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Roles of plug-in hybrid electric vehicles in the transition to the hydrogen economy

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Abstract

Closed-system regenerative fuel cells (RFCs) are an alternative to non-regenerative fuel cells as a transition technology and mainstay of a hydrogen economy. Substantially petroleum-free automobiles can spontaneously evolve from hybrid electric vehicles (HEVs) based solely on the economic viability of replacing batteries with RFCs as fuel cell prices decrease. The evolution can be projected first to plug-in HEVs (PHEVs) and finally to a substantially hydrogen-based transportation system.

While there is uncertainty in quantifying the projected costs of fuel cells, the qualitative price tend projections and resulting vehicle power system evolution can be projected with certainty. An important stage in the PHEV evolution is the "combined" use of battery packs and RFC systems as an alternative to relying on only battery packs for storing electrical power on PHEVs. The combined systems are projected to reduce the cost of PHEVs by more than \$1000 and reduce vehicular gasoline consumption by $> 80\%$.

Keywords: Fuel cell; Regenerative; Plug-in; Hydrogen

1. Introduction and definitions

A plug-in hybrid electric vehicle (PHEV) uses grid electricity to charge batteries on a vehicle, thereby allowing initial vehicle operation without engine operation. An engine is on the vehicle but only used when the battery charge is depleted. This technology would displace about 86% of the vehicle's gasoline consumption with indigenous electrical power. The technology is perhaps the only near-term option that can eliminate petroleum imports while saving consumers' money.

PHEVs are preferably charged at night, both because of the reduced production costs for off-peak power and because of the excess nighttime grid power that is available. Frank projects that about 20% of current gasoline consumption could be replaced with current excess electrical power generation capacity that is primarily nighttime electricity [1].

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Abbreviations: BEV, Battery Electric Vehicles 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 Electric Vehicles use battery packs that 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/charge; city FCEV, a city-EV that uses fuel cells in combination with batteries; HEV, Hybrid Electric Vehicle which is powered by an engine, and typically gasoline; PEM, Proton Exchange Membrane; PFCHEV, a PHEV that uses both batteries and regenerative fuel cells to store grid electricity and allow operation without the engine; PHEV, a Plug-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 10–60 miles after the batteries are charged, the engine need not operate; PHEV-20, a PHEV with 20 miles of range/charge; PHEV-50k, a PHEV with 50 km of range/charge

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The PHEV market provides an automotive market-entry opportunity for fuel cells due to the driving habits of the large number of consumers who work 8 or more hours/day at one job site. In this application, battery packs are considered to be the least costly method to store energy for the morning commute to work with anticipated costs as low as \$390/kWh. However, for the evening commute from work, a regenerative fuel cell that recharges the battery [2] while the vehicle is parked at the job site will ultimately be less costly than stocking addition batteries on the vehicle—a \$390/kWh battery could be replaced by a \$125/kWh fuel cell (i.e., a \$1000/kW fuel cell divided by 8 h for recharge time) performing as a mobile battery charger. By example, rather than designing a PHEV with an 8 kWh battery pack, it will ultimately be less costly to design the vehicle with a 4 kWh battery pack and a regenerative fuel cell system capable of recharging the battery pack from stored hydrogen while the fuel cell PHEV (PFCHEV) is parked at the job site.

The combination of a battery pack and regenerative fuel cell system is not equivalent to the system relying only on the battery pack; however, it provides substantially equivalent performance for consumers who use a vehicle primarily for commuting to and from an 8–10 hour-a-day job. Battery packs allow for more flexible use of the stored electricity while regenerative fuel cells (RFCs) weigh less. This application represents a major market for RFC systems. This paper evaluates the economic viability of using regenerative fuel cells to replace from 50% to 95% of the battery pack in a PFCHEV as a function of decreasing RFC costs. A dual-fuel fuel cell option is proposed as an eventual means to fully displace the use of petroleum-based fuels in automobiles.

2. Background

2.1. PHEV technology

A PHEV uses batteries and an engine just like a hybrid electric vehicle (HEV); only an expanded battery pack (>30 km) and AC to DC converter allows off-peak grid electricity to be used to charge the battery pack. In a PHEV, the first 30–100 miles of travel each day would be without the engine running, indirectly using grid electricity. The PHEV and related hybrid technology are substantially characterized and defined by a recent report published by the Union of Concerned Scientists [3].

