Batteries for Plug-in Hybrid Electric Vehicles (PHEVs): Goals and the State of Technology circa 2008

Jonn Axsen
jaxsen@ucdavis.edu

Andrew Burke
afburke@ucdavis.edu

Ken Kurani
knkurani@ucdavis.edu

Institute of Transportation Studies
University of California
Davis, CA

UCD-ITS-RR-08-14

May 2008

Abstract

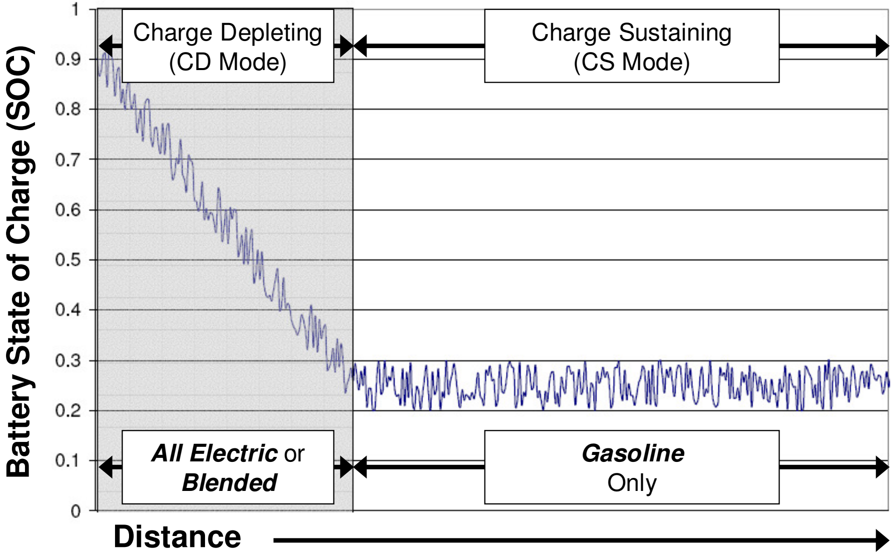
This report discusses the development of advanced batteries for plug-in hybrid electric vehicle (PHEV) applications. We discuss the basic design concepts of PHEVs, compare three sets of influential technical goals, and explain the inherent trade-offs in PHEV battery design. We then discuss the current state of several battery chemistries, including nickel-metal hydride (NiMH) and lithium-ion (Li-Ion), comparing their abilities to meet PHEV goals, and potential trajectories for further improvement. Four important conclusions are highlighted. First, PHEV battery "goals" vary according to differing assumptions of PHEV design, performance, use patterns and consumer demand. Second, battery development is constrained by inherent tradeoffs among five main battery attributes: power, energy, longevity, safety and cost. Third, Li-Ion battery designs are better suited to meet the demands of more aggressive PHEV goals than the NiMH batteries currently used for HEVs. Fourth, the flexible nature of Li-Ion technology, as well as concerns over safety, has prompted several alternate paths of continued technological development. Due to the differences among these development paths, the attributes of one type of Li-Ion battery cannot necessarily be generalized to other types. This paper is not intended to be a definitive analysis of technologies; instead, it is more of a primer for battery non-experts, providing the perspective and tools to help understand and critically review research on PHEV batteries.

Executive Summary

In this report we address the state of battery development for plug-in hybrid electric vehicles (PHEVs). This executive summary highlights our fundamental points, avoiding many of the technological details described in our full report. However, a full reading of our report is recommend for readers seeking to better understand and critically review PHEV battery research. A glossary of PHEV terms and acronyms is provided on pages 24-26.

Basic PHEV Design Concepts: Figure E-1 portrays the two basic modes of a PHEV: *charge depleting* (CD) and *charge sustaining* (CS). For a distance, the "fully" charged PHEV is driven in CD mode—energy stored in the battery is used to power the vehicle, gradually *depleting* the battery's state of charge (SOC). Once the battery is depleted to a minimum level, the vehicle switches to CS mode, *sustaining* the battery *SOC* by relying primarily on the gasoline engine to drive the vehicle (like a conventional hybrid electric vehicle). *CD range* is the distance a fully charged PHEV can travel in CD mode before switching to CS mode (without being plugged in). A PHEV with a *CD range* of 10 miles is referred to as a PHEV-10 (although notation can differ among reports). In CD mode, a PHEV can be designed to use grid electricity exclusively (*all-electric*) or electricity *and* gasoline (*blended*). All else equal, a PHEV designed for all-electric operation requires a more powerful battery than a PHEV designed for blended operation. The CD range and operation capabilities of a PHEV will depend on the assumed *drive cycle*, that is, how aggressively and under what conditions the vehicle is driven.

Figure E-1: Illustration of Typical PHEV Discharge Cycle



Source: Adapted from Kromer and Heywood (2007, p31). Used with permission from authors.

Battery Goals: Table E-1 summarizes PHEV battery goals from three different sources: The U.S. Advanced Battery Consortium (USABC), the Sloan Automotive Laboratory at

MIT, and the Electric Power Research Institute (EPRI). Battery goals are contingent on many assumptions, including CD range, CD operation (all-electric vs. blended), drive cycle, vehicle mass, battery mass, and other issues. We focus on USABC goals (Pesaren et al., 2007), which we compile into 5 main categories: power, energy, life, safety and cost. For power density, the PHEV-10 battery target is 830 W/kg, and the PHEV-40 target is 380 W/kg. The corresponding energy density targets are 100 Wh/kg and 140 Wh/kg, respectively. Not shown in Table E-1 are USABC safety goals, which are determined through abuse testing, and based on a general rating of "acceptability". Targeted battery costs are \$200-\$300 per kWh. We note that there are inherent tradeoffs among these attributes categories: increasing power density requires higher voltage that reduces longevity and safety and increases cost; increasing energy density tends to reduce power density; attempts to simultaneously optimize power, energy, longevity, and safety will increase battery cost.

Table E-1: Comparing PHEV Assumptions and Battery "Goals"

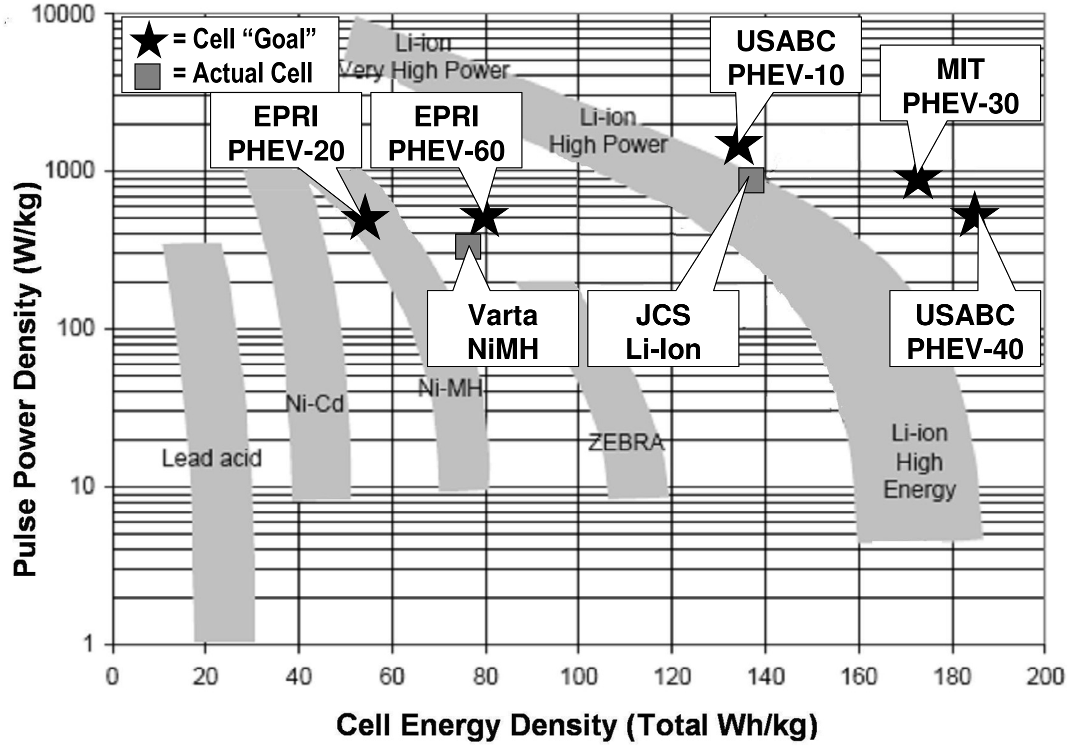
	Units	USABC[1]		MIT[2]	EPRI[3]	
Vehicle Assumptions						
CD Range	Miles	10	40	30	20	60
CD Operation	-	All-electric	All-electric	Blended	All-electric	All-electric
Body Type	-	Cross. SUV	Mid. Car	Mid. Car	Mid. Car	Mid. Car
Total Battery Mass	kg	60	120	60	159	302
Total Vehicle Mass	kg	1950	1600	1350	1664	1782
Battery "Goals"						
Peak Power	kW	50	46	44	54	99
Energy Capacity	kWh	6	17	8	6	18
Calendar Life	years	15	15	15	10	10
CD Cycle Life	cycles	5,000	5,000	2,500	2,400	1,400
CS Cycle Life	cycles	300,000	300,000	175,000	< 200,000	< 200,000

