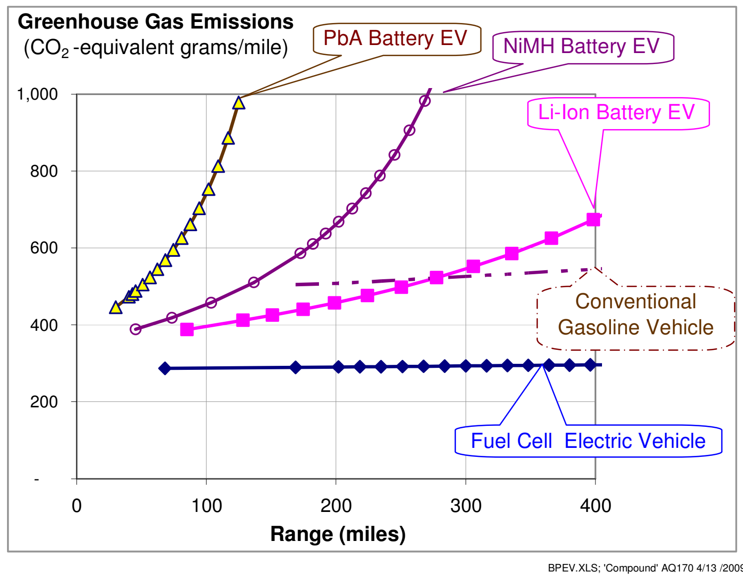

Figure 8. Estimated greenhouse gas emissions for battery EVs and fuel cell EVs, using existing average US marginal grid mix for electricity and assuming that all hydrogen is made from natural gas

The hydrogen FCEV running on hydrogen made from natural gas can achieve the 300 to 350 mile range demanded by American drivers with consistent GHG reductions. The gasoline ICE version the passenger vehicle analyzed here produces about 550 g/mile of CO_2-equivalent emissions, so the FCEV powered by hydrogen made from natural gas would immediately cut GHG emissions by 47% compared to gasoline cars.

3.4. Fueling Time

Hydrogen-powered fuel cell electric vehicles can be refueled in three to five minutes, similar to conventional gasoline fueling. Hundreds of thousands of high pressure natural gas-powered vehicles are refueled every day around the world, using technology comparable to high pressure hydrogen gas fueling systems.

Charging batteries for an all-electric vehicle will take longer. One of the challenges facing battery companies is to design and manufacture batteries that can accept rapid charging

to 45% for combined cycle generation plants, or a net rate of converting natural gas to electricity between 24% to at most 42% [8]

[9] Assuming that the added weight, volume, cost and longer fueling time of the battery banks were acceptable to consumers.

currents without overheating the battery cells or disrupting the voltage balance between cell banks. But even if batteries can be built to accept rapid charging, the local electrical supply system will still limit charging times for long-range BEVs. Residential electrical circuits are typically limited to less than 2 kW power for a 120 Volt, 20 Amp circuit (called Level 1 charging in the EV business), since the National Electrical Code requires that all branch circuits be rated at least 125% of the maximum charging load [10]. Special 240 Volt, 40 Amp, single phase circuits (Level 2 charging) used for dryers and electric stoves are limited to 8 kW. A battery EV with 200 miles range might need to draw 87 kWh of energy from the electrical outlet (of which 78 kWh would be stored in the car battery after charging losses). A Level 1 residential charging circuit would then require more than 45 hours to fully charge a 200-mile range BEV, and a Level 2 circuit would require 11 hours[10].

Higher power charging circuits are feasible in a commercial setting. Morrow et al. at the Idaho National Laboratory report that Level 3 fast charging outlets can provide 60 to 150 kW of power [8]. But even at these very high power levels, it would still take from 36 minutes to 1.5 hours to fully charge a 200-mile BEV battery bank, and 1 to 2.6 hours to charge a 300-mile Li-ion battery bank (assuming that the batteries could accept 60 to 150 kW charging rates without deterioration.) Minimum estimated charging times are summarized in Table 1.

Table 1. Estimated minimum fueling time for battery EVs and fuel cell EVs

	Battery Electric Vehicles					Fuel Cell EVs
Vehicle Range (miles)	Energy Required from Grid (kWh)	Level 1 Charging Time (hours)	Level 2 Charging Time (hours)	Level 3 Charging Time (hours)	Level 3 Charging Time (hours)	Hydrogen Tank Filling Time (hours)
		120V, 20A	240 V, 40A	480V, 3Φ	480V, 3Φ	
		1.92 kW	7.68 kW	60 kW	150 kW	
150	61	31.8	7.9	1.0	0.4	0.05
200	87	45.3	11.33	1.5	0.58	0.07
300	156	81.3	20.31	2.6	1.04	0.10

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3.5. Vehicle Cost

Kromer and Heywood at MIT analyzed the likely costs of various alternative vehicles in mass production [6]. They conclude that an advanced battery EV with 200 miles range would cost approximately $10,200 more than a conventional car in 2030, similar to an earlier estimate of $12,600 more for a BEV [7]. A FCEV with 350 miles range is projected to cost only $3,600 more in mass production [6]. Plug-in hybrid electric vehicles (PHEVs) with only 10 miles all-electric range would cost less than the FCEV as shown in Figure 9, but plug-in hybrids with 60 miles range are projected to cost over $6,000 more than conventional gasoline cars. If we extrapolate the Kromer and Heywood data for BEVs to 300 miles range, then the BEV would cost approximately $19,500 more than a conventional car.

3.6. Fuel Cost

The cost of vehicle fuel (electricity or hydrogen) per mile driven will depend on the fuel price per unit energy and the vehicle fuel economy. As discussed in Section 3.8 below, a battery

[10] These charging time estimates are based on a constant power charging profile; real charging profiles with variable power draws to protect the battery from overcharging will take longer than shown here.

system has higher efficiency than a fuel cell system, but a long-range battery EV will be much heavier than a fuel cell EV with the same range capability, which negates some of the battery efficiency advantage. The residential price of electricity is projected by the DOE's Energy Information Administration in their 2009 Annual Energy Outlook to be in the 10.8 cents/kWh range during the 2012-2015 time period, which corresponds to $31.64/MBTU. The 2008 NRC report (Table 6.6-[1]) estimates that hydrogen will cost approximately $3.30/kg by the time of hydrogen fueling system breakeven, or $29.05/MBTU. So costs of fuel per unit energy will be comparable once the hydrogen infrastructure is in place. Initially, hydrogen costs will be higher before there are enough FCEVs on the road to provide a reasonable return on investment to the energy companies. In addition, many BEV owners may receive lower off-peak electricity rates if they charge their batteries at night. As shown in Table 2, the cost per mile for a BEV owner with off-peak rate of 6 cents/kWh will be approximately half the cost of hydrogen fuel per mile for a FCEV owner.