A recent joint agency report by the California Energy Commission and California Air Resources Board [4] accurately conveys the PHEV-20 (PHEV with 20 miles of charge capacity) as the alternative fuel technology having the greatest propensity to add direct monetary benefit to the California economy—this was a comprehensive survey including comparison to all prominent alternative fuels (including electricity, as is the case with PHEVs). In this report, the PHEV was referred to as an "Adv. Grid Con. Hybrid LDV (20)". In a presentation at the Electrical Power Research Institute, Bob Graham [5] recognized the potential for HEV technology to evolve into PHEV technology. Graham projected PHEV market entry in 2005. As of 2003, the Kangoo PHEV has been for sale in France [6] and the Mercedes-Benz Sprinter PHEV was unveiled at the IAA Commercial Vehicle Show 2004 [7]. In a typical application, a conventional automobile consuming 600 gal of gasoline/year can be displaced with a HEV that consumes 400 gal/year and/or displaced with a PHEV that consumes 80 gal/year.

While the 1916 upgrades to the PHEV doubled the vehicle costs, Frank [1] projects that a current PHEV-20 would cost about \$4500 more than a conventional vehicle (100,000 veh./year). However, operating and maintenance costs during the life of the vehicle would result in about \$5500 in savings with a net annualized operating cost benefit to the PHEV over both conventional vehicles and HEVs. Most of the savings is in fuel costs—while \$0.46/l (\$1.75/gal) gasoline costs about 2.9 cents/km (4.6/mile), 4 cents/kWh electricity costs about 0.9 cents/km. While Frank projects current life cycle cost parity, Duvall projects life cycle parity of the PHEV-20 with conventional vehicles later this decade—this is contingent on HEV technology reducing the price of electric drives along with battery pack production volumes of 48,000–150,000/year at \$380–471/kW [8].

2.2. Use of fuel cells in PFCHEVs

RFCs (e.g. the Ovonic Regenerative Fuel Cell [9]) can be used as an alternative to batteries. In closed-system RFCs, water is converted to oxygen and hydrogen through electrolysis, and the hydrogen and oxygen provide electrical power similar to a battery. Closed-system RFCs have advantages over open-system fuel cells because the use of pure hydrogen and oxygen increase both specific power output and fuel cell life. While RFCs cost more than batteries on a power output basis (i.e., \$/kW), RFCs are readily less costly than batteries on an energy-storage basis (i.e., \$/kWh). Combinations that use battery packs to provide power output and fuel cell systems to extend range have cost advantages over the use of either alone [2].

To function as energy storage devices, RFC systems are comprised of RFC fuel cell stacks; storage of hydrogen, oxygen, and water; and control means to switch from electrolysis to fuel cell operation. To keep costs low, the hydrogen/oxygen storage must be at reasonably high pressures and electrolysis must produce the hydrogen/oxygen at these high pressures to avoid costly compressors. Giner Inc., has demonstrated that PEM electrolysis systems can be operated at pressures up to 20,685 kPa (3000 psig) [10] to allow direct routing of generated hydrogen/oxygen to storage tanks without mechanical compression.

Market-entry RFC system applications appear to be commercially viable today [2]; use of RFC systems in PFCHEVs is strategically important because further decreases in RFC costs will provide for lower costs than would be attainable with batteries alone. These further reductions in costs would increase annualized savings to consumers and possibly lead to market domination.

3. Basis for results and discussion

The potential for using RFC systems in PFCHEVs resides in economic viability. To evaluate economic viability, RFC costs must be projected and a base case PHEV must be defined.

3.1. RFC costs

At the end of 2003, proton exchange membrane (PEM) fuel cell costs were about $1100/kW when used with pure oxygen and about $2200/kW [11] when used with air. Air-operated fuel cell costs are projected [12] to be $650–1150 by 2010 for relatively low production volumes. The US Department of Energy (DOE) projects $300/kW based on mass production using today's technology [13], and the FY 2004 DOE PFI solicitation indicates $300/kW as the threshold level for DOE interest in electrolysis systems [14] to produce hydrogen.