Sources:

[1] Pesaren et al. (2007)
[2] Kromer and Heywood (2007)
[3] Graham et al. (2001)

Battery Technologies: We discuss two broad categories of battery chemistries: nickel-metal hydride (NiMH) and lithium-ion (Li-Ion). Figure E-2 presents Ragone plots of these chemistries adapted from Kalhammer et al. (2007). The light grey bands present the power and energy capabilities, and tradeoffs, of lead-acid, nickel-cadmium, NiMH, ZEBRA, and Li-Ion chemistries. Onto Kalhammer et al.'s Ragone curves we plot USABC, MIT, and EPRI goals as dark stars. The grey squares represent the performance of two prototype PHEV batteries tested by Kalhammer et al. (2007): one NiMH (Varta), and one Li-Ion (Johnston Controls Saft—JCS). Whereas EPRI's analysis suggests the performance goals for an *all-electric* PHEV-20 is achievable by current NiMH technology, the goals of the USABC and MIT are beyond even current Li-Ion technology capabilities. In any case, Li-Ion battery technologies hold promise for achieving much higher power and energy density goals, due to lightweight material, potential for high voltage, and anticipated lower costs relative to NiMH. NiMH batteries could play an interim role in less demanding blended-mode designs, but it seems likely that falling Li-Ion battery prices may preclude even this role. However, Li-Ion batteries face drawbacks in longevity and safety which still need to be addressed for automotive applications.

Figure E-2: Battery Potential and PHEV "Goals" (Ragone Plots)



Source: Image of battery chemistry "Ragone" plots from Kalhammer et al. (2007, p25).
Notes: All "goal" and "sample" points added by current authors.

Li-Ion Prospects: Li-Ion batteries can be constructed from a wide variety of materials, allowing battery developers to pursue several different paths. The main Li-Ion cathode material used for consumer applications (e.g. laptop computers and cell phones) is lithium cobalt oxide (LCO). However, due to safety concerns with using this chemistry for automotive applications, several alternative chemistries are being testing for PHEVs, including: lithium nickel, cobalt and aluminum (NCA), lithium iron phosphate (LFP), lithium nickel, cobalt and manganese (NCM), lithium manganese spinel (LMS), lithium titanium (LTO), and manganese titanium (MNS and MS). Table E-2 presents an *illustrative snapshot* of several key Li-Ion technologies according to USABC goals. We use a simple rating scale based on available literature: a rating of *poor* is far from reaching USABC goals in that category; a *moderate* rating shows some promise of meeting goals with further development; a *good* rating has shown evidence of being a good candidate to meet goals; and an *excellent* holds very strong promise of meeting USABC goals. Table E-2 further demonstrates the many inherent tradeoffs in battery development; a single battery has yet to meet power, energy, life, safety, *and* cost goals.

Table E-2: Illustrative "Snapshot" of Li-Ion PHEV Battery Chemistries

Name	Description	Automotive Status	Power	Energy	Safety	Life	Cost
LCO	Lithium cobalt oxide	Limited auto applications (due to safety)	Good[4]	Good[4]	Low[2,4], Mod.[3]	Low[2,4]	Poor[2,3]
NCA	Lithium nickel, cobalt and aluminum	Pilot[1]	Good[1,3]	Good[1,3]	Mod.[1]	Good[1]	Mod.[1,3]
LFP	Lithium iron phosphate	Pilot[1]	Good[1]	Mod.[2,6]	Mod.[1,2,4]	Good[1,4]	Mod.[1], Good[2,3]
NCM	Lithium nickel, cobalt and manganese	Pilot[3]	Mod.[3]	Mod.[3], Good[7]	Mod.[3]	Poor[3]	Mod.[3]
LMS	Lithium manganese spinel	Devel.[1]	Mod.[2]	Poor[1,2,3]	Excel.[1], Good[2]	Excel.[1] Mod.[6]	Mod.[2]
LTO	Lithium titanium	Devel.[3]	Poor[3], Mod.[7]	Poor[3]	Good[3]	Good [3]	Poor [3]
MNS	Manganese titanium	Research[1]	Good[1]	Mod.[1]	Excel.[1]	Unkwn.	Mod.[1]
MN	Manganese titanium	Research[1]	Excel.[1]	Excel.[1]	Excel.[1]	Unkwn.	Mod.[1]

Sources:

[1] Nelson, Amine and Yomoto (2007, p2)
[2] Kromer and Heywood (2007, p37)
[3] Kalhammer et al. (2007)
[4] Chu (2007)
[5] Kohler (2007)
[6] Anderman (2007)
[7] UC Davis Testing

Conclusions: Four main highlights can be drawn from this discussion:

1. PHEV battery "goals" are contingent on many assumptions. USABC, MIT and EPRI goals differ greatly based on CD range, CD operation (all-electric vs. blended), drive cycle, vehicle mass, battery mass, and other issues. The "true" requirements of PHEV technology will depend on consumers' driving and recharging behaviors as well as their valuation of different PHEV designs and capabilities. In turn, producer and consumer behavior alike can be shaped by government regulation, e.g., California's ZEV mandate. Thus, while the USABC (and others) provides a useful benchmark for the future of PHEV battery technology, there may be a role for less ambitious PHEV designs, such as those using *blended* operation.

2. Battery development is constrained by inherent tradeoffs among the five main battery attributes: power, energy, longevity, safety and cost. No battery currently meets all of the USABC's PHEV goals for these attributes.
3. Of the chemistries currently being considered for PHEV application, Li-Ion is best suited for the power and energy density goals of the USABC. Although NiMH batteries may be suitable for a less ambitious PHEV design may, Li-Ion technologies are still superior to NiMH in potential for lower cost. However, Li-Ion is not yet firmly established for automotive applications, and development must overcome issues of longevity and safety—and the resulting tradeoffs with performance—in order to achieve commercial success.
4. Li-Ion technology continues to follow multiple paths of development, each using different electrode materials in efforts to optimize power, energy, safety, life, and cost performance. We must not generalize the attributes of one battery, e.g. Toyota's concerns about safety with its LCO battery, to all Li-Ion batteries. Table E-2 shows how these attributes can vary substantially among different chemistries, and the uncertainty in selecting a single technological "winner" among advanced automotive battery chemistries.

In summary, electric-drive interest groups, including researchers, policymakers, companies, advocates and critics, should be aware of these fundamental battery issues to facilitate more grounded debates about the present and future of electric-drive vehicles, including plug-in hybrid vehicles.

1.0 Introduction

Electric-drive continues to pique imaginations of motorists: clean skies, quiet cars, and plentiful electricity produced from non-polluting domestic sources. So where are our electric automobiles? The answer depends in part on what is an electric automobile. We have seen variations in electric vehicle (EV) size, performance, and definition in efforts to overcome the fundamental challenge of electric drive—how to store energy and supply power. In short, where are our batteries? In this report we address one variation on the definition of an electric vehicle and the state of battery development for it—plug-in hybrid electric vehicles (PHEVs).[1]

Much effort and many resources have been devoted to the development of electric drive vehicles over the past three decades. These efforts have been spurred by petroleum supply and price disruptions, air pollution policy, and climate policy. The U.S. federal government drove initial efforts to develop alternatives to petroleum in the late 1970s and early 1980s. The oil crisis of 1973-4 lead to substantial government funding of research on alternative fuels. Perhaps most important for electric vehicles was the Hybrid and Electric Vehicle Act of 1976. The Act resulted in long term projects in the Department of Energy, some of which laid the ground work for the battery, motor, and power and control electronics technology that emerged during the 1990s (Turrentine and Kurani, 1995). Battery electric vehicles (EV) captured renewed attention in the 1990's, stimulated by General Motor's development of the EV-1 (*aka* Impact) and California's Zero-Emissions Vehicle (ZEV) mandate. After years of further technology development and policy debate, policymakers were convinced by automobile manufacturers in the late 1990s that battery technology was insufficient to meet manufacturers' EV design goals. However, some battery technologies later proved successful in less demanding hybrid-electric vehicle (HEV) applications, achieving significant commercial success, typified by the Toyota Prius. Currently, interest has turned to what many claim is the next logical step from the HEV: plug-in hybrid electric vehicles (PHEVs). For example, the California Air Resources Board amended the ZEV mandate in March of 2008 to provide incentives for automakers to produce and sell PHEVs (CARB, 2008a).

