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Plug-In Hybrid Electric Vehicles: Promise, Issues and Prospects

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Abstract

Plug-in hybrid electric vehicles (PHEVs) are now recognized as one of the most promising avenues to materially reduce automobile contributions to petroleum dependency, air pollution, and carbon dioxide emissions. Several issues remain, however, that could become barriers to the acceptance of PHEVs, thus creating uncertainty about their ultimate prospects. This paper addresses that uncertainty by examining the main technical, cost and infrastructure issues faced by PHEVs, and it shows that these issues are yielding to progress. The paper concludes that this progress, in combination with the rising costs of petroleum-based fuels, promises to make PHEVs fully competitive with conventional ICE and hybrid vehicles in the near future. Moreover, existing and planned electric generating systems will be adequate to provide off-peak power and energy for large populations of PHEVs, at least in the U.S. and probably also in other industrialized countries. The paper is based on a series of projects undertaken and supported by the U.S. Electric Power Research Institute (EPRI) working with industrial and government partners to model PHEVs, test and evaluate PHEV batteries, design and build prototype PHEVs, assess infrastructure requirements, and analyze the carbon dioxide releases associated with electricity provided by future electric power systems for the charging of PHEV batteries.

Keywords: Plug-in hybrid electric vehicles, lithium battery, battery cost, battery life, battery charging infrastructure, energy availability

1 Introduction

Plug-in hybrid electric vehicles (PHEVs) are now recognized as one of the most promising avenues to reduce automobile contributions to petroleum dependency, air pollution, and carbon dioxide emissions. The first quantification of the expected reductions was performed in a collaborative project initiated and coordinated by the Electric Power Research Institute in partnership with U.S. automobile manufacturers, government agencies, National Laboratories, and the University of California at Davis. This pioneering modelling and design study [1] established the characteristics and compared well-to-wheel energy use, carbon dioxide emissions and costs of conventional ICE, full hybrid, and plug-in hybrid electric vehicles for simulated driving cycles. Fig. 1, derived from results of that study, shows that, compared to the conventional and hybrid vehicle versions, the plug-in hybrid has much lower systems-level fuel consumption and pollutant emissions, and it causes substantially less carbon dioxide to be released to the atmosphere.

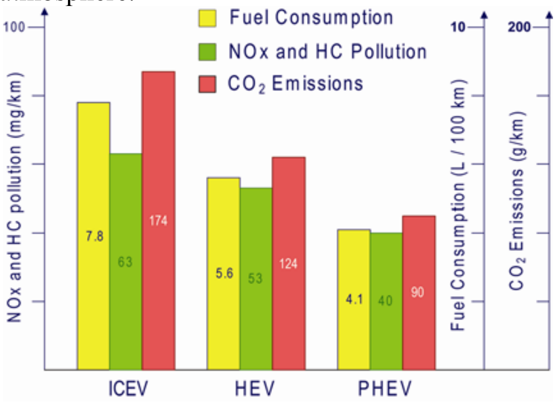

Figure 1: Vehicle Emissions and Fuel Consumption Comparison

The promise of these benefits spawned important initiatives to advance plug-in hybrid electric vehicle (PHEV) technologies, design and fabricate prototypical PHEVs, and demonstrate the technical feasibility, driver acceptance and benefits of these vehicles. Prominent early examples are the Daimler Sprinter plug-in hybrid electric van prototypes designed and fabricated in a collaborative project of the Daimler KEN (Advanced Product Engineering) Center in Mannheim, Germany, EPRI, and the Southern California Air Quality Management District. These are the world's first PHEVs from a major automobile manufacturer and, equally important, the first PHEVs using prototypes of lithium ion batteries designed for automotive propulsion. Fig. 2 summarizes key characteristics of, and operating experience with the Daimler PHEV Sprinter that is presently being optimized for commercial applications.