The specific power output (W/cm^2) of fuel cells is reported to double when pure oxygen is used as an alternative to air. This doubling of power output translates to about a $2\times$ decrease in FC stack costs for RFCs as compared to air-based fuel cell operation [15].

Taking into account current fuel cell costs, cited cost projections, and the higher power output from operation at higher pressure (above 1 bar), Fig. 1 is presented as a reasonable extrapolation of fuel cell costs for the fuel cell component of an RFC system (assumed production volumes increase from actual production in 2004 to about 100,000 stacks/year in 2010).

The transformation of a PEM fuel cell to a PEM RFC consists primarily of providing catalyst for the electrolysis. $IrO_2/Pt/carbon$ is a proven cathode-side catalyst for RFC applications [16–18]. Cathode-side water management and gas accumulation/storage are also important. In view of this, projected RFC costs are projected at 50% (in 2005) to 35% (2010) greater than the fuel cell costs in Fig. 1.

When storing energy, the cost of compressed-gas storage is about $6/kWh ($200/kg) for hydrogen in the near-term [19] (low production volumes) or about $10/kWh for both hydrogen and oxygen. These costs tend to be size-specific, and so for both hydrogen and oxygen storage the costs would be $\sim$ \$10/kWh for tanks <40 gal and $\sim$ \$5/kWh for tanks >100 gal. For comparison purposes, battery storage dominates the regenerative energy storage market where (based on an Argonne National Laboratory summary of projections) [20] nickel metal hydride batteries costs are about $400/kWh. Based on the indicated tank storage costs, storage of 6 kWh of hydrogen would cost about $60 plus an approximate additional $30 for the oxygen storage (oxygen tank is half the volume of the hydrogen tank). For the Fig. 1 projections, $500 (in 2005) was added to the fuel cell cost to account for tanks and control systems. This $500 decreases to $400 by 2010.

The fuel cell cost projections of Fig. 1 are debatably, quantitatively accurate. More certainly, the curves are qualitatively accurate. Subsequent analyses in this paper will perform calculations based on values from the projections; however, discussions will include results based on the more-certain qualitative extrapolations.

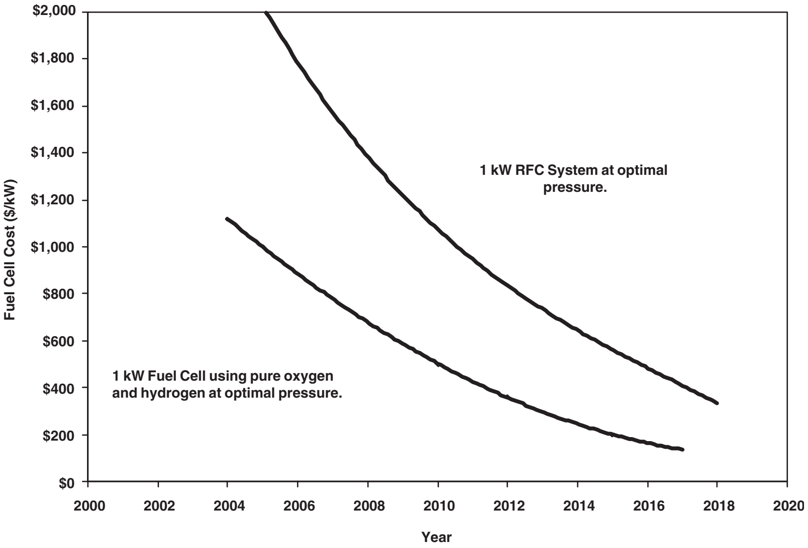

Fig. 1. Extrapolated and projected fuel cells and RFC system costs.

Table 1
Base case specifications and assumptions for a PHEV

Parameter	Specification	Justification
Recharge time	8 h (6–12)	Typical minimum time vehicle is in garage at night. Slightly less than typical time a vehicle is parked at site of employment.
Efficiency	6 km/kWh (5–8)	[38 miles/gal]/[115,000 Btu/gal] ×[3414.7 Btu/kWh]/[0.3 fuel-to-wheel efficiency] = 3.76 miles/kWh = 6.05 km/kWh.
Battery pack cost	$390/kWh (300–500)	Debatably, low cost target for batteries. Selected for "worst case" competition for RFCs. This is delivered power.
Battery storage cost	$65/km (50–100)	($390/kWh)/(6 km/kWh). This is $105/mile for battery pack costs.
Average power requirements	22 kW (15–50)	Maintained speed at 80 mph (129 km/h) divided by 6 km/kWh = 22.15 kW.
Fuel cell cost	$1000/kW	Estimate of price for 2004.
Fuel cell system factor	1.5 FCC+$500 (1.1–2.0; $300–1000)	A 50% markup in the fuel cell cost is assumed to provide regenerative capabilities.