Relative to other electric-drive and conventional gasoline vehicles, one advantage of PHEVs is fuel flexibility. A user could power their vehicle with electricity from the electrical power grid, gasoline (or another liquid fuel), or both. To do so, a PHEV has both an electric motor and a heat engine—usually an internal combustion engine (ICE).[2] This flexibility also complicates vehicle designs and possible ways of using energy from two different systems. Figure 1 shows two simple schematics of possible PHEV *architectures*, the overall design of the PHEV system to supply power from two different sources. A *series* drivetrain architecture powers the vehicle only by an electric motor using electricity from a battery. The battery is charged from an electrical outlet, or by the gasoline engine via a generator. A *parallel* drivetrain adds a direct connection between the engine and the wheels, adding the potential to power the vehicle by electricity and

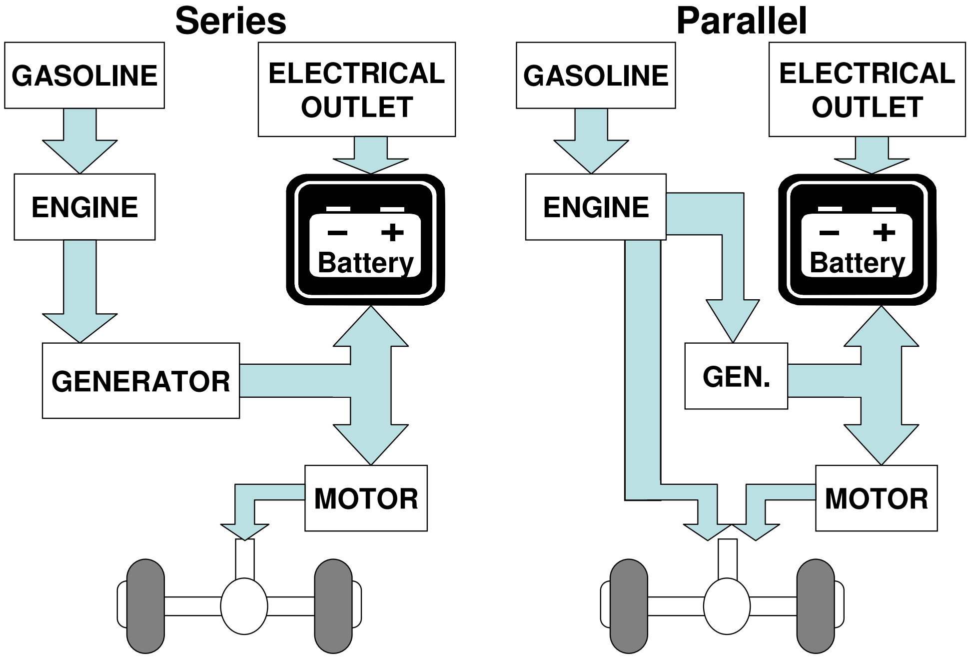
---

[1] A list of acronyms and glossary is provided in Section 8 (pages 24-26).

[2] As the ICE in most conventional vehicles is fueled with gasoline (or diesel), we will refer to gasoline and gasoline engines without precluding the possibility of different future fuels.

gasoline simultaneously and by gasoline only. While Toyota is currently developing a PHEV with a *parallel* architecture, i.e. a plug-in version of the Prius, General Motors is working with a *series* architecture, i.e. the Chevy Volt.

Figure 1: Basic PHEV Drivetrain – Series vs. Parallel Design



In any PHEV architecture the battery plays a crucial role in storing energy from the electrical grid and from the gasoline engine (through a generator), as well as passing energy back and forth with the electric motor to maximize efficiency.[3] "Pure" EVs only have an electric motor and only run on electricity and thus need batteries that can store large amounts of energy and deliver high power. However, PHEVs can be designed to emphasize energy or power requirements (or both) of batteries.

Ultimately, the commercial success of the PHEV depends on the development of appropriate battery technologies. There is much uncertainty about what exact requirements a battery must meet to produce a successful PHEV and where different battery technologies stand in meeting such requirements. On the one hand, electric drive advocates claim that battery technology is sufficient to begin the commercial introduction of PHEVs immediately (e.g. Calcars, 2008) or as early as 2010 (EPRI, 2007). On the other hand, critics counter that substantial technological breakthroughs are required before PHEVs should be introduced to the market (e.g. Kromer and Heywood, 2007). Anderman (2008) states that commercialization prior to 2015 would present substantial business risk. Also, as the difference in initial PHEV architectures between automakers shows, there is disagreement on what a PHEV is, or if the concept is flexible enough and

---

[3] During braking and coasting, an electric motor can convert—or, regenerate—some of the kinetic energy of the moving vehicle into electrical energy to be stored in the vehicle's battery.

the market diverse enough to support multiple incarnations. For their part, policymakers are unsure how to regulate PHEV emissions and "fuel" use under conditions of such technical and market uncertainty.

This report intends to help demystify some of the complexities of PHEV battery development. We discuss the basic design concepts of PHEVs, compare three sets of influential technical goals, and explain the inherent trade-offs in PHEV battery design. We then discuss the current state of several battery chemistries, comparing their abilities to meet PHEV goals, and their potential trajectories for further improvement. Four important conclusions are highlighted. First, PHEV battery "goals" vary according to differing assumptions of PHEV design, performance, use patterns and consumer demand. Second, battery development is constrained by inherent tradeoffs among five main battery attributes: power, energy, longevity, safety and cost. Third, lithium-ion (Li-Ion) battery designs are better suited to meet the demands of more aggressive PHEV goals than nickel-metal hydride (NiMH) batteries (currently used for HEVs). Fourth, the flexible nature of Li-Ion technology, as well as concerns over safety, has prompted several alternate paths of continued technological development. Due to the differences among these development paths, the attributes of one type of Li-Ion battery cannot necessarily be generalized to other types.

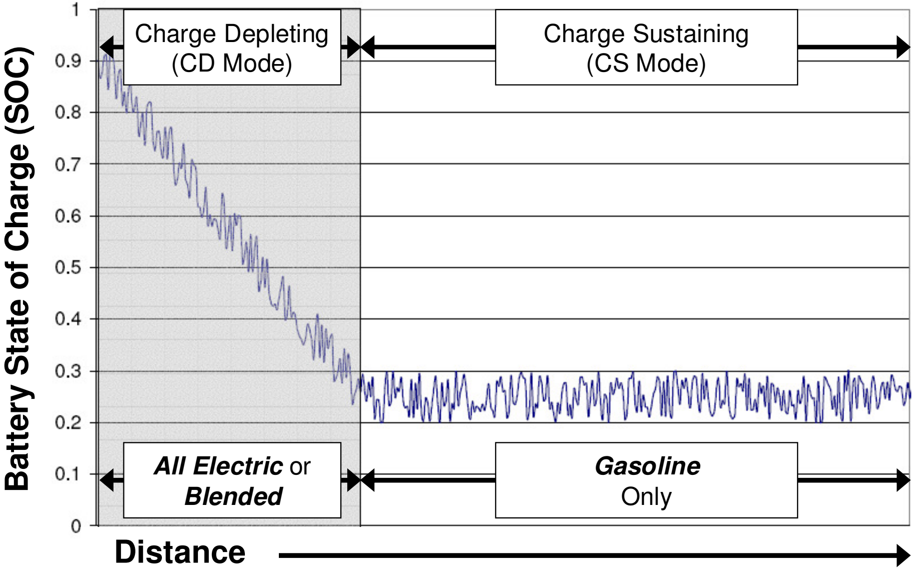
This paper is not intended to be a definitive analysis of technologies; instead, it is more of a primer for battery non-experts, providing the perspective and tools to help understand and critically review research on PHEV batteries.