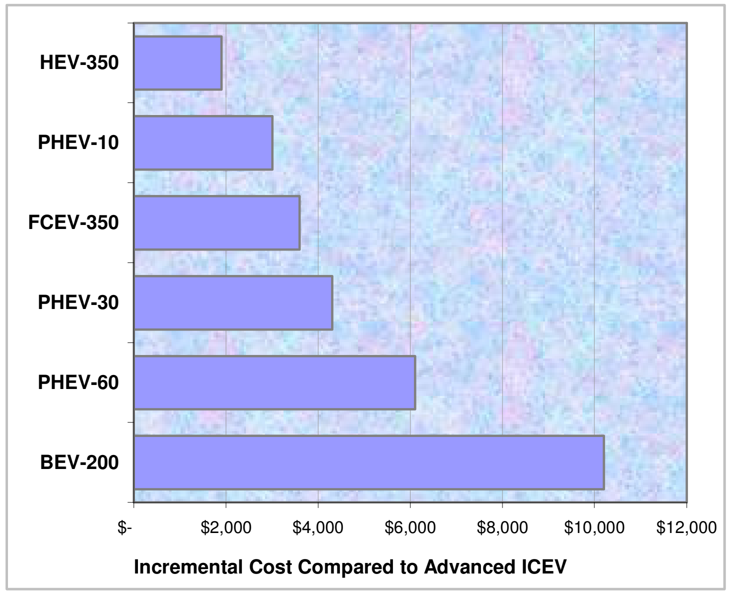

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Figure 9. Estimated mass production incremental cost of alternative vehicles [6] (numbers indicate all-electric range for the PHEVs and total range for the other vehicles)

Table 2. Estimated fuel cost per mile for battery EV drivers and fuel cell EV drivers

	Electricity		Hydrogen
	6 cents/kWh	10.8 c/kWh	$3.30 /kg
Range	Off-Peak	Residential	Hydrogen
Miles	cents/mile	cents/mile	cents/mile
100	2.26	4.07	5.35
150	2.43	4.37	5.38
200	2.62	4.72	5.41
250	2.84	5.12	5.44
300	3.12	5.62	5.47

Hydrogen Production Efficiency.XLS; Tab NG per mile'; AU 53 4/14 /2009

This lower fuel cost when off-peak rates are available will help to partially offset the higher initial price of the BEV. But the buyer of a 200-mile BEV will still pay $1,160 more for that vehicle including electricity to run it for 15 years than the purchaser of a 350-mile range FCEV will pay including 15 years of hydrogen fuel. A buyer of a 300-mile BEV would end up spending $11,315 more over 15 years[11].

3.7. Fueling Infrastructure Cost

The 2008 NRC report estimated that a hydrogen fueling station based on reforming natural gas would cost approximately $2.2 million when produced in quantities of 500 or more (Table

[11] Both calculations assume 13,000 miles traveled per year and zero discount rate; the cost differential would be even higher for drivers that apply a discount rate to future fuel savings.

6.4 [1]). This station would support approximately 2,300 FCEVs[12], so the average infrastructure cost per FCEV would be $955. The initial stations will cost more, on the order of $4 million each, which represents a per vehicle cost of $1,700.

Adding a residential Level 1 (120V, 20A) charging outlet is estimated to cost $878 by Idaho National Laboratory, but this capacity would require charging times of 36 hours for 200 miles range and 65 hours for 300 miles range [9]. A higher capacity Level 2 outlet (240V, 40A) would cost about $2,150 for a home residence and $1,850 for a commercial outlet. This would reduce charging times to 9 hours for 200 miles range, and 16 hours for 300 miles range. A residential charging outlet could in principle be used to charge two or more BEVs, since only one BEV in a family would generally travel the longer distances. A Level 2 commercial outlet would most likely be unable to service more than one BEV in a business day. The expected capital costs for long-range BEV charging outlets varies between $880 to $2,100 per BEV.

While the capital costs per vehicle are comparable once fueling systems are deployed, more drivers will have access to electricity initially than access to hydrogen fueling stations. An individual BEV owner able to pay $2,100 for a Level 2 home charging outlet will be able to utilize his or her car within half the vehicle range from home even if no other driver has a BEV in the area. A driver contemplating the purchase of a FCEV, however, would generally require at least one hydrogen fueling station within a few miles of home. No single FCEV owner could afford his or her own large-scale hydrogen fueling station[13]. We assume that some combination of government and private investment would supply the capital to build the initial batch of hydrogen fueling stations, starting in clusters around a group of major metropolitan cities. Governments would be motivated to jump-start the hydrogen fueling systems to reap the huge societal benefits that will follow from the introduction of large numbers of zero-emission fuel cell EVs. Private investors will eventually be motivated to build new hydrogen fueling stations since the return on investment will be very lucrative once there are many FCEVs on the road. (See Section 4 below for a more detailed description of the cost/benefit ratios for the hydrogen economy.)

3.8. Well-to-Wheels Energy Efficiency

Suppose we have one million btu's of natural gas to power a motor vehicle. What is more efficient: to convert that natural gas to electricity in a central power plant to charge a battery EV, or to convert that natural gas to hydrogen to run a fuel cell electric vehicle?

Figure 10 illustrates the answer: one would need to burn approximately 1.81 million btu's (MBTU) of natural gas in a combustion turbine to generate the electricity needed to power a battery EV for 300 miles on the EPA's 1.25X accelerated combined driving cycle. For a more efficient combined cycle gas turbine generator system, 1.21 MBTU's of natural gas would be required. But only 0.81 MBTU's of natural gas would be sufficient to generate enough hydrogen to power a fuel cell EV for 300 miles. On a full-cycle well-to-wheels basis,

[12] Assuming 4.5 kg hydrogen to travel 350 miles in a FCEV, 1,500 kg/day of hydrogen capacity, 70% average station capacity factor, and 13,000 miles traveled per year per FCEV.

[13] Although Honda and Plug Power are developing a hydrogen home fueling system, the cost may be too high initially for most FCEV owners.

then, **<u>the hydrogen-powered fuel cell electric vehicle would use between 33% to 55% less energy than a battery EV</u>** in converting natural gas to vehicle fuel with today's electrical power plants[14].

The improved well-to-wheels energy efficiency of the fuel cell electric vehicle is due to the higher efficiency of converting natural gas to hydrogen compared to converting natural gas to electricity. The steam methane reformer converts natural gas to hydrogen with approximately 75% efficiency. Current natural gas combined cycle power plants have at best 48% efficiency in converting natural gas to electricity, and simple natural gas combustion turbines have efficiencies between 26% to 32% [8] .

