High Pressure Fuel Processing in Regenerative Fuel Cells

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Abstract

Regenerative fuel cells are capable of operating in electrolysis or fuel cell modes. They can be used in applications much like batteries, only they weigh less and larger quantities of energy can be stored at relatively low costs through the use of large storage tanks. Whereas conventional fuel cells tend not to be as viable for operation at high pressures due to the costs and irreversibilites of compression of air to high pressures, regenerative fuel cells are capable of generating oxygen and hydrogen at the same pressure as the gas storage. Optimal operating parameters will typically mandate that fuel cell operation, electrolysis operation, and tank operation are all at the same pressure—the pressure will be the tank pressure and will depend upon the reserve of oxygen and hydrogen. Accordingly, the oxygen tank should be about one half the volume of the hydrogen tank so pressures remain the same as hydrogen/oxygen is consumed/generated. This paper reviews the use of regenerative PEM fuel cell technology in hybrid and electric vehicle applications.

Introduction and Definitions

With the widespread commercialization of hybrid vehicles and fuel cell technology, improved opportunities are available for effectively using grid electricity to power vehicles. Some old, not so old, and new options include the following:

BAT: **B**attery **E**lectric **V**ehicles rely solely on battery packs that are charged with grid electricity and would typically have a performance limited to 200-400 miles between charging.

city-EV: **city** **E**lectric **V**ehicles use battery packs are like BEVs, only the vehicles are light weight, designed for local travel in a city, and are typically limited to less than ~80 miles per charge.

city-EV-40: a **city-EV** is a city-EVwith 40 miles of range per charge.

HEV: **H**ybrid **E**lectric **V**ehicle which is powered by an engine, and typically gasoline.

PHEV: a **P**lug-in **HEV** is like a conventional HEV, only, in addition to the engine being able to charge the batteries of the HEV, the vehicle can be connected to grid electricity and grid electricity can be used to charge the batteries. For 10 to 60 miles after the batteries are charged, the engine need not operate.

PHEV-20: a **PHEV** with 20 miles of range per charge.

PFCHEV: a **PHEV** that uses both batteries and regenerative fuel cells to store grid electricity and allow operation without the engine.

PFCHEV[20,30]: a **PFCHEV** with 20 miles of range from charged batteries and 30 miles of range from hydrogen used to power the fuel cells.

city FCEV: a **city-EV** that uses fuel cells in combination with batteries.

In this paper, performance advantages of using a fuel cell in combination with batteries are evaluated.

Background

In previously published work, Suppes et al[1] described the advantages of using PHEV technology. The primary advantage is that domestic electricity is used to replace imported petroleum. Since about half of all miles in the U.S. are traveled by automobiles within the first 20 miles of travel each day, a plug-in range as low a 20 mile could substantially reduce oil imports. If most automobiles had plug-in ranges of 40 miles and improved fuel economy from the HEV component of the PHEV, the need to import petroleum would be eliminated.

Fuel cells add a degree of freedom in the design of PFCHEVs. This is a valuable degree of freedom for two reasons: 1) Regenerative fuel cells and associated stored hydrogen can provide extended range without the weight penalty of batteries, and 2) while high cycle-life batteries have costs of about $400 per kWh "near the bottom of their cost curve"[2], fuel cell ranges are limited by tanks for storing hydrogen that cost (compressed-gas) about $6 / kWh ($200 / kg) for hydrogen in the near-term[3] (low production volumes) or about $10 / kWh for both hydrogen and oxygen.. Relative to batteries, fuel cells are both lighter and less costly to provide range. However, PEM fuel cells tend to be more costly than batteries to provide power at about $300 / kW based on mass production of fuel cells using today's technology[4] as compared to batteries where cost is predominantly dominated by the kWh of stored energy.

In a PFCHEV, the synergy of power being provided by batteries and range being provided by regenerative fuel cells allows for lower cost power systems to be developed. This is particularly the case for PFCHEVs were the fuel cell is a battery charger that recharges the batteries while at work—effectively doubling the range of the vehicle as compared to what would be available for the batteries alone.[5] This previous study demonstrated that at fuel economies of 2.0 miles/kWh and battery costs of $200 per mile, a PFCHEV[15,15] was less costly than a PHEV-30. In fact, regenerative fuel cells would have to be >$2,500 / kW (fuel cell cost of $1,250 / kW) before the batteries would be less costly.