2.0 Basic PHEV Design Concepts

Before delving into specific technological goals, we first explain four fundamental PHEV concepts. First, for any given architecture, a PHEV can operate in one of two modes: *charge sustaining* (CS) or *charge depleting* (CD). Figure 2 (adapted from Kromer and Heywood, 2007, p31) illustrates these two modes. The vertical axis is the battery's state of charge (SOC), ranging from 0 percent to 100 percent; the horizontal axis is the distance traveled. In practice, the maximum SOC may be limited to less than 100 percent, and the minimum SOC constrained to more than 0 percent, both to preserve battery life and improve safety. The difference between the maximum and minimum SOC is known as the usable *depth of discharge* (DOD), which varies across battery and vehicle designs.

In the Figure 2 example, the battery is "fully" charged (from an electrical outlet) to 90 percent SOC at the beginning of the cycle. For a distance the PHEV is driven in CD mode—energy stored in the battery is used to power the vehicle, gradually *depleting* the battery's SOC. Once the battery is depleted to a minimum level, set at around 25 percent in this example, the vehicle switches to CS mode. In CS mode the SOC is *sustained* by relying primarily on the gasoline engine to drive the vehicle, using the battery and electric motor to increase the efficiency of the gasoline engine, as is now done in an HEV. Small cycles, or "waves," can be seen in the SOC during CS operation, where the battery takes on energy from the engine driven generator or from regenerative braking and uses the energy in the electric motor to improve the efficiency of engine operation. The vehicle remains in CS mode until the battery is plugged in again to recharge. The distance a fully charged PHEV can travel in CD mode before switching to CS mode is called *CD range*.

Figure 2: Illustration of Typical PHEV Discharge Cycle (65% DOD)



Source: Adapted from Kromer and Heywood (2007, p31). Used with permission from authors.

A second key PHEV concept is that a vehicle can be designed for *all-electric* or *blended* operation in CD mode. A PHEV designed for *all-electric* operation can be driven for the CD range using only electricity from the battery, and the engine is not used at all. In contrast, a PHEV designed for *blended* operation will use electricity *and* gasoline to power the vehicle during the CD range—energy from the engine and the battery are "blended" together through the electro-mechanical drivetrain. Thus, a PHEV designed for *all-electric* driving will require a battery capable of delivering more power than a PHEV designed for *blended* driving (as further detailed later) because the battery (and motor and power electronics) must be capable of providing the full power of the vehicle, not just partial power.

Third, PHEV designs are commonly described according to CD range; the common notation is PHEV-*X*, where *X* is the distance in miles. For instance, a PHEV-10 can be driven 10 miles in CD mode before switching to CS mode. However, this notation does not distinguish whether a PHEV in CD mode is operating *all-electrically* or using *blending*, nor does it specify the driving conditions that would allow CD operation for the stipulated distance. Comparisons of PHEVs, even those sharing the same PHEV-*X* designation, must reconcile assumptions regarding CD operation and driving behavior.

Kurani, Heffner and Turrentine (2007) discuss how further confusion in PHEV notation can result from two differing concepts of PHEV-*X*. First, Gondor and Simpson (2007) argue that *X* should be defined as the equivalent number of miles of petroleum displaced by electricity from the battery. This approach makes no distinction between *all-electric* and *blended* operation; a fully charged PHEV-10 could store and use enough electricity to reduce gasoline use by the amount of gasoline required to travel 10 miles, but not necessarily during the first 10 miles. On the other hand, the California Air Resources Board (CARB, 2003) defines *X* as the total miles that can be driven before the gasoline engine turns on for the first time, also known as *all-electric* range (or *zero-emissions* range).[4] By this definition, a fully charged PHEV-10 could be driven for the first 10 miles without using any petroleum. CARB's definition requires a more powerful electric motor and battery to avoid engine use during CD mode. Again, these distinctions must be clarified when discussing the battery requirements of a particular PHEV design. In our use of PHEV-*X* notation in this paper, the *X* refers to the CD range of the vehicle, and we will specify between assumptions of *all-electric* or *blended* operation.

A final point of clarification for PHEV design and notation is the assumed *drive cycle* used to estimate CD operation and CD range. A *drive cycle* is a pattern of changing accelerations, speeds, and braking over time used to test fuel economy, as well as battery performance. A cycle usually repeats one or more *schedules* designed by the U.S. Environmental Protection Agency (EPA). The Urban Dynamometer Driving Schedule (UDDS) is most common, established by the EPA to simulate city driving conditions. This schedule includes many accelerations and decelerations over a 23 minute period, with an average speed of 20 miles per hour. The federal highway schedule (HWFET) is typically used to simulate highway driving. Both the UDDS and HWFET have been criticized for not accurately representing the aggressive nature of U.S. drivers (Kromer and Heywood, 2007), and thus PHEV battery goals based on such schedules may overestimate the electric drive capabilities of a given battery. For instance, if an *all-electric* PHEV-20 is designed using the UDDS, a more aggressive driving cycle will shorten the CD range, or require engine assistance (blending) during CD mode to achieve the specified range, or both. Thus, in comparing different battery goals, readers must consider drive cycle assumptions, and assess how representative such assumption may be of actual driving behavior.

3.0 PHEV Battery Goals

The battery requirements of any given PHEV design are primarily determined by peak power (kW) and energy storage (kWh). As noted, both are dependent on assumptions about CD range, CD operation mode, i.e. all-electric or blended, drive cycle, vehicle design, recharge behavior, and other factors.

In this section we present the PHEV battery goals set by the US Advanced Battery Consortium (USABC), as summarized by Pesaran et al. (2007).[5] Table 1 provides a summary that will be referred to throughout this paper. We focus on USABC goals because these are the most recent and among the most influential goals. Pesaran et al. (2007) specify two main PHEV battery types: a high power/energy ratio battery

---

[4] As of the writing of this report, CARB is considering a proposal to allow PHEVs designed for *blended* operation to receive credits under the zero emissions vehicle regulation (CARB, 2008b). The USABC's goals were, in part, set to meet CARB's *all-electric* PHEV requirements, and do not consider the possibility of *blended* options (Pesaren et al., 2007).

[5] The USABC is a partnership between the US Department of Energy (DOE) and US auto companies.

providing 10 miles of *all-electric* range (PHEV-10), and a low power/energy ratio battery providing 40 miles of *all-electric* range (PHEV-40). These categories follow CARB's definition of PHEV-*X*, where *X* is the number of miles the vehicle can drive in *all-electric* mode during a particular *drive cycle*, before the gasoline engine turns on. Pesaren et al. (2007) used the Urban Dynamometer Driving Schedule (UDDS) to be consistent with CARB's testing methods. The USABC PHEV-10 goals are set for a "crossover utility vehicle" (an automobile-based SUV) weighing 1950 kg and the PHEV-40 goals are set for a midsize sedan weighing 1600 kg. The "basic" assumptions in Table 1 specify weight and volume limits of the battery system. We discuss the five groups of goals below: power, energy capacity, life, safety, and cost (as summarized by Pesaran et al, 2007).

Table 1: USABC Goals for Advanced PHEV Batteries

	Units	PHEV-10 (High Power to Energy Ratio)	PHEV-40 (Low Power to Energy Ratio)
1) Basic Assumptions			
Body Type	-	Crossover SUV	Midsize Car
All Electric Range	miles	10	40
Max System Mass	kg	60	120
Max System Volume	L	40	80
2) Power			
Peak Power (2 sec / 10 sec pulse)	kW	50 / 45	46 / 38
Power Density (2 sec / 10 sec pulse)	W/kg	830 / 750	380 / 320
3) Energy Capacity			
Available Energy	kWh	4	12
Total Energy (@ 70% DOD)	kWh	6	17
Total Energy Density	Wh/kg	95	140
4) Life			
Calendar Life	years	15	15
Deep Discharge Cycles (CD mode)	cycles	5,000	5,000
Shallow Discharge Cycles (CS mode)	cycles	300,000	300,000
Temperature Range	°C	-46 to +66	-46 to +66
5) Safety			
Abuse Tests	-	Acceptable	Acceptable
6) Cost			
OEM Price @ 100,00 units/year	$	$1,700	$3,400
OEM Price/Total kWh	$/kWh	$300	$200

Source: Compiled from Pesaran et al. (2007, p13)

Because USABC goals are highly dependent on various assumptions, we also present alternative analyses conducted by the Sloan Automotive Laboratory at the Massachusetts Institute of Technology (MIT), and the Electric Power Research Institute (EPRI). Table 2 summarizes the differing assumptions and “goals” of each. The term *goal* refers to the intended direction of long-term development for industry, as provided by the USABC. MIT and EPRI provide more neutral analyses of battery *requirements*, not necessarily setting goals. We refer to standards from all three studies as “goals” for the remainder of this paper for the sake of simplicity. Some of the assumption categories in Table 2 have been explained above; other assumptions and goals are addressed below.