Table 2
Projected incremental battery pack and RFC system costs for half of plug-in range in PHEV-50k and PHEV-100k; savings of PFCHEVs of PHEV alternatives

Year	Cost			Savings	
	1 kW FC	0.72 kW RFC system	4.16 kWh battery pack	PFCHEV-50k	PFCHEV-100k
2004	$1120	$1710	$1622		
2005	$1000	$1545	$1622	$77	$637
2008	$680	$1119	$1622	$504	$1441
2010	$500	$886	$1622	$736	$1873
2012	$360	$704	$1622	$919	$2204
2015	$200	$493	$1622	$1129	$2575

Estimates based on Fig. 1 projections of RFC system costs.

3.2. PHEV specifications

Table 1 specifies base case parameters for a PHEV including the rationale for each. The time needed to recharge the battery pack is referred to as the recharge time with 8 h used as the base case; 8 h is slightly less than the average work day at one job site for many consumers. The longest reasonable recharge time is 12 h with the RFC operating 24 h a day—12 h producing hydrogen and 12 h consuming hydrogen. Whether designed for 8 or 12 h recharge times, high on-line times and ample battery energy (waste heat and electrical power) minimize concerns about operating fuel cells in cold weather.

The base case efficiency is 6 km/kWh and is based on 16 km/l (38 mpg). The power requirement of 22 kW is based on maintaining 129 km/h (80 mph). The 16 km/l assumption is between the performance of a hybrid sports utility vehicle and a HEV sedan.

4. Results

A PHEV-50k is consistent with about 18,000 km (11,100 miles) of plug-in travel per year and would require an 8.33 kWh battery pack can provide this at $3250 (energy storage component of HEV) per the base case assumptions. A combined battery-RFC power system divides this 50 km into 25 km of initial battery pack energy and 25 km of RFC system energy. The cost is $1625 for the 4.162 kWh battery pack plus $1581 for the 5.77 kWh (8.33/2/85%/85%) RFC system using a 0.72 kW RFC (based on Fig. 1 cost curve, 50% premium for RFC and $500 to complete system, year 2005).

Table 2 projects the temporal, incremental PFCHEV-50k and PFCHEV-100k savings for using combined energy storage systems rather than batteries alone. The overriding driving force for savings is the decreasing costs of fuel cells while battery costs are assumed to be constant.

When the RFC system is used as a battery charger, a modest 0.72 kW RFC system can recharge a 4.1 kWh battery pack in the base case application. To fully replace the battery pack as opposed to replacing half the battery pack, the fuel cell is sized based on 22 kW of power output rather than energy storage. This 22 kW stack would be suitable for all plug-in ranges. Table 3 compares projected costs for a 22 kW RFC system to battery packs for PHEV-50k and PHEV-100k applications.

Table 3
Projected costs of 22 kW RFC to substantially replace battery packs in PHEV-50k and PHEV-100k

	FC costs/kW	22 kW RFC system	PHEV-50k 8.33 kWh battery	PHEV-100k 16.7 kWh battery
2004	$1120	$37,460	$3249	$6497
2005	$1000	$32,933	$3249	$6497
2008	$680	$21,377	$3249	$6497
2010	$500	$15,250	$3249	$6497
2012	$360	$10,663	$3249	$6497
2015	$200	$5707	$3249	$6497

Estimates based on Fig. 1 projections of RFC system costs.