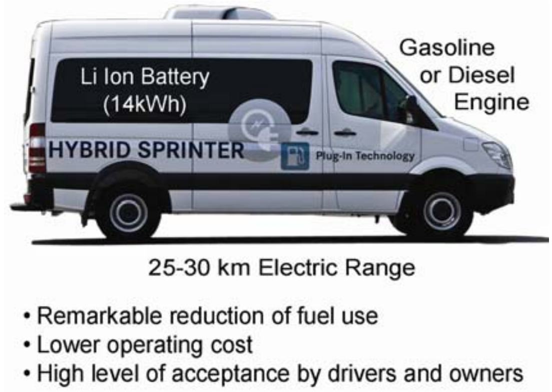

Figure 2: Daimler Sprinter Plug-In Hybrid Electric Van

Over the last several years, a number of smaller companies have fabricated PHEVs, many of them by converting commercially available Toyota Prius HEVs to plug-in operation, and often using batteries consisting of several thousand lithium ion cells of the type used in consumer electronic products. These custom conversions and their batteries are quite expensive, but their well-documented operation on public roads is demonstrating the fundamental practicality and gasoline savings potential of PHEVs.

Motivated by these advances and company-internal re-assessments, a few major automobile manufacturers initiated PHEV development programs in recent years. The most ambitious of these appear to be at General Motors: the conversion of the Saturn VUE HEV to PHEV operation, and the ground-up design and development of the Chevrolet Volt range-extender type PHEV.

Toyota and Ford also have developed and tested prototype PHEVs and announced plans for their introduction, and other automobile manufacturers including Volkswagen and Volvo will begin to field-test small fleets of prototypical PHEVs in the near future. Table 1 summarizes the PHEV characteristics and introduction dates released by major automobile manufacturers.

Table 1: PHEVs Announced by Major Automobile Manufacturers

Company	Vehicle Platform	Battery		Electric Range (km)	On-Road Evaluation (small fleets)	Planned Commercial Introduction
		Type	Capacity (kWh)			
Ford	Escape	Li Ion	10	48	2009-11	?
General	Malibu/Volt	Li Ion	16	64	2010-11	2010/2011
Motors	Saturn Vue	Li Ion	5	16	2010-11	2010/2011
Toyota	Prius	NiMH; Li Ion	~3	13	2009-11	?
VW	Golf	Li Ion	12	40-50	2010-12	?

General Motors was the first major manufacturer to project a commercialization date. However, even GM is still tying its production plans and commercialization schedule to the availability of lithium ion batteries that meet stringent automotive requirements for high performance, long life, a high level of safety, and acceptable cost. Other major automobile manufacturers also view the battery as a key issue and have concerns about the commercial viability of PHEVs. These issues and several other concerns are addressed in this paper, with the objective of reducing remaining uncertainties about the prospects of PHEVs.

2 Issues and Progress

2.1 Battery Technology

The prospects of PHEVs depend critically on the availability of batteries that meet demanding technical requirements for high performance, long cycle and calendar life, and a very high level of safety, all at a cost that makes PHEVs competitive with conventional vehicles. The progress of batteries against the technical requirements posed by PHEV applications is reviewed below; prospective first cost and life cycle cost are discussed in the subsequent section.

2.1.1 Performance

PHEV batteries need to have substantial storage capacity to enable displacement of meaningful quantities of automotive fuel by electricity, and they need to provide sufficient peak power for competitive PHEV performance when combined with the power output of the typically rather small IC engines chosen for high efficiency.

Detailed analyses of the battery power capabilities and storage capacities required for PHEVs with different electric ranges have not yet been reported. However, preliminary requirements for mid-size automobiles of approximately 1500kg weight were used [2] to estimate the battery specific performance parameters shown in Table 2; the table also lists the preliminary battery performance targets for PHEV batteries issued by the U.S. Advanced Battery Consortium.

Comparing the characteristics of Li Ion batteries developed for automotive applications (Table 3) with the battery specific power and energy requirements in Table 2 shows that lithium ion batteries designed around several different chemistries meet the performance requirements for a wide range of PHEV applications. High-power nickel metal hydride batteries (last line in Table 3) can meet the weight constraints and storage capacity requirements only for PHEVs with very short electric range, see Table 2. (NiMH batteries designed for higher specific energy do not meet specific power requirements for PHEV applications.)

2.1.2 Lithium Ion Battery Life

The requirements for PHEV battery life are very stringent: at least 10 and preferably 15 years calendar life, and a cycle life of at least 2500 and preferably more than 3000 deep cycles [1,3]. Less than ten years ago, lithium ion batteries were not able to meet these requirements. Although they still present major challenges, improvements of well-established lithium ion battery chemistries now indicate [4] that both, calendar and cycle life requirements can be met if battery temperatures are kept below approximately 35-40°C, especially if frequent very deep discharges and longer periods at full charge are avoided.