Table 2: Comparing PHEV Assumptions and Battery “Goals”

	Units	USABC[1]		MIT[2]	EPRI[3]	
Vehicle Assumptions						
CD Range	Miles	10	40	30	20	60
CD Operation	-	All-electric	All-electric	Blended	All-electric	All-electric
Electricity Use[4]	kWh/mile	0.42	0.30	0.19	0.24	0.24
Depth of Discharge	Percent	70%	70%	70%	80%	80%
Drive Cycle	-	UDDS	UDDS	UDDS, HFWET, US06	UDDS, HFWET	UDDS, HFWET
Body Type	-	Cross. SUV	Mid. Car	Mid. Car	Mid. Car	Mid. Car
Battery Mass, Total	kg	60	120	60	159	302
(Cells Only)[5]		(45)	(90)	(45)	(121)	(252)
Total Vehicle Mass	kg	1950	1600	1350	1664	1782
Battery “Goals”						
Peak Power	kW	50	46	44	54	99
Peak Power Density	W/kg	830	380	730	340	330
***Total* Energy Capacity**	kWh	6	17	8	6	18
***Total* Energy Density**	Wh/kg	100	140	130	40	60
Calendar Life	years	15	15	15	10	10
CD Cycle Life	cycles	5,000	5,000	2,500	2,400	1,400
CS Cycle Life	cycles	300,000	300,000	175,000	< 200,000	< 200,000

Sources:

[1] Pesaren et al. (2007)

[2] Kromer and Heywood (2007)

[3] Graham et al. (2001)

[4] Grid electricity only -- calculated as total *available* energy capacity divided by CD range

[5] Packaging factor of 0.75 assumed for “cells only” mass (except EPRI—both values were supplied)

The MIT goals are derived from Kromer and Heywood (2007), who used vehicle assumptions that differed from USABC in two important ways. First, Kromer and Heywood (2007) set goals for a midsize sedan PHEV with 30 miles of CD range in *blended* mode. As a useful side note, Kromer and Heywood illustrate the differences in PHEV goals for different levels of blending versus *all-electric* operation. Second, in addition to the UDDS used by the USABC, Kromer and Heywood (2007) used the HWFET schedule as well as the US06 schedule, the latter of which is the most aggressive due to longer accelerations and higher top speeds. They explain that this combination of schedules produces a drive cycle that is more representative of actual U.S. driving behavior than the UDDS or HWFET schedules alone, thus allowing more realistic (and stringent) battery goals. Although such a drive cycle requires higher battery performance than USABC's goals, this is largely offset by their assumptions of CD blending, and a lower vehicle weight. EPRI's goals are derived from a report conducted by Graham et al. (2001), investigating the power requirements of a midsize sedan PHEV with 20 or 60 miles of *all-electric* range.[6] Graham et al.'s drive cycle includes the UDDS and HWFET. The primary distinguishing factor of EPRI goals is the higher battery weight assumptions (159-302 kg) compared to USABC and MIT (60-120 kg).

3.1 Power

Power is rate of energy transfer; it is measured in watts or more typically for automotive applications, kilowatts (kW). The power of a conventional gasoline vehicle is typically reported in horsepower, where 100 horsepower is equivalent to 75 kW. For batteries, power is akin to the rate at which gasoline can be delivered to the engine—to accelerate faster you have to be able to draw energy out of the battery or deliver gasoline to the engine more quickly. However, the performance of conventional vehicles is not limited by rate of gasoline delivery, whereas in electric-drive vehicles, power delivery from the battery is critical. The USABC's peak power goals are based on short accelerations (pulses) of 2 and 10 seconds. According to Pesaran et al. (2007), the PHEV-10 requires the ability to provide 50 kW of power (67 horsepower), while the PHEV-40 requires 46 kW. Power requirements are not typically related to CD range; the PHEV-10 requires slightly more power due to the increased weight (+350 kg), rolling resistance, and frontal area (drag) of the crossover SUV compared to the sedan used for the PHEV-40 analysis.

For comparison, Kromer and Heywood (2007) demonstrate how different types of operation in CD mode can influence power requirements for a PHEV-30. While different levels of *blended* operation require only 23 to 40 kW of power, a PHEV with all-electric operation requires a battery that can deliver 60 kW (Kromer and Heywood, 2007). The latter value is higher than USABC goals due to Kromer and Heywood's use of more ambitious drive cycles, i.e., HFWET and US06 in addition to the UDDS. In contrast, EPRI's all-electric PHEV-20 requires 54 kW—likely higher than USABC due to the additional use of the HFWET cycle. EPRI's PHEV-60 goal is much higher—99 kW—in order to optimize overall performance by taking advantage of the heavy battery (302 kg) to allow the battery to replace the engine even in aggressive cycles (note that power density is about the same as for EPRI's PHEV-20).

In comparing battery technologies, analysts typically refer to *power density* as the power per kilogram of the battery system (W/kg). The USABC's target weight for the PHEV-40 battery pack is 120 kg, resulting in a power density of 380 W/kg. The target weight for the PHEV-10 battery pack is 60 kg, resulting in a power density of 830 W/kg—more than double the PHEV-40 density. In this sense, the power goals of the USABC's *all-electric*

---

[6] EPRI also estimated PHEV requirements for compact cars and sport utility vehicles (Duvall et al., 2002).

PHEV-10 are more challenging than the *all-electric* PHEV-40.[7] Of course, these power density goals could be significantly reduced for a *blended* PHEV design, as noted by Kromer and Heywood, 2007, or by allowing a heavier battery, e.g., EPRI's goals.

3.2 Energy Capacity

Energy capacity goals relate to the amount of energy stored in the batteries and the batteries' energy density; they determine the distance that can be traveled in CD mode and the mass of the battery system. Energy capacity is typically measured in kilowatt-hours (kWh), where 1 kWh = 1,000 Watts provided for 1 hour. In Table 1, an important distinction is made between *available* and *total* energy. While a battery may have 10 kWh of *total* energy, only a portion of this capacity is *available* for vehicle operations. As described in the previous section, and shown in Figure 2, a "fully" charged battery may be at less than 100 percent SOC, and it may be regarded as "depleted" at something more than 0 percent SOC, say 25 percent. This range of operation in practice is called the usable *depth of discharge* (DOD); DOD is 65 percent in the example in the previous sentence but varies across battery and vehicle designs. A battery with 10 kWh of total energy operating with a 65 percent DOD would have only 6.5 kWh of *available* energy. The USABC values in Table 1 assume a 70 percent DOD, meaning that the *total* energy goal required for each battery is 43 percent higher than the required *available* energy.

The USABC's PHEV-10 requires about 4 kWh of *available* energy, while the PHEV-40 requires 12 kWh. With a 70 percent DOD, these values correspond to battery systems storing *total* energy of 5.7 and 17 kWh, respectively. Graham et al. (2001) and Kromer and Heywood (2007) estimate similar requirements of available energy for the PHEV designs they analyze, indicating that estimates of energy capacity requirements are not as sensitive to differences in assumption (other than range in CD mode) as are power requirements. A common metric of battery energy is *energy density*, measured as the *total* Wh per kilogram of the battery system. The USABC's energy density goals are 100 Wh/kg for the PHEV-10, and 140 Wh/kg for the PHEV-40. MIT's goal is within this range (130 Wh/kg), while EPRI's goals are much lower (40-60 Wh/kg)—the latter difference is again largely due to the much heavier battery mass.