The sensitivity analysis on the PFCHEV with the fuel cell being a battery charger was fairly definitive, yet questions remain.

- Reports of batteries being available at $100 per mile suggest that the initial sensitivity analysis may have assumed battery costs that were a bit high.[6] Also, fuel economies may vary from 2.0 miles / kWh. Duvall[2] reports fuel economies of 2.5, 3.0, and 4.0 miles / kWh for PHEV 20, PHEV 60, and city-EV-40 vehicles respectively. A question that remains to be answers is in regard to how these "alternative" pricing and fuel economy structures impact the cost-effectiveness of the PFCHEV relative to the PHEV.
- Duvall reports that the consumer's net present value (NPV) for the life of a typical PHEV purchase is about -$1250 relative to a conventional vehicle (CV). A question remains as to the consumer NPV for a PFCHEV. An additional question remains as to the NPV of the consumer and electrical provider when they are considered as one "unified domestic entity".
- Finally, with current mass-produced prices of PEM fuel cells at about $300 / kW, the PFCHEV should become an even more attractive option as PEM fuel cell and regenerative fuel cell prices continue to reduce. A question remains as to the

evolutionary path of the least expensive PFCHEV options as the price of fuel cell and regenerative technology continues to reduce.

The calculations and studies of this paper are designed to provide answers to these questions.

Methods

Spreadsheet calculations were performed to compare the initial cost premium of a PHEV to a PFCHEV. In addition, the operating cost of the PHEV and PFCHEV are compared to a CV. Table 1 provides a summary of the base case calculations of PFCHEV and PHEV costs for vehicles with 30 mile plug-in ranges. The cost parameters for the base case were previously justified.[5]

Battery pack sizes in kWh are calculated by taking the miles of battery capacity and dividing by the fuel economy are converted to kW-h by dividing by the fuel economy (e.g. 30 miles ÷ 2.0 miles/kWh = 15 kWh or batteries). The kWh rating is in delivered power, and so, battery efficiency is not included in the calculations. The cost of the battery is calculated by multiplying the battery pack size (in kWh) times the specific cost (e.g. 15 kWh X $400/kWh = $6,000). The weight of the battery is calculated by dividing the battery pack size (in kWh) by the density (e.g. 15 kWh ÷ 0.07 kWh/kg = 214 kg). The cost of the weight of the battery is calculated by taking the weight of the battery times a cost per kilogram (e.g. 214 kg X $1.4/kg = $300).

The fuel cell stack was sized (kW) by dividing the battery pack size by the number of hours required to charge the battery pack and then dividing that by the square of the efficiency to charge and use the battery (e.g. 6.0 kWh ÷ 8 h ÷ 0.85 ÷ 0.85 = 1.04 kW). The cited fuel cell size is the cost per kW of delivered power at the conditions of operation. The cost of the fuel cell was calculated by multiplying the size of the fuel cell times the specific fuel cell cost (e.g. 1.04 kW X $500 / kW = $519).

The size of the hydrogen tank (kWh) was calculated by dividing the desired maximum range of travel from the fuel cell (miles) by the fuel economy (miles/kWh) and then dividing that by the square of the efficiency to charge and use the battery (e.g. 18.0 miles ÷ 2.0 miles/kWh ÷ 0.85 ÷ 0.85 = 12.5 kWh). The weight of the tank was calculated by multiplying the size of the hydrogen tank by the specific capacity of the hydrogen tank (e.g. 12.5 kWh X 2.0 kg/kWh = 25 kg). The cost of the tank was calculated by multiplying the size of the tank times a cost per kg of stored hydrogen (e.g. 12.5 kWh X $5 / kWh = $62.5). Additional cost from the weight of the hydrogen/tank was calculated by multiplying the weight of hydrogen times the cost of weight times a correction factor to take into account the weight of the tank/stack (e.g. 12.5 kWh X 2 kg/kWh X $1.4/kg X 2 = $70). The weight cost reflects the cost of the fuel cell system weight (e.g. $70) plus the cost of the battery pack (e.g. 86 kg X $1.4/kg = $120.4).

The cost of electrolysis is considered in terms of upgrading a fuel cell to having regenerative capacities. The cost is calculated as a percentage of the cost of the fuel cell.

The cost of the engine was assumed at $1000 per vehicle which is a less expensive engine than might be otherwise put on the vehicle.