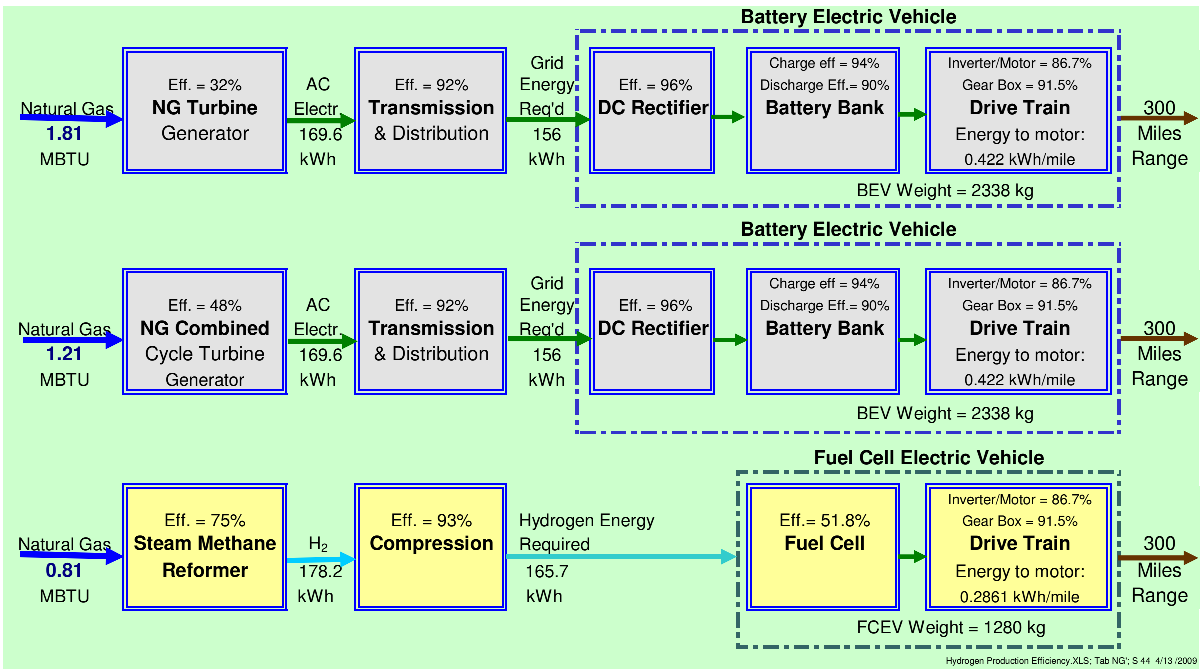


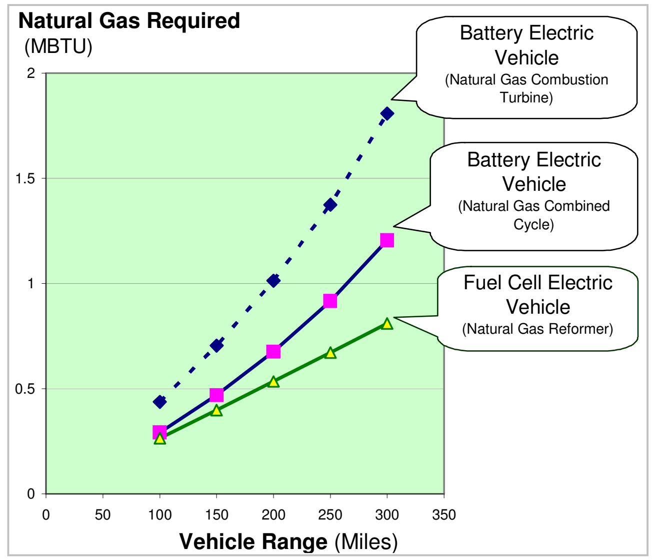
Figure 10. Comparison of the amount of natural gas required to propel a battery EV 300 miles compared to a fuel cell EV traveling 300 miles using existing technology

Some commentators point out that batteries are more efficient than fuel cells. This is correct when considering only the efficiency of transferring electrical energy on the vehicle. Averaged over an aggressive customer driving cycle, the fuel cell system has a net efficiency of approximately 52% in converting hydrogen to electricity, while batteries are typically 90% efficient at delivering electricity to the motor (10% losses being due to internal battery resistance that cuts efficiency at high power draw, plus any parasitic losses such as thermal management of the battery stack). But one has to consider the full system, not just one isolated component. Even though a battery is more efficient than a fuel cell when considered alone, the hydrogen and FCEV system takes less total energy. This is due to the greater

[14] Natural gas is also used directly to fuel natural gas (internal combustion engine) vehicles; here too it is better to convert that natural gas to hydrogen at 75% efficiency for use in a FCEV with 2.4 times better fuel economy than an NGV. The net relative efficiency of the natural gas to hydrogen FCEV route compared to an NGV is 0.75 x 0.93 x 2.4 = 1.67. The FCEV will consume 67% less natural gas energy than an NGV to travel the same distance.

conversion efficiency of natural gas to hydrogen (as described above) and the fact that the battery EV is heavier than the FCEV for a given vehicle range. The battery EV requires more energy to travel a given distance, which cancels out much of the battery's efficiency advantage[15].

This FCEV advantage diminishes at shorter range as the battery EV becomes lighter. As shown in Figure 11, the efficiency of a battery EV with only 100 miles range is almost identical to the total system efficiency of a fuel cell EV, assuming that the electricity is generated by a modern combined cycle turbine with 48% electrical generation efficiency[16].



Hydrogen Production Efficiency.XLS; Tab NG per mile'; AM 69 4/14 /2009

Figure 11. Quantity of natural gas required to propel battery EVs and a fuel cell EV as a function of vehicle range

3.9. Summary of Battery & Fuel Cell Comparisons

Table 3 summarizes the main comparisons between the battery electric vehicle and the fuel cell electric vehicle. The table and Figure 12 also show the ratio of each BEV attribute to the corresponding FCEV attribute. A ratio greater than one indicates superior performance for the FCEV.

Table 3. Summary of battery and fuel cell EV attributes

		200 miles Range			300 miles Range		
		Fuel Cell EV	Battery EV	Ratio BEV/FCEV	Fuel Cell EV	Battery EV	Ratio BEV/FCEV
Vehicle Weight (kg)		1259	1812	1.44	1280	2338	1.83
Storage Volume (Liters)	70 MPa	184	391	2.13	232	704	3.03
	35 MPa	234		1.67	308		2.29
Greenhouse Gases (g/mile)		290	458	1.58	293	545	1.86
Incremental Vehicle Cost ($)		2,830	10,200	3.60	3,600	19,500	5.42
Fuel Cost (cents/mile)		5.41	2.62	0.48	5.47	3.12	0.57
Fueling Cost per Vehicle ($)		955	878	0.92	955	2150	2.25
Incremental Life Cycle Cost ($)		13,380	16,187	1.21	14,267	27,734	1.94
Natural Gas Req'd (MBTU)	NG CC	0.53	0.68	1.28	0.81	1.21	1.49
	NG CT		1.01	1.91		1.81	2.23
Fueling Time (hours)	Level 1	0.07	45	675	0.08	81	972
	Level 2		11.3	169.5		20.3	244
	Level 3		0.58	8.70		1.04	12.48

NG CC = natural gas combined cycle; NG CT = natural gas combustion turbine

Level 1 Residential Charging = 120V, 20A single phase 1.9kW; Level 2 Charging = 240V, 40A, single phase, 7.7 kW; Level 3 = 480V, 3-phase, 150 kW

Off-peak Electricity = 6 cents/kWh; hydrogen = $3.30/kg

Story Simultaneous.XLS; Tab 'AFV Cost'; N 73 4/17 /2009

[15] Note from Figure 10 that the heavy battery EV (2,338 kg) requires almost as much input energy (156 kWh) in the form of AC electricity as the fuel cell EV (165.7 kWh) needs in the form of hydrogen fuel to travel 300 miles, despite the higher efficiency of the battery system compared to the fuel cell system.