3.3 Life

With use and over time, battery performance can substantially degrade, including power, energy capacity, and safety. Table 1 portrays four key measures of battery longevity. First, *calendar life* is the ability of the battery to withstand degradation over time, which may be independent of how much or how hard the battery is used. The USABC goal for batteries for both vehicles is 15 years at a temperature of 35 °C, where exposure to hotter temperatures can accelerate degradation. MIT also targets 15 years of calendar life. EPRI uses a less ambitious target of 10 years, which they cite as being consistent with previous

---

[7] Conceptually, it is possible to combine multiple electricity storage technologies in a single vehicle, for example batteries with good energy characteristics could be combined with ultracapacitors with good power characteristics. So a PHEV-10 could use batteries primarily to provide energy and ultracapacitors to provide short bursts of power. This possibility is not discussed further in this report.

studies, but also consider a 15 year life.[8] Also note that all of the USABC goals are set for the battery's *end of life*. In other words, the power and energy goals described in the sections above must apply after 15 years of life regardless of use. If these attributes are expected to degrade over time and/or use, initial values will have to be even higher than the stated goals.

Second, *deep cycle life* is the number of discharge-recharge cycles the battery can perform in CD mode. For example, Figure 2 portrays one complete deep discharge, starting at 90 percent SOC, ending at 25 percent SOC; recharging back to 90 percent SOC would complete one full cycle. The USABC's battery goal is 5,000 deep cycles. This goal assumes one complete deep cycle each day, 330 days of the year, for the 15 year life span of the vehicle. Other studies set less ambitious targets; MIT states 2,500 deep cycles for a PHEV-30, and EPRI states 2,400 and 1,400 deep cycles for the PHEV-20 and PHEV-60, respectively. EPRI's target is lower due to the assumption of shorter life (10 years), whereas Kromer and Heywood's target is based on different assumptions about recharge behavior. One might also consider potential differences in deep cycle goals between different PHEV designs. For example, Kromer and Heywood (2007) note that because the charge of a PHEV-10 will be expended more quickly than that of a PHEV-30, the PHEV-10 will likely undergo more deep discharge cycles (3200) than the PHEV-30 (2500). In considering the USABC goals, a PHEV-40 may require fewer deep cycles than a comparable PHEV-10 during the same calendar life.

Third, *shallow cycles* refer to SOC variations of only a few percent. These smaller variations occur throughout CD and CS mode, as portrayed in Figure 2. The battery frequently takes in electric energy from the gasoline engine via a generator and from regenerative braking, and passes energy to the electric motor as needed to power the vehicle. These frequent shallow cycles cause less degradation than deep cycles, but still affect longevity. The USABC longevity target is 300,000 shallow cycles for both PHEV designs, again much higher than the 175,000 set by MIT, or the 200,000 set by EPRI. Although this range of targets (200,000-300,000) is achievable by current hybrid electric vehicles (HEVs), in a PHEV most of the shallow cycles would likely occur at a relatively low SOC (e.g. 25 percent), which can cause relatively more wear on the battery. Thus, USABC goals to produce both 5,000 deep discharge cycles and 300,000 shallow cycles at a low SOC presents a formidable challenge for battery manufacturers.

Fourth, *survival temperature range* is the range of temperatures the battery can be subjected to while not in operation, neither charging nor discharging. The USABC target range is -46°C to +66°C, which more than covers natural conditions of the continental US. Most studies do not address temperature effects on battery operation, particularly cold climate effects. We do not further address temperature issues in this paper, but readers should keep in mind the potential importance of this factor.

---

[8] Because passenger vehicles typically last longer than 10 years, a battery with this calendar life would have to be replaced during vehicle life. Such a constraint could substantially add to consumer costs. Graham et al. (2001) estimate that battery replacement costs could range from $2,000-7,000 (with salvage value).

3.4 Safety

Safety is another important factor because batteries store energy and contain chemicals that can be dangerous if discharged in an uncontrolled manner, such as through short circuits, impacts, overcharging, or high heat (Kalhammer et al., 2007).[9] Public perception of battery safety for automotive application is an especially large concern after millions of laptop computer batteries were recalled in 2005-2006 due to fire hazard (e.g. Fahey, 2006). However, in automotive applications, batteries use battery management units that provide a higher degree of safety than typical consumer applications, i.e. monitoring cell voltage and temperature, and taking corrective action when necessary. As discussed in the following sections, battery safety depends on battery chemistry, design, and manufacturing quality control.

The USABC's battery goals do not include specific safety objectives, although safety is implied in goals of longevity and operation temperature. Safety is typically measured through abuse tolerance tests. Doughty and Crafts (2005) outline several abuse tests to be performed on batteries, including mechanical crushing, perforation, external short circuit, overcharging, overheating, fuel fire immersion and water immersion. In each test, the battery's response is recorded and assessed in regards to longevity and threats to personal safety. Doughty and Crafts (2005) state that the magnitude of the response, e.g. mild or catastrophic, should be considered in light of the likelihood of the abuse condition to occur in normal operation. For example, Kalhammer et al. (2007, p35) outline the results of such abuse tests on one particular battery, where responses range from "no event" to "smoke (venting)" or "flame (low rate combustion)." However, the overall rating of battery safety appears to be subjective, where Doughty and Crafts (2005, p9) suggest that the abuse tests they outline can be used to help determine what is "acceptable." Thus, we portray the USABC's safety goal in Table 1 as one of "acceptability," where the literature does not provide quantitative measures appropriate for this report.

3.5 Costs

Battery cost is thought to be one of the most crucial factors affecting the commercial deployment of electric drive technologies (Kalhammer et al., 2007). The USABC cost goals are $1,700 and $3,400 for the PHEV-10 and PHEV-40 battery packs, respectively, under a scenario where battery production has reached 100,000 units per year (Pesaran et al. 2007). These goals are stated as costs to the original equipment manufacturers (OEMs), and do not include the markup that would be passed on to consumers.[10] To facilitate comparison, battery cost is commonly measured in dollars per *total* kWh (not just *available* kWh), which equates to $300/kWh for the PHEV-10 and $200/kWh for the PHEV-40. In the MIT analysis, a value of $320/kWh is assumed to be required for the commercialization of a PHEV-30. In either analysis, these cost targets are much lower

---

[9] We note that automotive consumers have become habituated to handling toxic, carcinogenic, mutagenic, and highly flammable fuels, i.e., gasoline and diesel. This is not to diminish the safety challenges of batteries, but to note that so far as we know, they are challenges, not insurmountable barriers.

[10] Estimates of the markup on advanced automotive batteries from OEM to consumer range from 25-33% (Kromer and Heywood, 2007).

than current prices; Pesaran et al. (2007) estimate that in general, current advanced battery costs range from \$800/kWh to \$1000/kWh or higher.

3.6 Summary of Trade-offs

In summary, this section has described the five main attributes considered by the USABC for PHEV batteries: power, energy capacity, life, safety, and cost. Specific goals used by other analysts for each attribute differ from the USABC, depending on assumptions about PHEV design, drive cycle, vehicle and battery weight, and recharge behavior. We have chosen to focus on the USABC targets detailed by Pesaran et al. (2007). These goals are more demanding than most studies, largely due to the stated target of 10 and 40 miles of *all-electric* range (with no gasoline use), and restricted battery weight. Many of these goals would be decreased for less demanding PHEV drivetrain specifications, such as the use of *blended* operation in CD mode.

There are inherent trade-offs among the attributes discussed above. The USABC presents a combination of goals for battery developers to work towards. Some existing battery technologies can achieve some of these goals. However, meeting all goals simultaneously is far more challenging. For example, higher power, i.e., for USABC's PHEV-10, can be achieved through the use of thinner electrodes. However, these designs tend to reduce cycle life and safety, while increasing material and manufacturing costs. In contrast, high energy batteries, i.e., for USABC's PHEV-40, use thicker electrodes that increase safety and life, but reduce power density. Thus, it can be very difficult to meet ambitious targets for both power and energy density in the same battery technology, let alone also meeting the additional considerations of longevity, safety, and cost. Understanding these trade-offs is key to understanding the complexities and challenges of PHEV battery development. Next, we discuss the current state of battery technologies vis-vis USABC's PHEV goals.