Table 4
Projected costs of 22 kW RFC to substantially replace combined systems in PHEV-100k

	1 kW FC	22 kW RFC system	PHEV-100k 16.7 kWh combined
2004	$1120	$37,460	$6164
2005	$1000	$32,933	$5852
2008	$680	$21,377	$5049
2010	$500	$15,250	$4617
2012	$360	$10,663	$4285
2015	$200	$5707	$3914
2020	$100	$2653	$3738

5. Discussion

5.1. PFCHEVs versus PHEVs

PFCHEVs use optimal combinations of batteries and RFCs as compared to PHEVs that use only batteries for energy storage. In 2004 prices, fuel cells are able to use stored hydrogen on a vehicle at about $125/kWh ($1000/kW divided by 8 h for recharge time). Taking into account costs associated with converting the fuel cells to closed-cycle regenerative systems, the combined use of RFC systems with battery packs is more cost effective than use of batteries alone starting in about 2004 (see Table 2). These projections are consistent with a previously published sensitivity analysis focusing on this milestone [2].

Table 2 summarizes two important trends in the savings offered by the combined systems. First, the greater the PHEV range, the greater the savings presented by the PFCHEV. Second, as the prices of fuel cells continue to decrease, the PFCHEVs offer greater savings to the consumer. For a PFCHEV-100k, the savings are projected to be more than $1800 by 2010. Based on estimates of annualized cost parity for PHEVs versus conventional vehicles in 2004 [1], this $1800 in savings provides the opportunity for PFCHEV domination of large automobile market segments by 2010.

A PFCHEV-100k would reach 250,000 km of plug-in travel in about seven years at 36,000 km/year. The annualized savings would be about $257/year. In addition, about $600/year that would otherwise be spent on gasoline ($1.75/gal, 87% reduction in gasoline consumption for PFCHEV versus conventional vehicle) would be either diverted to regional economies associated with grid electricity or be realized as part of this $257/year savings by the consumer.

5.2. RFCs as primary power sources

As fuel cell costs continue to decrease, it becomes more cost effective to use RFC systems to provide sustained power output rather than just as a cost-effective energy storage means. Table 3 projects the RFC systems will be more cost effective than battery packs by about 2014 for the PHEV-100k. This RFC milestone is more cost effective for vehicles having/needing greater plug-in range, and so the substitution is viable with the PHEV-100k before it is viable with the PHEV-50k. Table 3 does not take into account the savings of combined battery-RFC systems (PFCHEV systems). Calculations for comparison to PFCHEVs are summarized in Table 4.

The substantial displacement of combined battery-RFC systems with RFC power systems appears viable in about 2018. The long delay between commercial viability of the combined systems (in 2004) as compared to use of RFCs alone (in 2018) is a manifestation of the inherent performance advantages of the combined systems.

One approach to improve the viability of the RFC system over the combined system is to target sedans that may only require 15 kW of sustained power delivery. However, lower power specifications reduce the cost of the required battery packs as well as the required RFC systems with little change in relative advantage to either system.

An alternative approach is to use larger plug-in capacities which will increase the size of compressed-gas tanks. To a first approximation, compressed gas storage for hydrogen and oxygen (together) requires about 18 times the volume as compared to the same range of gasoline. At a fuel economy equivalent to 61 km/gal, approximately 120 l of compressed gas storage is needed for 100 km of range—about 60 l of compressed gas storage would be required for the PFCHEV-100k using combined energy storage. Systems based only on RFC storage to achieve greater than 100 km of range begin to create a significant space burden. It should be noted that the compressed gas storage is addition to about 50 l of gasoline tank volume unless the engine is displaced—this vehicle would offer little performance advantage over a PFCHEV-100k while costing more until after about 2017. This approach would be viable for city-EVs (no engines).

Yet another alternative approach is to justify reducing the engine size/cost or eliminating the engine while maintaining refueling capabilities. This could reduce the PHEV costs by \$1000–3000. This makes commercial viability possible 2–4 years earlier. The lower cost engine option is a good alternative in applications where the engine would rarely be relied upon to extend range. However, the viability of the combined system still persists for over a decade.

Ultimately, the consideration of these three alternatives to enhance the viability of the 22 kW RFC reaffirms the inherent performance advantages of the combined systems.

5.3. Reducing engine costs

For applications where $> 80\%$ of the power is being delivered by the combined system, the advantages of having a high-performance engine are diminished. Markets will likely exist where a \$2000–3000 engine system can be replaced with a $<$ \$1000 air-cooled engine. When this is possible, the \$257 in annualized savings can increase to $>$ \$500 in annualized savings. Air-cooled engines are especially viable since less than 20% of the range will typically be provided by the engine—50,000 km of engine life would be more than sufficient. This evolution is likely to occur prior to combined systems being displaced with substantially RFC systems.