[16] Advanced natural gas combined cycle plants have demonstrated 55% to as much as 60% efficiency. If these plants replace all older power plants in the future, the total system efficiency of the battery EV would equal that of the fuel cell EV at ranges of 200 miles or less. By that time, however, hydrogen production would also most

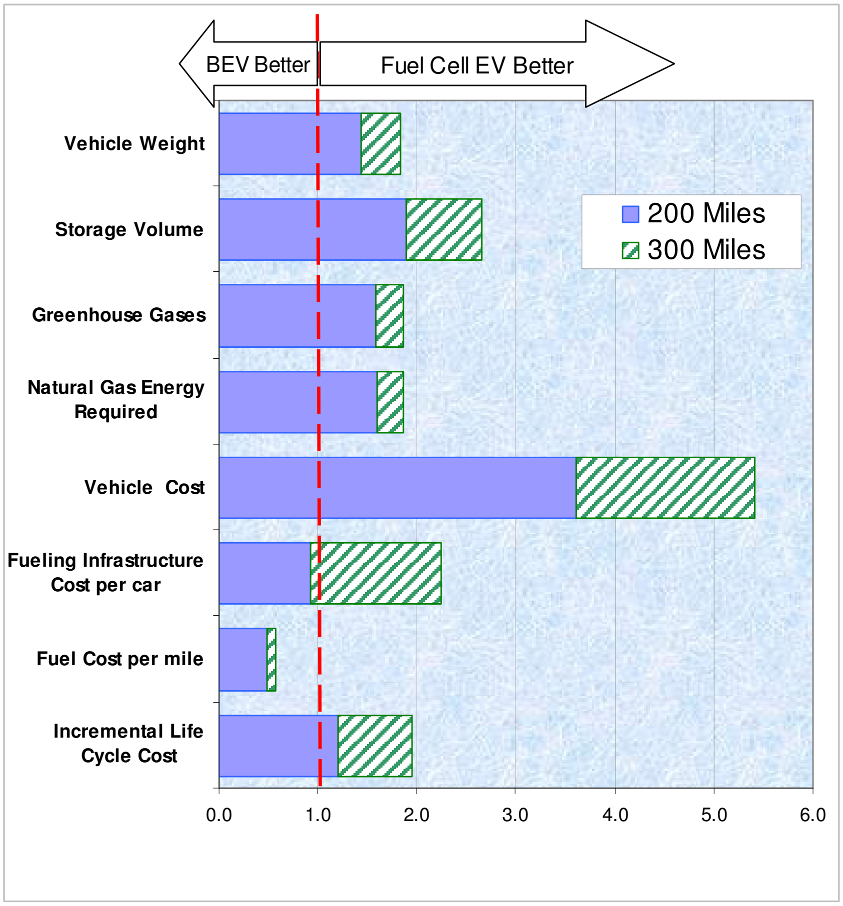


Figure 12. Ratios of battery EV parameter divided by fuel cell EV parameter (Value greater than one favors the fuel cell EV)

4. Alternative Vehicle/Fuel Societal Cost/Benefit Comparisons

We next consider the societal benefits of five main alternative vehicle/fuel combinations, and compare those benefits with the investment costs necessary to implement each of the scenarios. The five main scenarios reported from our 100-year simulation model are:

- The base case of gasoline hybrid electric vehicles gradually replacing conventional cars
- The gasoline plug-in hybrid electric vehicle scenario where PHEVs replace conventional cars and HEVs over the century
- The ethanol PHEV scenario, with ethanol replacing gasoline in the plug-in hybrids
- The fuel cell electric vehicle scenario, with hydrogen-powered FCEVs replacing the other three vehicles over the century.
- The battery EV scenario, with battery EVs replacing fuel cell EVs in the previous scenario

likely also shift to more energy-efficient routes such as direct coal or biomass gasification (with carbon capture and storage in the case of coal).

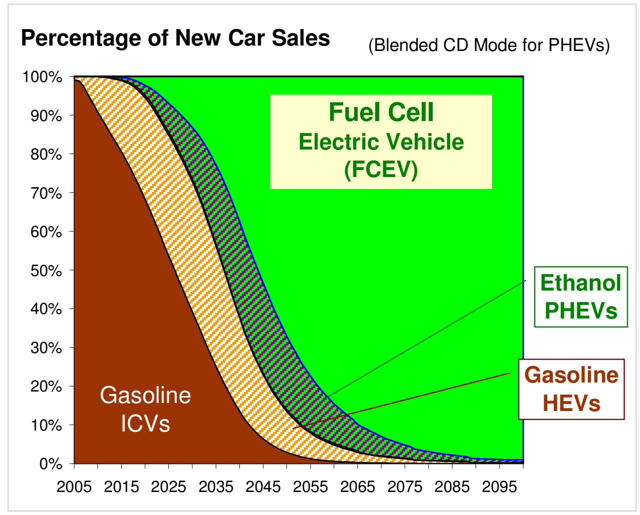
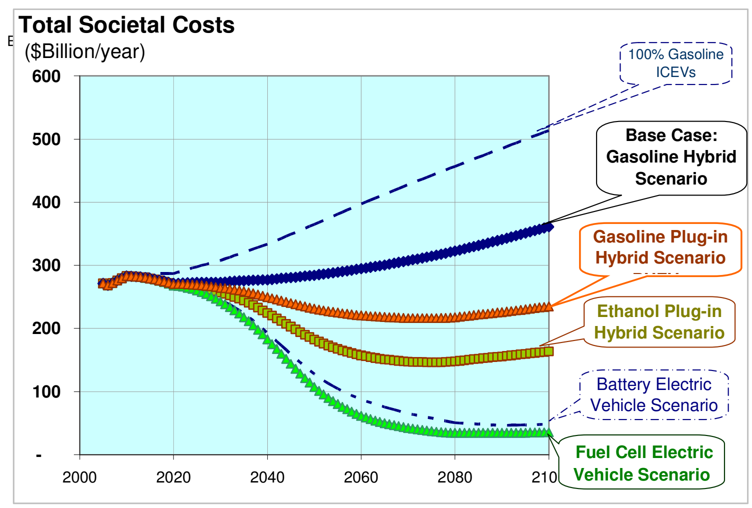


Figure 13. Fraction of new cars sold in the fuel cell EV scenario (The battery EV scenario replaces FCEVs one-for-one, with other vehicle numbers unchanged.)

Each scenario includes a mixture of alternative vehicles and fuels over the century. Figure 13 shows the fraction of new cars sold for the FCEV scenario. Note that the bulk of new cars sales are conventional gasoline cars, hybrid and cellulosic ethanol plug-in hybrids in the first half of the century. Fuel cell EVs do not begin to dominate new car sales until after 2044, and the actual number of FCEVs on the road does not reach 50% of the fleet until 2051.

4.1. Societal Benefits

The societal benefits of introducing alternative vehicles were measured by monetizing three main deleterious effects of vehicle transport: urban air pollution, oil imports and climate change gases. The urban air pollution costs are the average from five studies that estimated the avoided health costs of local pollution [2]. The CO_2-equivalent costs were varied from \$25/tonne in 2010 up to \$50/tonne by 2100. The societal cost of crude oil was estimated at \$60/barrel of oil[17].