Table 1. Base case calculations of premium for PFCHEV and PHEV options.

	PFCHEV [12,18]	PHEV -30
Total Range (Miles)	30	30
Battery Pack Range (Miles)	12	30
Fuel Economy (miles/kWh)	2	2
Battery Pack (kWh)	6	15
H2 Range (Miles)	18	0
H2 (kWh)*	12.5	0.0
Fuel Cell Power (kW)**	1.04	0
Engine ($)	$1,000	$1,000
Battery Cost ($ / kWh)	$400	$400
Battery Cost ($)	$2,400	$6,000
Specific Fuel Cell Cost ($ / kWh)	$500	$500
Fuel Cell Cost ($)	$519	$0
Battery Weight (kWh / 0.07[kWh/kg])	86	214
Fuel Cell Weight (kg)	50	0
Cost of Weight ($/kg)	$1.4	$1.4
Weight Cost ($)	$190	$300
Tank Cost ($)***	$62.3	$0.0
Weight and Tank Costs ($)	$252	$300
Electrolyzer (% of FC Cost)	100%	100%
Electrolyzer ($)	$519	$0
Total Power System Cost	$4,690	$7,300
Annual Cash Flow at $0.05 / kWh	**-$319**	**-$504**
Annual Cash Flow at $0.01 / kWh	**$150**	**-$148**

Discussion

As summarized in the base case of Table 1, the PFCHEV costs significantly less than the PHEV. The PFCHEV benefits from a synergy where the regenerative fuel cell stack and gas storage provides extended range and the battery pack provides power output.

Impact of Lower Battery Costs

Table 2 summarizes the impact of battery pack costs going from $2,000 for every 10 miles of capacity to $1,000 for every 10 miles of capacity. The most likely scenario for the lower batter costs was estimated to be a combination an improved fuel economy of 3.0 miles/kWh (rather than 2.0) and lower battery costs of $300 per kWh (versus $400), and these estimated were based on the report of Duvall[2], The PFCHEV is about $1,140 less expensive.

Table 2. Impact of lower battery costs.

	PFCHEV [12,18]	PHEV-30
Fuel Economy (miles/kWh)	3.0	3.0
Fuel Cell Power (kW)**	0.69	0.00
Battery Cost ($ / kWh)	$300	$300
Fuel Cell Cost ($ / kWh)	$500	$500
Electrolyzer (% of FC Cost)	100%	100%
Total Power System Cost	$3,060	$4,200
Annual Cash Flow at $0.05 / kWh	**$33**	**-$15**
Annual Cash Flow at $0.01 / kWh	**$383**	**$260**

Impact of Alternative PCHEV

While many applications would allow a PFCHEV[12,18] to perform on par with a PHEV-30, there are many applications in which the PHEV-30 would have superior performance. On the other hand, there are no applications where the PFCHEV[12,18] would have superior performance relative to the PHEV-30. A more balanced comparison is to compare the cost of the PHEV-30 to the PFCHEV[14,34]. The costs of these alternatives are summarized in Table 3. The PHEV-30 would be able to travel further on a charge in the first hour of travel, but the PFCHEV[14,34] would be able to travel further in a day on a charge. An example of a typical full-utilization of the charge of a PFCHEV[14,34] is a 14-mile commute to work in the morning, a 2-mile roundtrip for lunch, a 14-mile return from work, and a 4-mile roundtrip to the store in the evening. With each vehicle having its own performance advantage and with each vehicle having comparable value, the PFCHEV has a price advantage of about $800.

Table 3. Impact of upgrade to PFCHEV[14,34]..

	PFCHEV [14,20]	PHEV-30
Fuel Economy (miles/kWh)	3.0	3.0
Fuel Cell Power (kW)**	0.81	0.00
Battery Cost ($ / kWh)	$300	$300
Fuel Cell Cost ($ / kWh)	$500	$500
Electrolyzer (% of FC Cost)	100%	100%
Total Power System Cost	$3,399	$4,200
Annual Cash Flow at $0.05 / kWh	**-$6**	**-$15**
Annual Cash Flow at $0.01 / kWh	**$333**	**$260**

Impact of Lower Fuel Cell Costs and Regenerative Fuel Cells

The cases of Tables 1-3 assume a fuel cell cost of $500 / kW. Projected fuel cell costs based on today's technology under mass production are $300 / kW. The impact of these lower fuel cell costs are summarized in Table 4. The PFCHEV[14,20] costs about $1,125 less than the PHEV-30.