Limited-range combined versions of BEV (no engine) are also likely to evolve spontaneously from the combined systems.

5.4. Stages of evolution

In view of the projections of Tables 2 and 3, the following six progressive stages of automobile evolution are identified with eventual elimination of petroleum with hydrogen used as the predominant energy carrier:

Stage 1: HEV technology
Stage 2: PHEV-50k technology using batteries
Stage 3: PFCHEV-100k combined approach using batteries and regenerative fuel cells
Stage 4a: PFCHEV-100k combined approach with cheap engine
Stage 4b: city-EV without engine backup.
Stage 5: PFCHEV-100k technology using mostly regenerative fuel cells
Stage 6: PFCHEV technology using dual-fuel fuel cells that eliminate need for engine

Stage 1 has already started with close to a dozen different versions of HEVs commercially available.

Stage 2 has already been initiated with Renault's Kangoo. A PHEV version of the Mercedes-Benz Sprinter was on display at the Hanover IAA Commercial Vehicle Show 2004. When using batteries alone, the 50 km plug-in range will have a larger market and cost less.

Stage 3 is estimated to be commercially viable today, but the concept has yet to leave the drawing boards. The PFCHEV-100k is an appropriate entry level vehicle for the combined approach since the advantages of the combined approach increase as the plug-in range of the vehicle increases. Base case entry vehicles would have a battery pack with 50 km of range with an RFC system providing an additional 50 km of range. The analysis of this paper reveals that this combined approach is likely to dominate the market for over a decade. Eventually, RFC systems would reduce the incremental costs of PFCHEVs by over \$2000 relative to using only batteries.

Stage 4 includes recognizing that in many markets the engine will rarely be used—there would be little downside of replacing higher-performance engines with the cheapest viable alternative engine. The advantage is that the initial cost of the vehicle would be reduced by \$1000–3000 (i.e., $>$ \$200/year annualized savings). Stage 4 is likely to occur shortly after Stage 3 in niche markets such as second family cars and cars for teenagers.

Stage 5 is the substantial replacement of battery packs on the vehicle with RFCs. It is likely that 0.3–1.0 kWh of capacity will be retained to better handle surges in both charging and assisting. An unexpected artifact of the analysis of this paper is that this Stage 5 evolution is likely to lag over a decade behind Stage 3. This is because the < 1.0 kW RFC system must be increased to > 15 kW when its function is transformed from that of a battery charger to the primary energy converter on the vehicle.

Stage 6 includes eliminating the use of petroleum-based fuels in automobiles and can be based on fully renewable, fully sustainable, and fully indigenous energy sources. Today, most versions of low-temperature fuel cells are powered from hydrogen; however, modified fuel cells are able to run from methanol. As methanol (or ethanol) fuel cell technology is improved, it will be viable to produce fuel cells that can be fueled by either hydrogen or methanol. (This is actually possible today, but debatably, a fuel cell optimized for use with methanol is not best used with hydrogen as a fuel.) When $> 80\%$ of the miles are from plug-in hydrogen, both supply and cost issues related to use of ethanol or methanol are subdued.

To the advantage of alcohol refueling, only liquids would have to be handled and existing service stations would require little modification. In the transformation from Stage 5 to Stage 6, the fuel cell component of the RFC would have to go from operating on electrolysis oxygen to air oxygen, and this will bring with it a decrease in specific power output (higher stack costs). This transformation is likely only when fuel cell costs are less than about \$100/kW (costs based on use of pure oxygen at optimal pressures).

5.5. RFC Evolution versus fuel cell revolution

Hydrogen refueling will be an easy upgrade/option for the Stage 3 through Stage 6 vehicles—hydrogen refueling would be an alternative to dual-fuel fuel cells. By example, a 24 km/l "city PFCHEV" averaging 48 km/h (30 mph) would require only a 5.5 kW RFC system and be economically viable prior to 2010. If both hydrogen and oxygen are refueled the power output of the RFC system will not decrease, and so this approach would have market niches where refueling infrastructure can be justified. Hydrogen refueling of PFCHEV vehicles could be a cost effective alternative "evolution" to alcohol refueling once the PFCHEVs are in use.