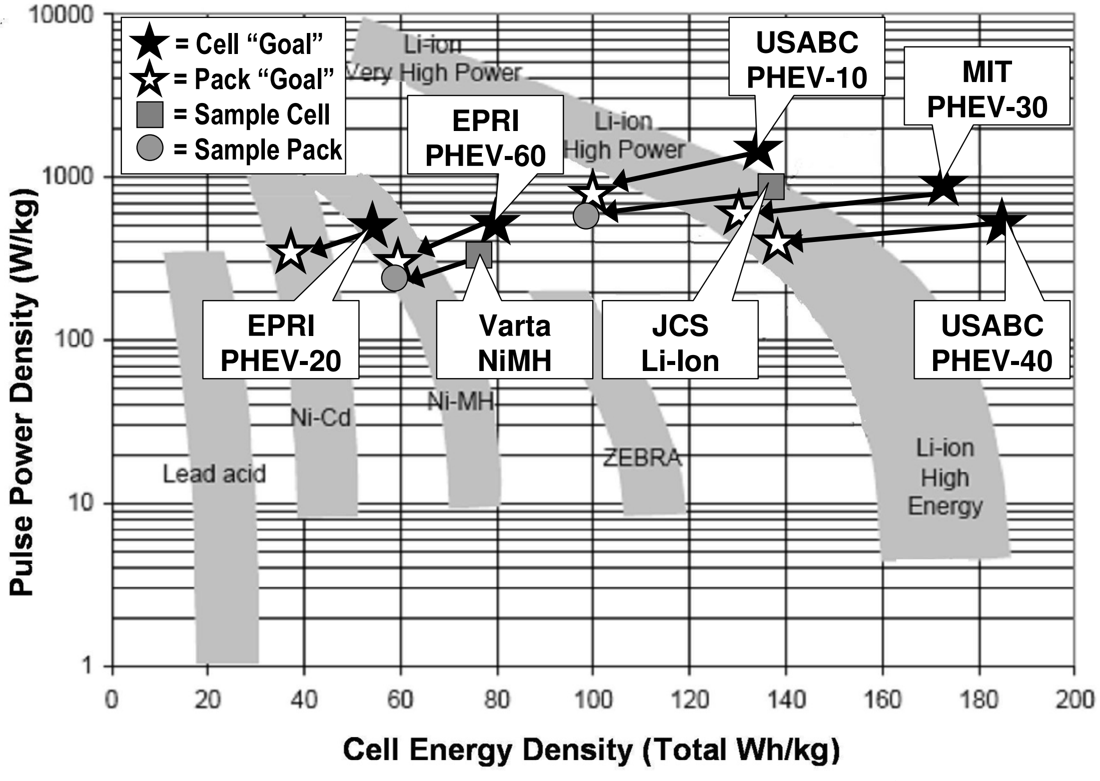
4.0 Battery Technologies

In this section we discuss two broad categories of battery chemistries: nickel-metal hydride (NiMH) and lithium-ion (Li-Ion). These and several other battery chemistries are compared in Figure 3 using Ragone plots modified from Kalhammer et al. (2007, p25). A Ragone plot represents the trade-offs between power density and energy density for a given battery chemistry. Power density (W/kg) is plotted on the vertical axis on a logarithmic scale. Energy density (Wh/kg) is presented on the horizontal axis for a specified discharge rate, say C/1 (complete discharge over 1 hour). The light grey bands present the present power and energy capabilities of lead-acid, nickel-cadmium, NiMH, ZEBRA, and Li-Ion chemistries. The curves represent the trade-offs inherent in designing batteries for high energy or high power applications. Onto Kalhammer et al.'s Ragone curves we have plotted USABC, MIT, and EPRI goals presented in the previous section (dark stars). The grey squares represent the performance of two prototype PHEV batteries tested by Kalhammer et al. (2007): one NiMH (Varta), and one Li-Ion (Johnston Controls Saft—JCS).

To understand Figure 3, we must make an important distinction between the performance attributes of a battery *pack* and an individual *cell*. The PHEV goals discussed in Section 3

(USABC, MIT, and EPRI) were reported for a battery *pack*. However, the values represented by the grey bands in Figure 3 are for an individual battery *cell* (which is common practice for Ragone plots). The battery *pack* (or system) designed for a particular PHEV consists of many individual battery cells, plus a cooling system, inter-cell connectors, cell monitoring devices and safety circuits. The added weight and volume of the additional components reduce energy and power density of the *pack* relative to the *cell*. In addition, the inter-cell connectors and safety circuits of a battery *pack* can significantly increase resistance, decreasing the power rating from that achievable by a single *cell*. Thus, when applying *cell*-based ratings to a battery *pack*, and vice versa, a *packaging factor* conversion must be applied. The packaging factor for energy density is the ratio between the combined weights of the *cells* to the weight of the entire battery *pack*. This factor varies across battery designs in the range of 0.6 to 0.8. There is typically a larger reduction for power density—and thus a smaller packaging factor—than energy density due to added resistance, in addition to the added weight.

Figure 3: Battery *Cell* Potential and PHEV “Goals” (Ragone Plots)



Source: Image of battery chemistry “Ragone” plots from Kalhammer et al. (2007, p25).

Notes: All “goal” and “sample” points added by current authors. Goals are from Table 2, sample data is from Table 3. Packaging factor assumed to be 0.75, except JCS Li-Ion points, which is actual data from Kalhammer et al. (2007, p29).

For illustration, see the grey circle and square representing JCS’s Li-Ion PHEV battery in Figure 3. A single cell has an energy density of 136 Wh/kg (grey square), while the entire battery pack has 94 Wh/kg (grey circle), yielding a packaging factor of 0.69. Similarly, the cell's power density of 794 W/kg is reduced to 540 W/kg for the pack, yielding a packaging factor of 0.68. To further emphasize the importance of this conversion, each battery goal in Figure 3 is reported as both *pack* level estimates (white stars) and *cell* level estimate (black stars), linked by an arrow. We assume an optimistic packaging factor of 0.75 for each conversion. Only the *cell* estimates (black stars) should be compared with the grey chemistry bands in Figure 3. Although we have taken efforts to clarify these distinctions, readers are cautioned that in much of the battery literature, cell and pack level values are not clearly distinguished.

The various PHEV goals in Figure 3 illustrate the implications for differing vehicle assumptions on battery performance goals—and resulting conclusions about chemistry capabilities. Whereas EPRI's analysis suggests the performance goals for an *all-electric* PHEV-20 is achievable by current NiMH technology, the goals of the USABC and MIT are beyond even current Li-Ion technology capabilities. In any case, it is clear that lead-acid, nickel-Cadmium (Ni-Cd) and sodium-nickel chloride (ZEBRA) technologies are not likely to achieve goals for even the less ambitious PHEVs. In contrast, Li-Ion battery technologies hold promise for achieving much higher power and energy density goals. Thus, it appears that while NiMH could be used for lower performance PHEV designs (e.g. *blended* operation with lower CD range), only a chemistry with the energy and power density capabilities of Li-Ion can meet USABC goals for PHEVs with *all-electric* range. NiMH and Li-Ion chemistries are further described next.

4.1 Nickel-Metal Hydride (NiMH)

NiMH batteries are used for most HEVs currently sold in the US. The primary advantage of this chemistry is its proven longevity in calendar and cycle life, and overall history of safety (Kalhammer et al., 2007). However, the primary drawbacks of NiMH are limitations in energy and power density, and low prospects for future cost reductions (Anderman, 2008). For illustration, Table 2 presents the attributes of one NiMH PHEV battery manufactured by Varta, as presented by Kalhammer et al. (2007, p38).[11] The Varta battery *pack* falls far short of the power density goals for USABC's PHEV-10 (15 versus 50 kW), as well as the available energy density goals of USABC's PHEV-40 (5.4 versus 9.0 kWh).

Although Table 2 only provides an illustrative snapshot of one NiMH battery technology, it does demonstrate power and energy limitations. More importantly, battery researchers generally report that because NiMH battery technology is reaching productive maturity, there is relatively little room for further improvement (Kalhammer et al., 2007; Kromer and Heywood, 2007; Anderman, 2008). Not only are energy and power densities unlikely to improve much further (due to limitations shown in Figure 3), but NiMH costs are not expected to drop much further with increased production. Kalhammer et al. (2007) estimate that at 100,000 units of production per year, NiMH battery prices may fall as

---

[11] The reported Varta battery weighs 35 kg. To facilitate comparison to USABC goals, we scaled the power and energy density values up to 60 kg (equivalent to USABC's PHEV-10 weight goal) and 120 kg (equivalent to USABC's PHEV-40 weight goal). For example, the reported energy density of the 35kg Varta battery pack (57 Wh/kg) was applied directly to a hypothetical 60 kg version of the battery, with total energy capacity of (0.057 kWh/kg)*(60 kg) = 3.4 kWh.

low as $530/kWh for a PHEV-10 and $350/kWh for a PHEV-40. These forecasts are far from reaching USABC's goals of $300/kWh and $200/kWh, respectively.