Table 2: PHEV Battery Performance Requirements

PHEV (Electric Range)	Battery			Specific Power (kW/kg)	Specific Energy (kWh/kg)
	Weight Allowance (kg)	Peak (Pulse) Power (kW)	Storage Capacity[1] (kWh)		
PHEV(10)	100	50	4-4.5	500	40-45
PHEV(20)	120	50	7-9	≥400	60-75
PHEV(40)	150	65	14-18	≥400	95-120
USABC					
PHEV(10)	60	45	3.4[2]	750	≤70[3]
PHEV(40)	120	38	11.6[2]	~320	≤120[3]

[1] Capacity is defined as total energy available from 100% discharge of battery
[2] numbers refer to "available energy" as defined by USABC
[3] calculated with assumption that available energy is ≥80% of battery storage capacity for Li Ion batteries designed for low impedance and deep discharge

Table 3: Candidate Battery Technologies for PHEV Applications

Developer	Chemistry		Power (kW)	Capacity (kWh)	Weight (kg)	Specific Power (kW/kg)	Specific Energy (kWh/kg)
	Negative	Positive[5]					
JCS[1]	Li/carbon	LiNCA	87	15	160	540	94
LEJ[2]	Li/carbon	LiMS	60	7.6	65	917	117
A123[3]	Li/carbon	LiFP	>100	14	~100[6]	≥700[7]	≥100[7]
ANL[4]	Li titanate	LiMS	100	6.7	100	1000	67
Various	M Hydride	Ni oxide	~50	~5	~100	~500[8]	~50[8]

[1] Johnson Controls-SAFT joint venture
[2] Lithium Energy Japan, joint venture of GS, Yuasa, Mitsubishi, and Mitsubishi Motors
[3] A123Systems
[4] Argonne National Laboratory; ANL battery is conceptual using representative materials, cell designs and battery composition
[5] LiNCA: Li nickel/cobalt/aluminum oxide, LiMS: Li manganese spinel, LiFP: Li iron phosphate
[6] Weight of battery modules; complete batteries exceed weight of modules by 25%-60%
[7] Battery performance estimated by authors from A123 module data
[8] Authors' estimate of best performance of high-power, medium-energy NiMH battery designs

Fig. 3 shows the results of an ongoing test in which a pack of automotive-design lithium ion battery modules is being cycled under conditions simulating battery use in a PHEV. To date, the module pack has delivered 4000-cycles of at least 75% depth of discharge (DOD). Modest extrapolation of the data indicates about 300 more cycles can be expected before the original battery capacity will have declined by 20% to the nominal end of life (EOL). The peak power rating at 80% 'nominal' DOD has reached the EOL criterion after approximately 3,600 cycles, but this is an artefact. For the storage capacity remaining at this point in the life of the battery, 80% nominal DOD corresponds to 92% relative DOD for which a lower peak power capability and earlier EOL must be expected. (Nominal DOD is calculated using the initial capacity of the new battery; relative DOD is calculated using the current capacity of the battery). Because most analyses of battery requirements use power vs. relative DOD, Fig. 3 also shows peak power data recalculated for 80% relative DOD. These indicate that peak power is still well above the EOL criterion after 4000 cycles, actually degrading more slowly than capacity. The data of Fig. 3 also suggest that cycling beyond the nominal EOL will be possible because both, capacity and power are declining only gradually. Apparently, the discontinuities causing EOL in other batteries are not encountered in Li Ion batteries.

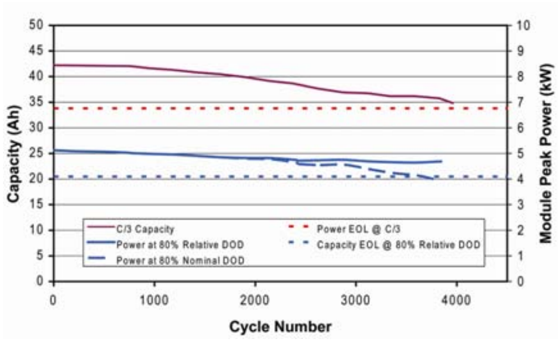

Figure 3: Deep Cycling Performance of SAFT Li Ion Battery Module Packs [5]