The approach of first establishing the use of hydrogen as a fuel in the RFC systems of PFCHEVs and then building niche-market hydrogen-refueling stations for the established PFCHEV fleet is clearly superior to approaches using fuel cell vehicles relying solely on hydrogen refueling. The approach is superior both because each step can be justified by immediate economic impact and because the fuel cell stacks will cost less in the PFCHEV vehicle because of higher power outputs made possible when using pure oxygen and hydrogen.

Hydrogen storage methods will find useful applications in the Stage 3 through Stage 6 vehicles. Improved storage methods would have huge PFCHEV market applications as soon as they are cost effective vs. compressed gas storage. It should be noted that the typical drawback of compressed hydrogen storage is the large volume of the tanks—this is not as severe a problem when only 50 km of range is required per the PFCHEV-100k application.

The advantage of the PFCHEV evolution approach as compared to other methods for achieving the hydrogen economy is that all stages are spontaneous—based solely on decreases in fuel cell costs and reasonable RFC developments. The threshold fuel cell cost that results in potential, substantial elimination of oil imports is $1000/kW/Stage 3. This compares to the need for robust fuel cells at less than $100/kW for use with hydrogen produced from reformed gasoline, natural gas, or coal.

5.6. Greenhouse gas emissions

In addition to displacing 80% to $>90\%$ of the vehicle's gasoline consumption with indigenous electricity, the use of electricity rather than petroleum will allow for substantial reductions in greenhouse gas emissions. Primary reductions result from using energy sources such as wind or nuclear power rather than petroleum. Secondary reductions result from increasing the base load electrical power demand by charging PHEVs at night. Since 8 h of night charging is followed by 16 h of use by other applications, these secondary effects can be greater than the primary. Increased base load demand will provide the incentives to build new power plants with efficiencies $>50\%$ (and possibly from sustainable resources) that will displace peak demand units having efficiencies $<30\%$. This is discussed further in an earlier publication [21].

In this approach to greenhouse gas reductions, the PFCHEV utilization is spontaneous due to savings realized by the consumer. The building of an improved electrical power generation is spontaneous based on a continuation of investment practices of electrical power providers—investors simply respond to increased market demands for more base-load electricity. The anticipated market for PFCHEVs would provide an unprecedented opportunity to upgrade and improve the entire electrical power grid infrastructure. Carbon dioxide emissions are achieved for both the transportation and electrical power sectors.

6. Conclusions

The evolution of HEVs to vehicles that do not rely on petroleum fuel is projected to be spontaneous based on trends in fuel cell costs and use of these fuel cells in RFC alternatives to batteries. This transition is cost effective due to reduced fuel and maintenance costs. PFCHEVs using combined battery-RFC energy storage are projected to reduce annualized vehicle operating costs by over $200/year by 2010 and up to $500/year if less-expensive air-cooled engines are used in PFCHEVs. In view of these savings, the California Energy Commission and California Air Resources Board report likely underestimates the positive economic impact of PFCHEV technology by at least an order of magnitude.

Six stages of evolution are projected with Stage 1 being the commercialization of HEVs and Stage 2 being the commercialization of PHEVs. Of the six stages, the Stage 3 use of combined battery-RFC energy storage is projected to dominate vehicular markets until fuel cell prices are below $200/kW. This dominance is projected to last greater than a decade with the vast majority of hydrogen economy benefits being realized, including (1) 80% to $>90\%$ displacement of the vehicle's gasoline consumption, (2) opportunities for substantial reductions in greenhouse gas emissions, (3) opportunities for beneficial restructuring of the US national electrical power grid, (4) saving consumers money, (5) zero vehicle source emissions for plug-in operation, and (6) further vehicle evolution to drive-by-wire technology. Systems based primarily on RFC energy storage should replace the combined systems at fuel cell prices below $200/kW.

The benefits of the Stage 3 evolution are so great that there is a reduced incentive to evolve to full displacement of petroleum. Nonetheless, evolution past Stage 3 is only an incremental step, and so full displacement of petroleum as an automobile fuel is likely to occur spontaneously with decreasing fuel cell costs.

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