Table 5 summarizes the impact of using an electrolyzer that only has a 25% cost penalty. The cost reduction is greater than $1,300 for the PFCHEV[14,20] relative to the PHEV-30 under these reduced electrolysis costs estimates.

Table 4. Impact of lower fuel cell costs.

	PFCHEV [14,20]	PHEV-30
Fuel Economy (miles/kWh)	3.0	3.0
Fuel Cell Power (kW)**	0.81	0.00
Battery Cost ($ / kWh)	$300	$300
Fuel Cell Cost ($ / kWh)	$300	$300
Electrolyzer (% of FC Cost)	100%	100%
Total Power System Cost	$3,076	$4,200
Annual Cash Flow at $0.05 / kWh	**$34**	**-$15**
Annual Cash Flow at $0.01 / kWh	**$374**	**$260**

Table 5. Impact of lower fuel cell costs with lower electrolysis costs.

	PFCHEV [14,20]	PHEV-30
Fuel Economy (miles/kWh)	3.0	3.0
Fuel Cell Power (kW)**	0.81	0.00
Battery Cost ($ / kWh)	$300	$300
Fuel Cell Cost ($ / kWh)	$300	$300
Electrolyzer (% of FC Cost)	25%	25%
Total Power System Cost	$2,894	$4,200
Annual Cash Flow at $0.05 / kWh	**$57**	**-$15**
Annual Cash Flow at $0.01 / kWh	**$397**	**$260**

Electric Vehicle

Just as PFCHEVs have cost advantages over PHEVs, so also, city-FCEVs are expected to have cost advantages over City-EVs. Table 6 compares the cost of the power supply for a city-FCEV[40,50] with an EV-80. The city-FCEV[40,50] having a range of 90 miles per day costs $3,150 less than the city-EV-80 which only has a range of 80 miles per day. Table 6 summarizes this and a city-EV-40 comparison.

The city-FCEV[20,25] costs $1,580 less than a city-EV-40. Duvall reports the cost of the city-EV-40 to be $423 less than the cost of a CV. An extrapolation of these results indicates the NPV of the indicated city-FCEV[20,25] is $1,157 more than a CV. The comparison with an improved fuel economy consistent with a city-EV that is ultra-light-weight, leads to similar conclusions and advantages for the city-FCEV versions. Even at $500 / kW fuel cell costs and electrolyzer upgrades representing 100% of the fuel cell cost, the city-FCEV is less expensive than the city-EV and the city-FCEV has a higher NPV than the CV.

Table 6. Comparison of city-EV to city-FCEV.

	city-FCEV [40,50]	**city-EV-80**	**city-FCEV [20,25]**	**city-EV-40**	**city-FCEV [20,25]'**	**city-EV-40'**
Fuel Economy (miles/kWh)	3.0	3.0	3.0	3.0	4.0	4.0
Fuel Cell Power (kW)**	2.31	0.00	1.15	0.00	0.87	0.00
Battery Cost ($ / kWh)	$300	$300	$300	$300	$300	$300
Fuel Cell Cost ($ / kWh)	$300	$300	$300	$300	$300	$300
Electrolyzer (% of FC Cost)	25%	25%	25%	25%	25%	25%
Total Power System Cost	$5,376	$8,533	$2,688	$4,267	$2,016	$3,200
Annual Cash Flow at $0.05 / kWh*	**-$715**	**-$781**	**$55**	**$22**	**$247**	**$223**
Annual Cash Flow at $0.01 / kWh*	**-$21**	**-$349**	**$402**	**$238**	**$508**	**$385**

*Analysis assumes that the CV base case has a fuel economy of $30 mpg. In the case of city-EVs and city-FCEVs, the small and compact nature of the "mini" car provides much of the savings, and comparing to a 30 mpg base case may not be the most appropriate comparison.