Several newer lithium ion technologies promise even longer calendar and cycle life because of the greater chemical and/or electrochemical stability of the materials they use. For example, Li Ion cells with iron phosphate-based positive electrodes have demonstrated more than 5000 deep cycles [6]. Such cells also have superior safety characteristics. Li Ion cells using lithium titanate as the negative electrode have demonstrated more than 2000 cycles [7] with zero degradation of power capability and storage capacity, even when cycled between full discharge and charge at very high rates and at temperatures as high as 55°C. More than 6000 deep cycles at ambient temperature are claimed by Altair Nanotechnologies for their titanate-based cells. The exceptional life of these cells derives directly from the fact that the titanate negative electrode operates at approximately 1.5 Volt positive potential relative to lithium. At this potential, discharge of lithium ions to lithium and the subsequent reaction of lithium with the electrolyte to form the so-called SEI (solid-electrolyte interface) layer are precluded, and with it the main mechanism for gradual loss of power capability and storage capacity through growth of the SEI layer with time. Although titanate-based cells and batteries in theory have about 35% lower specific energy than technologies using carbon/graphite-based negative electrodes, the practical difference is substantially smaller because titanate cell resistances can be extremely low due to absence of an SEI layer. As a result, an exceptionally high percentage of the cell and battery capacity is available for high-power charge and discharge.

Calendar and cycle life test data for multi-cell batteries using advanced Li Ion chemistries in cell sizes suitable for PHEV applications have not yet been reported. However, with appropriate thermal and electrical controls battery-level calendar and cycle life performance can be expected to approach cell-level performance and thus meet the requirements for PHEV applications.

2.1.3 Lithium Ion Battery Safety

Concerns about safety have long kept automobile companies from committing to lithium ion batteries for their emerging HEV products and, even more so because of the higher battery capacity and energy content, for application in future PHEVs. Recent, widely publicized fires of lithium ion cells in some laptops have added to this concern because several of the lithium ion cell chemistries of batteries intended for automotive applications are similar to those used in today's laptop batteries. Also, under severe abuse test conditions (such as continuous heating, or overcharging at high rates with all control and safety systems removed) such cells can vent flammable gases. Table 4 [4] illustrates this cell behaviour for an early Li Ion technology of JCS that uses carbon/graphite negative and LiNCA positive electrodes.

Abuse tests are useful to characterize lithium ion chemistries and cell designs in terms of abuse tolerance. However, they are not measures of battery safety which is determined primarily by the design and operation of the hierarchical cell-, module- and battery-level electric and thermal controls used in automotive lithium ion battery systems. This is demonstrated by the observations summarized in Table 4: although severe electrical and thermal abuses can result in cell venting, they do not compromise the safety of a complete battery protected by a series of safety strategies and devices.

Table 4: Results of Abuse Testing

Test	HEV Cell[1]	EV Battery[2]
Mechanical Crushing	no event	no event
Perforation (Nail Test)	smoke (venting)	not applicable
External Short Circuit	no event	no event
Overcharging (High Rate)	smoke (venting)	no event
Over discharging	no event	no event
Overheating (External Heat)	smoke (venting)	n.d.a.[3]
Fuel Fire Immersion (890ºC)	flame	flame (low rate combustion)
Water Immersion	no event	no event

[1]USABC test procedure with all safety devices and controls disabled
[2] USABC test procedure but with safety devices and controls operating
[3] No data available

In part because of the careful, redundant approach to battery safety, no serious incidents have been reported in the demonstrations of the many EVs and HEV prototypes that have used lithium ion battery technology during the past five years in California, Japan and Europe. Since then, the understanding and control of lithium ion battery safety factors have continued to advance, and new battery chemistries -- including those using the iron phosphate positives or lithium titanate negatives mentioned above -- with inherently higher abuse tolerance are now being readied for HEV, small EV and PHEV applications.