Pollution Costs	PM-10	PM-2.5	SOx	VOC	CO	NOx	CO2
($/metric tonne):	1,608	134,041	29,743	6,592	1,276	13,844	25 to 50
Crude Oil Societal Cost:		\$60/bbl					

Story Simultaneous.XLS; Tab 'Graphs'; BC 95 4/15 /2009

Figure 14. Estimated annual societal costs for the five vehicle scenarios including the costs of urban air pollution, greenhouse gas emissions and imported crude oil

The resulting annual societal costs for each scenario are summarized in Figure 14. The societal benefits were then defined as the reduction in these societal costs over time for each scenario compared to the base case scenario with only gasoline hybrids and regular (non-hybrid) gasoline vehicles. The fuel cell EV scenario would reduce societal costs by \$325 billion *per year* by the end of the century compared to the base case with only gasoline HEVs, and by more than \$450 billion per year compared to the 100% gasoline (non-hybrid) vehicle case.

[17] Note that this \$60/bbl societal cost estimate is *not* the price of oil, nor the cost of producing oil. Rather, it is the estimated cost to society of importing a barrel of oil including the balance of trade and other economic costs as well as the estimated cost of military protection of our foreign sources of oil.

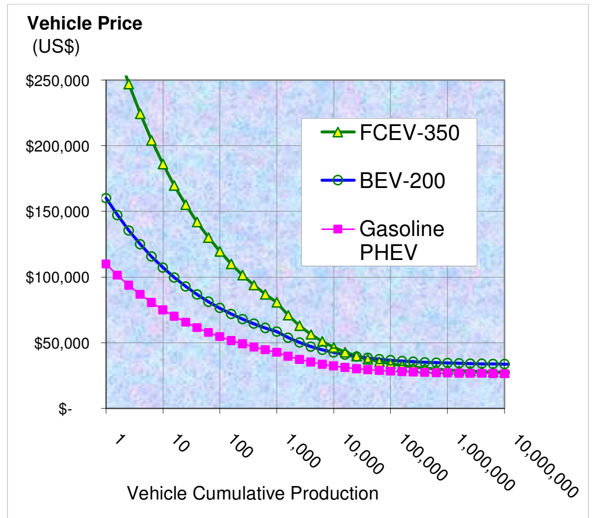
4.2. Societal Investment Costs Required

Each of the four alternative scenarios to the base case will require some early capital investments to start the conversion to alternative vehicles. These investments could come from some combination of private equity firms and local, state, and federal governments. Very early investments will most likely have to come from governments, since the return on investment for private equity may be too low initially.

For each scenario, two investments may be required early in the process: subsidies or incentives to car owners to buy-down the incremental cost of the alternative vehicle, and investments to build the initial fueling systems.

4.2.1. Vehicle Buy-Down Incentives

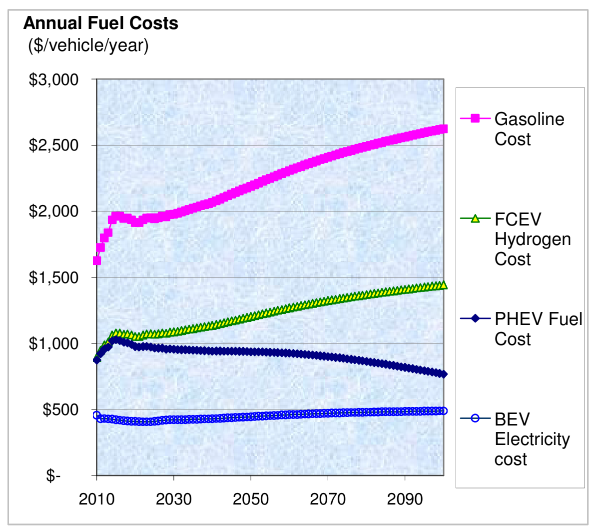
The model assumes that the FCEV with 350 miles range begins with a cost of $300,000 after the few hundred vehicles each that have been built to date by the major auto companies, dropping to the incremental cost of $3,600 in mass production estimated by MIT [6]. Conventional gasoline cars are assumed to cost $23,000. Battery EVs with 200 miles range start at $160,000, dropping to an incremental cost of $10,200, and plug-in hybrids start at $110,000, dropping to $3,709 incremental cost by 2030[18]. The vehicle cost reductions follow the curves shown in Figure 15 as production ramps up over time.



	Initial Cost	Final Cost	Incremental Cost (2030)
FCEV-350	$ 300,000	$ 26,600	$ 3,600
BEV -200	$ 160,000	$ 33,300	$ 10,300
PHEV	$ 110,000	$ 26,162	$ 3,709

Story Simultaneous.XLS; Tab 'Progress Ratios'; AF 49 4/15 /2009

Figure 15. Estimated cost of alternative vehicles as a function of cumulative production volume



Off-Peak Electricity = 55% of Residential Rate
Hydrogen Price = 55% of gasoline price per mile

Story Simultaneous.XLS; Tab 'Driver'; BI 53 4/15 /2009

Figure 16. Estimated annual fuel cost per vehicle based on extrapolations of the EIA's 2009 Annual Energy Outlook [11]

[18] The model assumes that the PHEVs start with 12 miles all-electric range in 2010, and gradually ramp up to 52 miles AER by the end of the century. The incremental cost also increases over time for PHEVs due to the cost of the additional batteries to achieve these added all-electric ranges.

As shown in Figure 16, we expect that the cost of fuel for these alternative vehicles will be less than the cost of gasoline. We assume that drivers will account for 80% of the fuel savings over the life of the car when deciding whether to purchase an alterative vehicle. We also assume that the driver will pay an extra $1,000 for each alternative vehicle, given that buyers of gasoline hybrids are already paying several thousand dollars extra for gasoline hybrids. The government buy-down incentive is therefore equal to the vehicle cost differential compared to a conventional car, minus the sum of $1,000 plus 80% of any fuel savings compared to gasoline over the life of the car. The resulting cash flow for the aggregate of all FCEV buyers is shown in Figure 17. Initially the incremental vehicle costs exceed the fuel savings, resulting in a negative cash flow until 2026. The cumulative negative cash flow reaches $15 billion by that time; this is the subsidy governments would have to pay under these conditions.

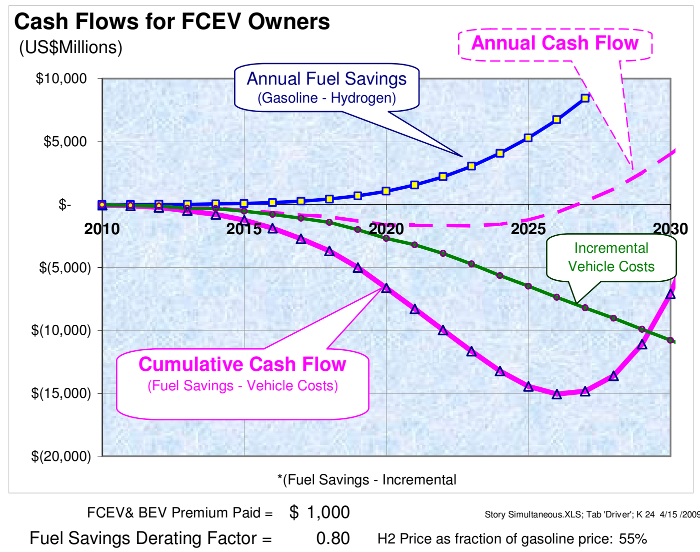


Figure 17. Annual and cumulative cash flows for the aggregate of all fuel cell EV owners

This $15 billion subsidy over 16 years depends on the assumptions of drivers accounting for 80% of fuel savings and their willingness to pay a $1,000 premium for a zero emissions FCEV. The sensitivity to these two parameters is shown in Figure 18, which shows that the government buy-down incentives would be reduced below $10 billion as long as buyers were willing to pay more than $2,000 premium, even if they discounted the fuel savings by 60%.