Evolution of PFCHEV and city-FCEV

Neither the PFCHEV nor the city-FCEV are intended to be able to serve all automobile markets. In fact, the city-FCEV[40,50] would serve some applications quite well that would not be cost effective for the PFCHEV[14,20] and visa versa. Some applications will be best served by the CV or at least a decade. However, one of the strengths of the "fuel cell battery charger" approach is that it is cost effective in certain applications today and will certainly evolve to serve more applications better. Key aspects of the evolution can be projected based on observed trends in fuel cell costs—based on fuel cell costs continuing to decrease with the bottom of their cost curves below $40/kW. Projected evolutionary paths include:

1. As the engine is used less and less, less expensive and higher emitting engines will be viable. When the typical 4-stroke, water-cooled engine is replaced with 2-stroke, air-cooled engines, the costs of the PFCHEV (including weight credit) should decrease by more than $800. It is possible that these 2-stroke engines would run from an alternative fuel that is cleaner-burning. See Table 7.
2. As indicated by the projections of Figure 1 (fuel economy of 2.0 miles/kWh, 100% FC cost is electrolysis cost, $400/kW batter costs), fuel cells will continue to be sized based on charging the battery pack in 8 hours (sizes near 1 kW) until fuel cell costs reach about $150/kW. At that price, the battery pack would be replaced with fuel cells except for a nominal batter (or capacitor) capacity (e.g. 2-4 miles). This $150/kW threshold price would go down if cheaper batteries were available. The fuel cell stack would be designed to allow 20 miles of travel in 30 minutes—more demanding travel would require use of the back-up engine.

3. When fuel cells are sufficiently inexpensive (less than about $75 / kW), the fuel cells could replace the engine. Here, regenerative fuel cells that could operate from both hydrogen and alcohol (ethanol or methanol) would be preferred, and extended travel would be achieved by refueling with the liquid fuel.

In this evolutionary path, an evolution to a substantially-hydrogen economy is possible without major risk associated with infrastructure costs. The first aspects of this transition/evolution are economically viable today, and increased use of the fuel cell (displacing engines and batteries) occurs incrementally as new options become economically competitive with decreasing regenerative fuel cell system costs.

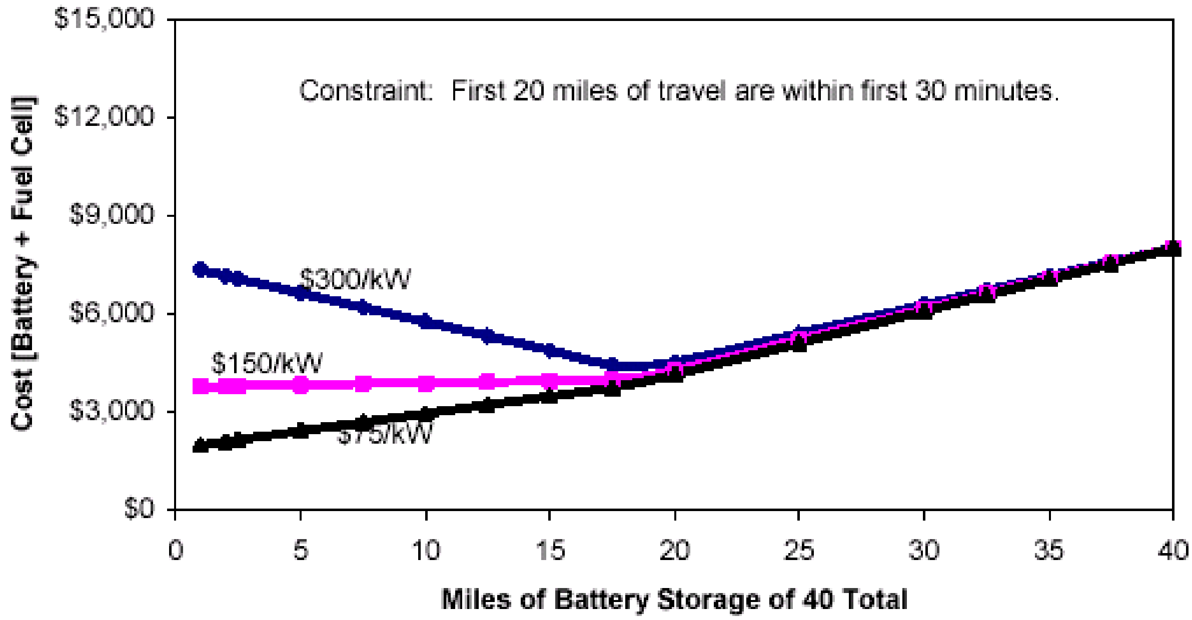

Figure 1. Cost curves for use of regenerative to replace batteries in PFCHEV applications.