2.2 Battery Cost

2.2.1 Battery Capital Costs

Prospective high first costs were one major argument against use of lithium ion batteries in the electric vehicles developed under the California ZEV mandate. Although the battery cost issue is much reduced for PHEVs because of their smaller batteries, it will remain an important concern of prospective PHEV manufacturers until the achievement of acceptable costs through mass production of batteries meeting PHEV performance, life and safety requirements is demonstrated. To help resolve the cost issue ahead of mass production and thus remove one important barrier to PHEVs, a number studies projecting lithium ion battery costs for various rates of production have been undertaken over the past ten years.

These studies [2,8,9,10] differ in methodology, basic assumptions, and in the specific lithium ion chemistries and manufacturing techniques assumed. However, the newer results tend to converge, especially for true mass production rates for which materials costs dominate battery costs.

Table 5 lists approximate costs for PHEV and HEV batteries derived from the work of Santini and Nelson presented at EVS24 that represents the newest and most detailed Li Ion battery cost analysis. The Santini and Nelson battery cost and capacity data were used to determine battery specific costs as a function of battery capacity. From that relationship, specific and total costs were determined for the batteries in the capacities used in this paper, see Table 5.

Table 5: Li Ion Battery Cost[1] Projections

Vehicle Type	Battery Capacity (kWh)	Specific Cost[2] ($/kWh)	Battery Cost ($)	Cost Difference (PHEV – HEV)
Full HEV	2	700	1400	0
PHEV(10)	4-4.5	395	~1680	~280
PHEV(20)	7-9	255	~2040	~640
PHEV(40)	14-18	210	~3360	~2060

[1] Mass production costs to vehicle manufacturer in 2008 dollars
[2] For 40kW PHEV battery using LiNCA chemistry [8]

Although these costs are substantial, the battery cost increments for each step of increasing nominal electric range capability are only modest. In particular, the battery cost increments for shorter-range PHEVs over HEVs are quite small. All of the battery costs appear to be lower than the energy cost savings that can be expected over the life of the vehicles from the displacement of fuel energy by electricity, as discussed in the following.

2.2.2 Battery Cost Payback Times

There is agreement among automobile manufacturers that the initial costs of PHEVs will be significantly higher than those of conventional vehicles of similar size, performance and accommodations, and that in mass production the battery will account for much or most of that cost difference. Thus, when considering the acceptance of PHEVs by prospective owners or users, one important question is how the savings in driving energy costs of HEVs and PHEVs compare with the cost of PHEV batteries. Table 6 shows the annual energy cost savings relative to the baseline ICE vehicle, and it gives estimated payback times for the PHEV battery costs shown in Table 5.

A second useful competitiveness test of PHEVs is their comparison with the conventional hybrid electric vehicles that are now finding increasing acceptance in vehicle markets worldwide. Since the drive trains of PHEVs and HEVs are quite similar, this test can be reduced to comparing the cost difference between PHEV and HEV batteries with the annual driving energy cost savings offered by a PHEV relative to an HEV. These savings and the corresponding payback times are included in Table 6 as well.

The conclusion is that investments in HEVs and PHEVs with mass-produced Li Ion batteries promise to pay back within the nominal 10-15 year lifetime of a vehicle, even at today’s driving energy (fuel and electricity) prices and vehicle efficiencies. Note also that the payback times for PHEVs with nominal electric ranges less than 20 miles (32 km) appear comparable to those for HEVs. At the higher energy prices and vehicle efficiencies that can be expect in the longer term future, battery payback times are attractive for all of the hybrids, and PHEVs up to 40 miles (64 km) electric range offer reasonable payback compared to HEVs.

These conclusions hold without invoking longer-term economic incentives for PHEVs and/or penalties for excess CO2 emissions from conventional vehicles. However, such incentives and penalties will be instrumental in helping to offset the higher costs of batteries produced at lower rates during the introduction of PHEVs.

Table 6: Battery Payback Times[1]

Vehicle Type	Annual Mileage (km/year)		Fuel Energy (Gasoline)		Electric Energy (AC energy to charger)		Energy Savings vs. ICEV	Payback vs. ICEV	Energy Savings vs. HEV	Payback vs. HEV
	HEV mode	EV mode	Use (L/km)	Price ($/L)	Use (kWh/km)	Price ($/kWh)	($/year)	Time (years)	($/year)	Time (years)
HEV										
near term	15	0	0.055	0.60	n.a.	n.a.	270	~6	n.a.	n.a.
longer term	20	0	0.045	1.20	n.a.	n.a.	480	~3	n.a.	n.a.
PHEV(20)										
near term	9	6	0.055	0.60	0.25	0.08	330	~6.5	78	~8
longer term	12	8	0.042	1.20	0.17	0.12	792	~2.6	312	~2
PHEV(40)										
near term	7	8	0.055	0.60	0.25	0.08	350	~10.5	94	~20
longer term	9	11	0.042	1.20	0.17	0.12	882	~4	402	~5