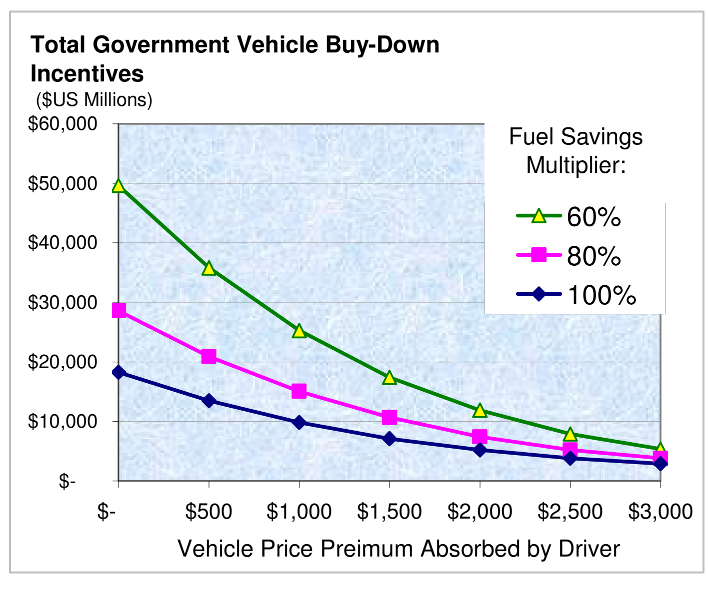


Figure 18. Sensitivity of the government buy-down incentives for fuel cell EVs to buyer price premium and fuel savings discount

4.2.2. Fueling Equipment Investments

Governments will also have to pay for initial fueling stations before there are enough alternative vehicles to fully utilize the stations. We have estimated hydrogen fueling station costs that are higher than those used in the 2008 NRC study, as shown in Table 4. All stations use on-site reforming of natural gas initially, with three differed sizes of fueling capacity, 100 kg/day, 500 kg/day and 1,500 kg/day that can fuel 20 FCEVs per day, 100 per day and 300 cars per day. The smaller fueling systems are installed first, and the larger systems are added in each metropolitan area as FCEV fleets demand higher capacity.

Table 4. Estimated hydrogen fueling system costs

Capacity	Fueling Station Costs		NRC
	Single Qty	500 Qty	500 Qty
100 kg/day	$ 772,800	$ 535,000	$ 397,000
500 kg/day	$ 2,212,000	$ 1,534,000	$ 905,500
1,500 kg/day	$ 4,181,700	$ 2,900,000	$ 2,178,000

H2 Energy Story.XLS; Tab 'Annual Sales';EC 18 4/15 /2009

From a business perspective, the fueling station owners must pay for the hydrogen fueling equipment up front and then earn revenues from selling the hydrogen. Initially there will be too few FCEVs to earn a reasonable return on investment. The cash flow for the fueling industry is shown in Figure 19. The industry has negative cash flow until 2024 in this model, when hydrogen revenue exceeds the cost for all capital equipment, fuel and other operating expenses. The cumulative negative cash flow reaches $7.7 billion. Presumably governments will have to provide subsidies to jump-start the hydrogen economy, although private investors may provide some of the capital in the later years as the future profit margins meet their investment objectives.

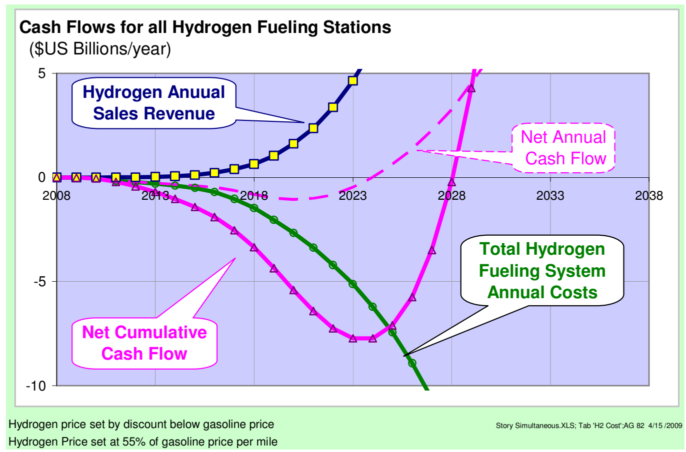
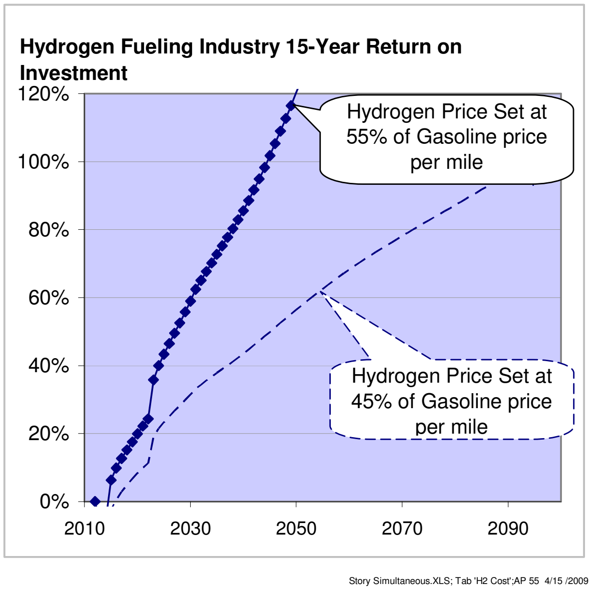


Figure 19. Cash flow for the entire hydrogen fueling industry during the early years of FCEV market penetration, showing a maximum cumulative incentive of $7.7 billion required over 16 years

The hydrogen industry cash flow shown in Figure 19 assumes that hydrogen is sold at 55% of the cost of gasoline per mile traveled. Raising this price would reduce the required investments for the fueling station owners, but would increase the incentives required for FCEV owners. As shown in Figure 20, hydrogen priced at the 55% cost of gasoline level minimizes the sum of these two subsidies.

This hydrogen pricing will only be sustainable if the fueling station owner makes a reasonable return on its investment. As shown in Figure 21, their returns will be very lucrative after 2024 with hydrogen price set at 55% the price of gasoline per mile. Their 15-year IRR will exceed 40% by 2025 and rise steeply thereafter as hydrogen fueling equipment becomes less expensive and as fueling station capacity factors approach 70% (the maximum limit in the model to account for fluctuating station hydrogen demand). Hydrogen prices could be even lower, as shown by the fueling industry return on investment with hydrogen at 45% the price of gasoline where fueling equipment IRR's would exceed 60% by mid-century.