Table 7. Impact of replacing $1000 4-stroke, water-cooled engine with $200 2-stroke, air-cooled engine.

	PFCHEV [14,20]	PHEV-30
Fuel Economy (miles/kWh)	3.0	3.0
Fuel Cell Power (kW)**	0.81	0.00
Battery Cost ($ / kWh)	$400	$400
Fuel Cell Cost ($ / kWh)	$300	$300
Electrolyzer (% of FC Cost)	100%	100%
Total Power System Cost	$2,742	$4,400
Annual Cash Flow at $0.05 / kWh	**$148**	**-$40**
Annual Cash Flow at $0.01 / kWh	**$415**	**$235**

Annualized Costs

To gain insight into the cost-effectiveness of these technologies, a simplified annualized economic analysis was performed per the following assumptions:

- The capital cost (less $1,000) was divided evenly over eight years. The $1,000 was subtracted from the capital cost to reflect the fact that the engine costs were included in the HEV power system costs.
- 12,000 miles of travel was assumed each year with plug-in being 80% of the maximum possible from the plug-in range, but not exceeding $12,000 miles per year.
- Due to the HEV component, the fuel economy was improved from a CV value of 30 mpg to a HEV value of 50 mpg. These values were used to estimate the base case fuel costs and projected fuel costs based on miles traveled using gasoline. Gasoline was assumed at $1.75 per gallon.
- The "at wheel" battery energy (kWh) was divided by $[0.85]^2$ to account for battery efficiencies when converting to electricity consumed at the plug.
- The "at wheel" fuel cell energy (kWh) was divided by $\{[0.85]^2 \ [0.75]^2\}$ to account for both battery and fuel cell efficiencies when converting to electricity consumed at the plug.
- A consumer price of $0.05 / kWh was assumed for electricity cost by the consumer as an electricity cost cash flow analysis.
- A "consumer + producer/distributor" price of $0.01 / kWh was assumed for fuel component of the electricity cost in a "unified domestic entity" approach to the cost.

In the cash flow analysis the annualized capital and operating costs of the plug-in operations were subtracted from the fuel costs of the CV (30 mpg, 12,000 miles per year).

Table 8 provides an example calculation for the 2-stroke, air-cooled engine option. In this analysis, the PFCHEV[14,20] saved $148 per year with electricity at $0.05/kWh and $415 per year based on a fuel consumed to make electricity at $0.01 / kWh. The economics are highly favorable, even without incentives. The bottom two lines of each previous analysis (Tables 2-7) provide these annualized cash flow analyses.

In every case except the base case, the PFCHEV option was cost effective. The base case assumed a lower fuel economy of 2 miles / kWh. In every case, the use of fuel cells in combination with the batteries provided considerably better economics than the use of batteries alone in the plug-in option. All PFCHEV cases showed considerable annual savings when evaluated from the perspective of "unified domestic entity" that included the electrical producers and providers working with the consumers to make the technology happen.

A cost item not included in any of the analyses is the cost of electronics and control systems. If these are assumed to cost $1000 and have an annualized cost of $125, most of the cash flow is positive for all "unified domestic entity", but is not cost effective for the consumer (alone) except if inexpensive 2-stroke air-cooled engines are used on the vehicles.

Conclusions

The NPVs and associated economic viability of PFCHEVs and city-FCEVs are considerably better than the non-fuel-cell versions of these plug-in vehicles. In fact, when attaining high fuel economies (3 miles per kWh) and replacing the 4-stroke water-cooled engine with an inexpensive 2-stroke air-cooled engine, the economics of the PFCHEVs are extremely favorable. In these vehicles, the 2-stroke engine is viable because the vast majority of travel is under the plug-in option.

Advantages of plug-in vehicles as cited by Duvall include:

- Less maintenance,
- Substantially fewer trips to the gas station,
- Convenience of having a fully-charged battery every morning,
- Reductions in vehicle air pollution, petroleum use, and global warming gases,
- Less noise/vibration,
- Improved acceleration,
- Convenience features such as pre-heat/pre-cool with the engine off or use of 120 V appliances (tools, TVs, refrigerators, lights, etc) form the vehicle electricity,
- Better handling due to balanced weight distribution, and
- Better handling and other benefits due to lower center of gravity.