[1] assumed gasoline use of baseline mid-size ICE vehicle: 0.08L/km (near term), 0.065L/km (longer term)

2.3 Charging Infrastructure

A continuing question for PHEVs and EVs is the capability of the electricity infrastructure to meet the charging power requirements that will arise from the extensive penetration of these electric vehicles. To help answer this question, we need to consider the charge profile of the individual vehicle as defined, for example by SAE in Standard SAE J1772 summarized in Table 7.

Table 7: PHEV Charging Model Characteristics

Type	Power Level
Level 1: 120 VAC	1.2 – 2.0 kW
Level 2 (low): 208 – 240 VAC	2.8 – 3.8 kW
Level 2 (high): 208 – 240 VAC	6 – 15 kW
Level 3: 208 – 240 VAC	> 15 kW – 96 kW
Level 3: DC charging 600 VDC	>15 kW – 240 kW

The PHEV charge profile defines how the distribution system is affected. Because PHEVs are always ready to be driven regardless of the state of charge of the battery, they do not need to be recharged rapidly. As a consequence, we foresee the widespread use of Level 1 and Level 2 (low-rate) charging in most PHEV scenarios. Off-peak, low-rate charging will enable PHEV owners to take advantage of the generally lower prices of off-peak power and avoid investments in new higher-power charging equipment. The result will be that each individual PHEV creates a relatively low demand extended over a fairly long period of time. Higher-power charging levels will also be demanded but typically only at commercial and industrial sites that are likely to readily accommodate higher power levels.

The impacts of PHEVs on the electric power network at large will be mitigated by the diversity of users who can be expected to plug in and recharge at various times and locations around the day. Negative effects of large penetrations of PHEVs on the electric distribution system can also be mitigated through the deployment of two-way communication systems that allows electric utilities to coordinate charging ("smart charging"), thereby reducing the extent of coincident charging by a large number of PHEVs. Nearly all utilities that are anticipating the introduction of PHEVs in their service territories are already planning to incorporate smart charging schemes into their systems, whether specifically for PHEVs or as part of comprehensive plans for a "smart grid" architecture.

Finally, recent studies show that PHEV loads are likely to be clustered in certain areas, with attendant local peak load effects on the distribution system. However, electric utilities already have the analytic tools to identify and manage such situations in the same way they plan for new electric loads associated with housing or businesses.

2.4 Availability of Off -Peak Energy and Power

While concerns have been raised about the availability of electric energy to serve increasing and potentially large populations of PHEVs, the electric energy impact of PHEVs will be relatively small for a number of years. Most projections, even those using relatively aggressive sales predictions for PHEVs, show a relatively low rate of penetration of PHEVs in the near term. Fig. 4 projects market shares for PHEVs, HEVs and conventional ICEVs among new vehicles between 2010 and 2030. In one representative projection [11], PHEVs will grow to approximately 10% of new vehicle sales by 2015, amounting to about 2.5 million PHEVs on the road.

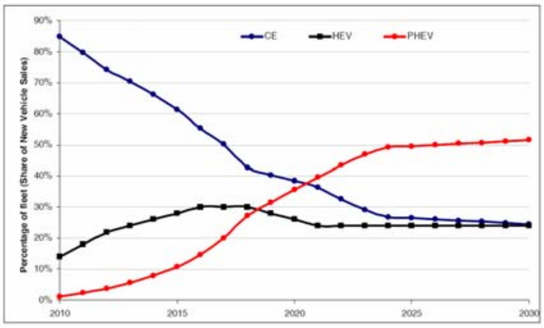

Figure 4: Projected Market Shares of PHEVs, HEVs and ICE vehicles [from 11]

Assume, then, that 2.5 million PHEVs are operating in 2015, each using 0.25 kWh_{AC}/km, and driven 64 km (40 miles) daily for a full year. Their total electricity consumption would be only 14.6 billion kWh, or less than 0.4% of the U.S. electricity consumption projected by the EIA for 2015 [12]. At a current load growth of about 1% per year, PHEVs would use well less than the annual increment of the off-peak energy that would become available from the generation increases added to satisfy load growth.