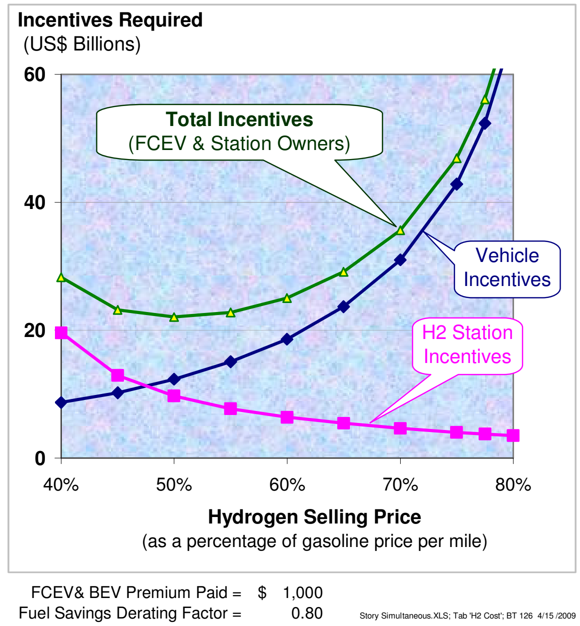


Figure 20. 15-year internal rate of return (IRR) for the hydrogen fueling system owners for hydrogen selling at 55% and 45% the price of gasoline per mile

Figure 21. Government incentives required for FCEV owners and hydrogen fueling station owners as a function of the price of hydrogen

4.3. Societal Cash Flows

If we consider the government as a business enterprise, then the incentives required to start up the alternative vehicle business can be considered as the capital investment required up front to start the enterprise. The income from this enterprise is the savings in societal cost that accrue over time compared to the base case scenario (gasoline ICEVs & HEVs only).

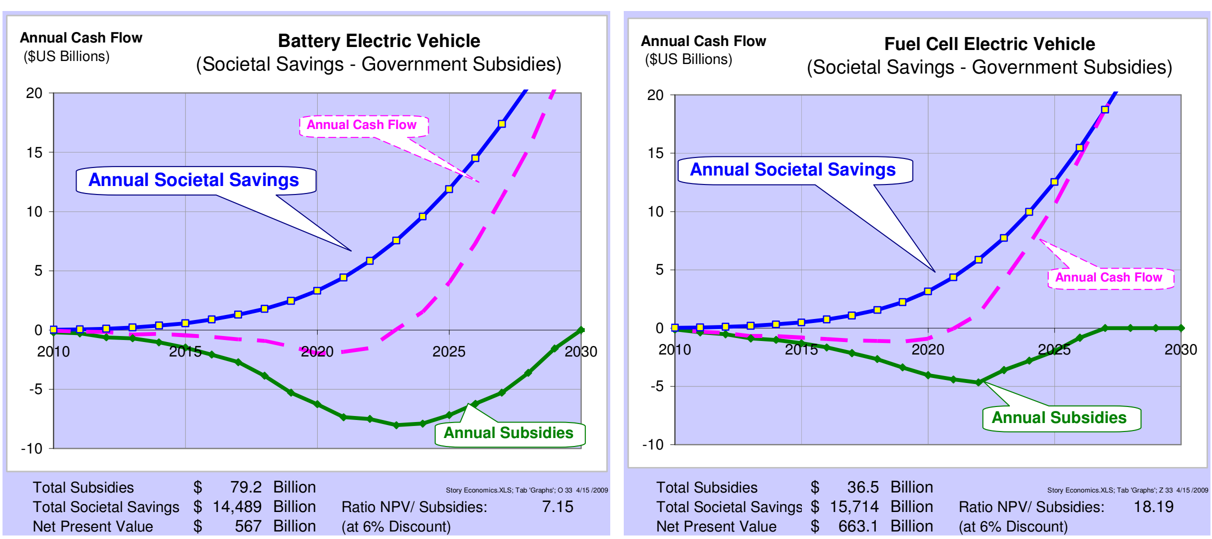


Figure 22. Government enterprise "cash flow" showing initial investments in vehicles and fueling equipment with the annual societal savings from reduced urban air pollution, reduced greenhouse gas pollution and reduced oil imports for a) battery EVs on the left and b) fuel cell EVs on the right

The resulting cash flow statements in Figure 22 for the battery EV scenario and fuel cell EV scenario show that both scenarios require large investments up front ($36.5 billion for FC EVs and $79.2 billion for battery EVs). Recall that both scenarios include ethanol PHEVs that also require subsidies, since they cost more than $1,000 over the cost of a regular gasoline car. The ethanol PHEV subsidies amount to $13.7 billion of the above totals.

The societal savings on these investments are enormous: $14.5 to $15.7 *trillion* over the century. With a 6% discount rate, the net present values of these societal savings are $663 billion for the FCEV scenario and $567 billion for the BEV scenario. The ratios of NPV of the societal savings divided by the NPV of the subsidy investment costs are 18 to one for the FCEV scenario and 7 to one for the BEV scenario.

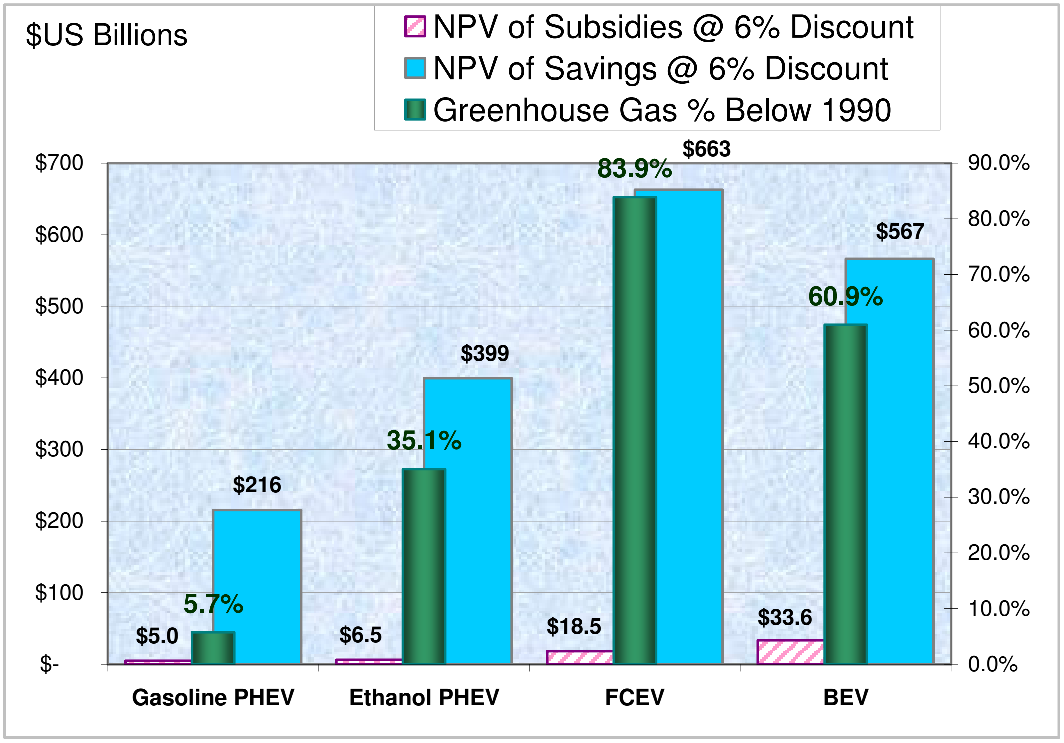
The similar cash flow and NPV results for the gasoline plug-in hybrid and ethanol plug-in hybrid scenarios are summarized in Table 5 and Figure 23, along with the estimated reduction in greenhouse gas pollution for each scenario. All four scenarios are very rewarding in terms of the savings to investment ratios. On this basis, governments would be fully justified in pursuing each of these options.