Additional advantages of FC plug-in vehicles and/or specifically not cited by Duvall, include:

- An effective peak-load-shifting technology that provides the incentive for more efficient power plants that produce less-costly electricity (relative to peaking power cycles), reduce the amount of emissions, and provide for substantial transportation the consumes zero fuel (when a peaking power plant at 28% efficiency is replaced with a base load power plant at 53% efficiency, more power is produced without expending burning additional fuel),
- Substantial savings to the consumer,
- Huge new markets for electrical providers along with improved regional economies,
- Improved national security due to replacements of imported petroleum with domestic electricity, and
- Improved domestic economy due to reduction in trade deficit.

The use of inexpensive 2-stroke engines with the plug-in fuel cell technology should lock in economic viability for vast markets. The reason why 2-stroke, air-cooled engines work well with PFCHEVs in select applications is that the engine would not be used for greater than about 80% of the time, and so, emission and fuel economy disadvantages of the 2-stroke engine are less important allowing benefits of light weight, compactness, and low cost to dominate. For plug-in technology to reach is greatest potential and same consumers the most possible money, the following guidelines should be followed: 1) fuel cells should be used in combination with batteries with the range of travel from stored hydrogen being 20% to 40% more than from batteries; 2) vehicles should be designed with fuel economies of 3.0 miles per kWh or greater; 3) initial applications should be for commuting where the miles of plug-in ranges are 10% to 40% greater than the roundtrip daily commute, most of the vehicle miles are associated with the commute, and the typical time the vehicle is parked at the job location is at least 8 hours; 4) the vehicles standard engine is replaced with an inexpensive and light-weight 2-stroke engine; and 5) electrical providers work with consumers to maximize and share the benefits of peak load shifting.

Terminology

The following terms were used in addition to the vehicle power systems previously specified:

CV: **C**onventional **V**ehicle using a gasoline engine and no hybrid technology.
NPV: **N**et **P**resent **V**alue.
PEM: **P**roton **E**xchange **M**embrane

Table 8. Cash flow summary for PFCHEV[14,20] with 2-stroke, air-cooled engine option.

	2-Stroke PFCHEV [14,20]	2-Stroke PHEV-30
Total Range (Miles)	34	30
Battery Pack Range (Miles)	14	30
Fuel Economy (miles/kWh)	3	3
Battery Pack (kWh)	4.67	10
H2 Range (Miles)	20	0
H2 (kWh)*	9.2	0.0
Fuel Cell Power (kW)**	0.81	0
Engine ($)	$200	$200
Battery Cost ($ / kWh)	$400	$400
Battery Cost ($)	$1,867	$4,000
Specific Fuel Cell Cost ($ / kWh)	$300	$300
Fuel Cell Cost ($)	$242	$0
Battery Weight (kWh / 0.07[kWh/kg])	67	143
Fuel Cell Weight (kg)	37	0
Cost of Weight ($/kg)	$1.4	$1.4
Weight Cost ($)	$145	$200
Tank Cost ($)***	$46.1	$0.0
Weight and Tank Costs ($)	$191	$200
Electrolyzer (% of FC Cost)	100%	100%
Electrolyzer ($)	$242	$0
Total Power System Cost	**$2,742**	**$4,400**

	2-Stroke PFCHEV [14,20]	2-Stroke PHEV-30
Maximum Plug-In Miles Per Year	12,410	10,950
80% of Maximum Capacity	9,928	8,760
Electricity Use at Wheel (kWh)	3,309	2,920
Battery Fuel Use at Wheel (kWh)	1,363	2,920
Fuel Cell Use at Wheel (kWh)	1,947	0
Battery Fuel Use at Plug (kWh)	1,886	4,042
Fuel Cell Use at Plug (kWh)	4,790	0
Total Miles	12,000	12,000
Fuel Cost ($1.75 / 30 X X)	$700	$700
Annualized Cost (Cap Cost / 8)	$218	$425
Fuel Cost ($1.75 / 50 X [fuel miles])	$0	$113
Electricity Cost ($ / kWh)	$0.05	$0.05
Electricity Cost ($)	$334	$202
Electrical Fuel Cost ($/kWh)	$0.01	$0.01
Domestic Fuel Cost ($)	$67	$40
Cash Flow at $0.05 / kWh	**$148**	**-$40**
Cash Flow at $0.01 / kWh	**$415**	**$235**

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