Of greater interest is the impact of PHEV introduction on power availability, generally a more important limitation of the electric power system. Two points are noted here. First, as described above, most PHEV charging is expected to occur at off-peak periods. Fig. 5 shows the system load profile over the course of an average summer day in the service territory of the California Independent System Operator (CAISO), the organization that monitors and controls the operation of the electrical power system in California. If we assume Level 1 charging (see Table 7)) at 2 kW per vehicle, one million vehicles in California charged at the same time would add about 2000 MW to the off-peak power demand, keeping the off-peak load well below peak load and generating capacity.

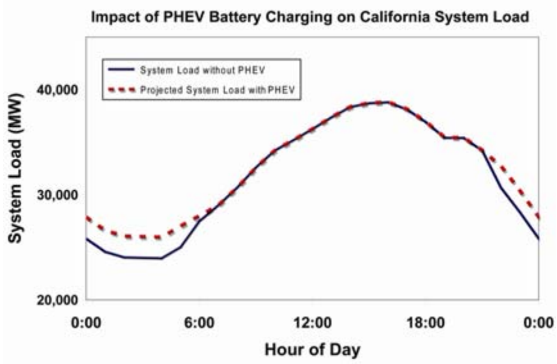

Figure 5: Summer Load Shape in California ISO on July 23, 2008 [13]

In short, while the increasing adoption of PHEVs will undoubtedly have effects on electric power systems, these effects are predictable, often beneficial especially in the nearer term, and manageable using systems tools that are being developed to increasing levels of sophistication. Overall, the adoption of PHEVs is unlikely to be impeded by limitations of the electrical power network.

2.5 The Carbon Footprint Question.

With global warming and climate change rapidly moving to the top not only of institutional and political but also of energy strategy and transportation technology agendas, questions have been raised whether the introduction of PHEVs might release more carbon dioxide to the atmosphere than other advanced-technology vehicles such as HEVs, fuel cell vehicles, or even diesel-powered conventional automobiles. The concern is that in a number of U.S. and world regions much of the electric power will continue to be generated by coal plants, and that the CO_2 emissions associated with PHEV battery charging will negate the CO_2 emission reductions enabled by the vehicles themselves.

Whether this concern is justified depends in complex ways on a number of factors, including vehicle fuel and electric efficiencies, electricity generation fuel mixes during periods of battery charging, and coal power plant efficiencies. Over the longer term, key factors will be the penetration of nuclear and renewable fuels into electricity generation, and the prospects for the paradigm shift that power plant-generated CO_2 is sequestered and thus removed from the atmospheric carbon cycle.

The first well-to-wheel analysis [1] of PHEV-associated CO_2 releases assumed gradual addition of high-efficiency, natural gas-fired combined-cycle power plants to charge the batteries of incremental populations of PHEVs. In that scenario, PHEVs substantially reduce systems-level ("well-to-wheel") releases of CO_2, as illustrated in Fig. 1. If the incremental electricity were instead derived from nuclear and renewable energies -- or from future coal plants with CO_2 sequestration systems – this advantage would increase substantially. On the other hand, if a large portion of the electric energy used to charge PHEV batteries were to be supplied by coal-fired power plants, PHEV-associated releases of CO_2 to the atmosphere could be higher than those shown in Fig. 1.

To illustrate these differences, Table 8 compares the CO_2 emissions of conventional ICE and hybrid electric vehicles with the total (vehicle plus power plant) CO_2 releases caused by PHEVs and pure (battery-powered) electric vehicles for four scenarios: one nearer term scenario in terms of vehicle and electric power plant efficiencies, and three longer-term scenarios.

Table 8. Carbon Dioxide Releases of Different Vehicle Types

Vehicle Type	Near Term	Longer Term		
	50% Coal Power	50% Coal Power	Natural Gas Power	Carbon-Free Power
IECV	178	144	144	144
HEV	122	102	102	102
PHEV(20)	131	91	84	61
PHEV(40)	135	88	77	46
EV	146	76	57	0

In the near-term and first longer term scenarios, 50% of the electric power is assumed to be generated by coal power plants, 50% to be carbon-free through various combinations of nuclear and renewable energy, and power from coal plants with sequestration of CO_2. The efficiency of these coal power plants is assumed to be 38% in the near term, 50% in the longer term [14].