Table 5. Summary of net investments and societal savings for the four main alternative vehicle scenarios, including the estimated greenhouse gas reductions below 1990 levels for the light duty vehicle fleet

	Gasoline PHEV	Ethanol PHEV	FCEV	BEV
Total Subsidies & Investments ($US Billions)	$ 8.6	$ 12.4	$ 36.5	$ 79.2
Total Societal Savings ($US Billions)	$ 5,424	$ 9,367	$ 15,714	$ 14,489
Ratio of Savings / Subsidies	628	753	431	183
Discount Rate = 6%				
NPV of Subsidies & Investments ($ Billions)	$ 5.0	$ 6.5	$18.47	$ 33.6
NPV of Societal Savings ($US Billions)	$ 215.7	$ 399.4	$ 663.1	$ 566.7
Ratio of NPV(Savings) / NPV (Subsidies)	43.1	61.8	35.9	16.9
Greenhouse Gas % Below 1990 Levels	**5.7%**	**35.1%**	**83.9%**	**60.9%**

Story Economics.XLS; Tab 'NPV'; K 17 4/15 /2009

In this model, the BEV scenario and the FCEV scenario are mutually exclusive, with each BEV replacing one FCEV, so these two scenarios can be compared directly. Thus the BEVs require twice the investment due to the higher incremental cost of the BEV compared to the FCEV, and the societal savings are slightly lower for the BEV case. In particular, the greenhouse gas potential reduction with BEVs does not meet the 80% reduction target, although BEVs added to the ethanol scenario is still justified if the fuel cell vehicles do not meet expectations.



Story Economics.XLS; Tab 'NPV'; K 49 4/17 /2009

Figure 23. Net Present Value (NPV) of investments (subsidies for cars and fueling equipment) and NPV of societal savings (reduced urban air pollution, reduced greenhouse gases and reduced oil imports) with a 6% discount, showing that savings far outweigh the initial investments, along with the percentage decrease in greenhouse gases for the four main alternative vehicle scenarios

5. Conclusions

- To reach societal goals of an 80% reduction in greenhouse gases below 1990 levels in the light duty transportation sector, to eliminate almost all dependence on imported oil for transportation and to eliminate most local air pollution, we must transition to electric-drive vehicles
- All-electric vehicles must be powered by either batteries or fuel cells
- Fuel cell electric vehicles are superior to advanced Lithium-ion full function, long-range battery electric vehicles, since the fuel cell EV:
  - Weighs less
  - Takes up less space on the vehicle
  - Generates less greenhouse gases
  - Costs less (lower vehicle costs and life-cycle costs)
  - Requires less well-to-wheels energy
  - Takes less time to refuel

- Battery electric vehicles have two advantages compared to fuel cell EVs:
  - Lower fuel cost per mile[19]
  - Greater access to fueling capability initially
- The societal benefits of all four major alternative vehicles far outweigh the required investments/subsidies to jump-start the alternatives:
  - The fuel cell electric vehicle scenario has the highest societal benefit ($660 billion with a 6% discount rate) and the highest potential greenhouse gas reduction factor (84% below 1990 levels)
  - The battery electric vehicle scenario has societal benefits of $570 billion and potentially cuts greenhouse gases by 61% by the end of the century
  - The ethanol plug-in hybrid electric vehicle scenario saves $400 billion and may cut greenhouse gases by 35%
  - The gasoline plug-in hybrid electric vehicle scenario saves $215 billion but only reduces greenhouse gases by 6%.

We conclude that society should pursue all four options; delaying the introduction of any option could have serious future consequences for both energy security and the environment.

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[19] Although the fuel cost advantage requires off-peak electricity rates in the range of 6 cents/kWh and night-time charging, and even then is not enough to off-set the added capital cost of the battery EV over the life of the vehicle.

References

1. Michael P. Ramage, Chair, Committee on the Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, "Transitions to Alternative Transportation Technologies—A Focus on Hydrogen," National Research Council of the National Academies, Washington, DC, 2008 http://books.nap.edu/catalog.php?record_id=12222#toc
2. C.E. Thomas, "Comparison of Transportation Options in a Carbon-Constrained World: Hydrogen, Plug-in Hybrids and Biofuels," the National Hydrogen Association Annual Meeting, Sacramento, California, March 31, 2008. See also the National Hydrogen Association "Energy Evolution" story at http://www.hydrogenassociation.org/general/evolution.asp
3. Sandia National Laboratory and General Motors, *90- Billion Gallon Biofuel Deployment Study*, February 2009.
4. Michael Q. Wang : *Greenhouse gases, Regulated Emissions, and Energy use in Transportation*, Argonne National Laboratory, http://www.transportation.anl.gov/software/GREET/ ; Argonne has also released version 2.8a that includes the impact of vehicle manufacturing
5. Jayanti Sinha, Stephen Lasher, Yong Yang and Peter Kopf, "Direct hydrogen PEMFC manufacturing cost estimation for automotive applications," Fuel Cell Tech Team Review, September 24, 2008, Tiax LLC.
6. Matthew A. Kromer and John B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet,* Sloan Automotive Laboratory, Massachusetts Institute of Technology, Publication No. LFEE 2007-03 RP, May 2007.
7. Daniel Sperling and Susan A. Shaheen, *Transportation and Energy: Strategies for a Sustainable Transportation System,* Institute of Transportation Studies, University of California, Davis, American Council for an Energy-Efficient Economy, Washington D. C. 1995, page 248.
8. Mark Duvall, Eladio Knipping et al., Environmental Assessment of Plug-In Hybrid Electric Vehicles: Vol.1: Nationwide Greenhouse Gas Emissions, Electric Power Research Institute/National Research Defense Council, Final Report # 1015325, July 2007
9. Kevin Morrow, Donald Karner, and James Fancfort, "Plug-in hybrid electric vehicle charging infrastructure review," Final Report INL/EXT-08-15058, Idaho National Laboratory, November 2008
10. Sandeep Dhameja, *Electric Vehicle Battery Systems, Newnes*, Boston, 2002.
11. Annual Energy Outlook-2009, U.S. Department of Energy, Energy Information Administration http://www.eia.doe.gov/oiaf/aeo/index.html