In the second longer term scenario, all of the incremental power used to charge PHEV and EV batteries is assumed to come from natural gas-fired, high-efficiency combined-cycle power plants. In the last scenario, all power generation is assumed to be carbon-free.

Table 8 shows that all advanced-technology vehicles– HEVs, PHEVs and EVs – will have substantially lower CO_2 emissions than conventional ICEVs in the near- as well as longer-term. The data also support several other important conclusions:

- In the near term, and for an electric power system based about half on coal fired power plants (the situation in the US), a PHEV causes about 10% greater CO_2 releases than a HEV but approximately 10% less than an EV.
- In the longer term, PHEVs promise to cause 10-20% lower CO_2 emissions per vehicle than HEVs in the 50% coal power and 100% natural gas power scenarios, about 35-45% less than conventional ICEVs. The emissions differences between PHEVs with different electric ranges are relatively small. .
- In a carbon-free generation scenario, the emissions advantages of PHEV(20) and PHEV(40) over HEVs grow to 40% and 5%, respectively, and the reductions of CO_2 emissions from those of ICEVs reach nearly 60% and 70%, respectively.
- EVs cause even lower emissions than PHEVs in the longer term including the 50% coal power scenario. However, their total impact will be limited by an expected, smaller market penetration due to the EV's limited range and probable higher costs.

The data in Table 8 indicate the general trends and sensitivities of system-level CO_2 releases. However, only a detailed analysis of the most likely future scenarios of electric power generation, vehicle efficiencies, and vehicle market penetration can resolve how the CO2 releases attributable to PHEVs compare with those caused by conventional ICE vehicles and HEVs. Fig. 6 presents the results of a recent analysis of likely scenarios for the United States, comparing the greenhouse gas emissions of three types of PHEV in each of three different electricity generation scenarios.

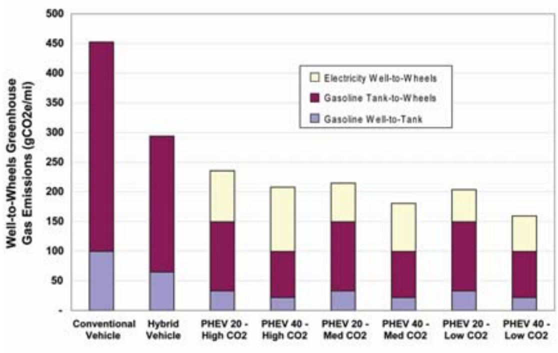

Figure 6: Greenhouse Gas Emissions for ICEVs, HEVs, and PHEVs [11]

The three generation scenarios used in the analysis made different assumptions about the generation mix, with one producing relatively high CO2 emissions, one with low CO2 emissions, and a third in between. In all cases, PHEVs cause significantly lower emissions than the conventional vehicles, and also lower than conventional hybrid vehicles.

3 The Prospects of Plug-in Hybrid Electric Vehicles

In summary, progress in every aspect of PHEV technology but especially in lithium ion batteries has established the technical basis for development of PHEVs with competitive performance and reliability. Lithium ion battery safety, already demonstrated in the past by many EV and HEV prototypes on public roads, is benefiting from the emergence of advanced technologies resistant even to severe abuse conditions. Because of their larger batteries, PHEVs will cost more than hybrid vehicles. However, in the likely future energy cost scenarios the fuel cost savings of PHEVs over conventional ICE vehicles and HEVs promise to pay back the extra costs of mass-produced lithium ion batteries for PHEV within two to five years. .

Existing and planned electric generating capacity in the U.S. will be sufficient to provide off-peak power for large and growing populations of PHEVs. These populations will greatly reduce the dependence of automobiles and other road transport on imported oil, and they will enable large, energy system-level reductions in future emissions of carbon dioxide, with reductions even in regions where much of the electricity is generated with coal power plants.

For the U.S automobile manufacturers now engaged in their development, PHEVs promise a vital opportunity to regain leadership in automotive products that meet the needs of our time.

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