4.2 Lithium-Ion (Li-Ion)

In contrast to NiMH, Li-Ion technology has the potential to meet the requirements of a broader variety of PHEVs. Lithium is said to be very attractive for high energy batteries due to its lightweight nature and potential for high voltage, allowing Li-Ion batteries to have higher power and energy density than NiMH batteries (Kromer and Heywood, 2007). Table 2 illustrates the relative advantage of Li-Ion chemistry using a PHEV battery manufactured by JCS, as presented by Kalhammer et al. (2007, p29).[12] While still falling short of the ambitious power targets of the USABC's PHEV-10, and the energy targets of the PHEV-40, the JCS Li-Ion battery has more than double the power density and more than 50 percent greater energy density than the Varta NiMH battery.

Table 3: Illustration of NiMH Vs. Li-Ion PHEV Battery Technologies (*Pack*)

		PHEV-10			PHEV-40		
	Units	USABC Goals	Varta[1] Ni-MH	JCS[2] Li-Ion	USABC Goals	Varta[1] Ni-MH	JCS[2] Li-Ion
1) Basic							
Chemistry	type	--	NiMH	Li-Ion	--	NiMH	Li-Ion
Total Weight	kg	**60**	60	60	**120**	120	120
2) Power							
Peak Power	kW	**50**	15	32	**46**	30	65
Power Density	W/kg	**830**	250	540	**380**	250	540
3) Energy Capacity							
Available Energy	kWh	**3.9**	2.7	4.5	**12**	5.4	9.0
Total Energy (at 80% DOD)[3]	kWh	**4.9**	3.4	5.6	**15**	6.8	11
Total Energy Density[3]	Wh/kg	**82**	57	94	**125**	57	94
4) Life							
Calendar Life	years	**15**	N/D	> 12	**15**	N/D	> 12
Cycle Life	cycles	**5,000**	> 3000	> 3200	**5,000**	> 3000	> 3200

Source: Adapted from Kalhammer et al. (2007, p29 and p38)

Notes: [1] Scaled from 35 kg battery

[2] Scaled from 160 kg battery

[3] USABC values do not much up with Tables 1 and 2 because a 80% DOD was applied (instead of 70%) to be consistent with Varta and JCS batteries.

Again, more important than this illustrative snapshot is the long-term prospects for improvements to Li-Ion batteries. As portrayed in Figure 3, the potential power and

---

[12] The reported JCS battery pack weighs 160 kg. As we did with the Varta battery, the power and energy density values were scaled down to 60 kg (equivalent to USABC's PHEV-10 weight goal) and 120 kg (equivalent to USABC's PHEV-40 weight goal). For example, the reported power density of the 160 kg JCS battery pack (540 W/kg) was applied directly to a hypothetical 120 kg version of the battery, with total peak power of (0.54 kW/kg)*(120 kg) = 65 kW.

energy density of Li-Ion batteries are much higher than other chemistries, indicating there is more room for development. Also, Li-Ion battery costs are predicted to fall as low as $395/kWh for a PHEV-10 and $260/kWh for a PHEV-40, with 100,000 units of production (Kalhammer et al., 2007). Although still not sufficient to meet USABC's goals, such costs would be a substantial improvement over NiMH batteries. Note, however, that not all analysts are so optimistic about low costs; Anderman (2008) expects Li-Ion batteries to maintain costs around $600/kWh even with increased production.

Although Li-Ion batteries hold promise in power and energy density, and perhaps cost, Kalhammer et al. describe potential drawbacks in longevity and safety. High chemical reactivity provides a greater threat to calendar life, cycle life, and safety compared to NiMH batteries. For instance, sustained high rate or voltage overcharge and shorting have potential to trigger thermal runaway, cell venting, and even burning of the electrolyte solvent and graphite. Thus, Li-Ion batteries require a greater degree of control over cell voltage and temperature than do other battery chemistries (Kalhammer et al., 2007).

Technological advances appear to be overcoming longevity problems, as seen with the high calendar and cycle life of the JCS battery in Table 3. In addition, abuse testing of the JCS battery did not cause catastrophic failure (Kalhammer et al., 2007). Still, Anderman (2008) states that Li-Ion batteries remain far from being "proven" technologies for automotive applications. This statement was supported by Toyota's 2007 announcement to halt deployment of a Li-Ion battery for the next-generation Prius model (HEV) due to safety concerns, instead proceeding with an advanced NiMH battery (Shirouzu, 2007). Thus, safety and reliability remain relatively uncertain for Li-Ion batteries, and further development and testing is required before mass market launch is likely.

In summary, of the sample battery chemistries presented in Figure 3, as in Figure 2, Li-Ion technologies are most capable of meeting PHEV performance requirements. In particular, Li-Ion appears to be the *only* chemistry that is currently suited for more demanding PHEV designs, such as the *all-electric* PHEV-10 and PHEV-40 goals set by the USABC. NiMH batteries could play an interim role in less demanding blended-mode designs, but it seems likely that falling Li-Ion battery prices may preclude even this role. For these reasons, most current attention for PHEV battery development is on Li-Ion technologies. However, the Li-Ion development process is multi-directional, and the next section provides an illustrative discussion of several specific Li-Ion battery chemistries that are in various stages of development.

5.0 Li-Ion Prospects

Li-Ion batteries can be constructed from a wide variety of materials, allowing battery developers to pursue several different paths. Specific battery chemistries are typically named according to the material used for the positive electrode (cathode), although the negative electrode (anode) material can also be a distinguishing factor. Li-Ion battery designs also vary by electrolyte, packaging, structure and shape (Anderman, 2007). The main Li-Ion cathode material used for consumer applications (e.g. laptop computers and cell phones) is lithium cobalt oxide (LCO). However, due to safety concerns with using this chemistry for automotive applications, several alternative chemistries are being testing for PHEVs, including: lithium nickel, cobalt and aluminum (NCA), lithium iron phosphate (LFP), lithium nickel, cobalt and manganese (NCM), lithium manganese spinel (LMS), lithium titanium (LTO), and manganese titanium (MNS and MS).

Table 4 presents battery performance ratings from tests of three of these chemistries: LFP, NCM and LTO. The performance attributes among these batteries—as with batteries in general—yield tradeoffs between power and energy density, as well as safety and longevity (not shown in Table 4). The higher voltage batteries have higher energy density, and generally higher power density (although power is also affected by other design aspects). However, battery research is exploring newer chemistries with relatively low voltage (and energy and power density), such as LTO, due to goals for battery safety and longevity, despite reductions in performance.

Table 4: Comparison of Li-Ion Battery Performance (*Cell*)

Technology Type	Voltage Range (V)	Cell Energy Density (Wh/kg)	Cell Power Density (W/kg)
LFP – Iron Phosphate	3.6-2.5	90	1100
NCM – Nickel, Cobalt, Manganese	4.2-3.0	140	900
LTO - Titanium	2.8-1.5	70	700

Source: Testing by A. Burke at UC Davis, April 2008.

A broader summary of Li-Ion technologies is presented in Table 5 (page 19). Table 5 is intended solely as an *illustrative snapshot* of several key Li-Lion technologies, and not as an exhaustive or definitive analysis of the present state of the art or prospects for future development. Instead, these brief descriptions portray the complexity and variety of Li-Ion battery development, where the attributes of one particular technology may not represent Li-Ion technology in general. Consistent with the USABC goals described throughout this paper, Table 5 presents qualitative ratings of the five main attribute categories: power, energy, safety, life and cost attributes. We use a simple rating scale based on available literature: a rating of *poor* is far from reaching USABC goals in that category; a *moderate* rating shows some promise of meeting goals with further development; a *good* rating has shown evidence of being a good candidate to meet goals; and an *excellent* holds very strong promise of meeting USABC goals. Table 5 lists several manufacturers that are currently working with each class of battery chemistry; however, each manufacturer may follow different design strategies. Thus, it may be inappropriate to generalize our qualitative ratings for a given chemistry to all listed (or unlisted) manufacturers working with that chemistry. Our qualitative ratings are based only on the sources we explicitly cite in Table 5.

Table 5 further demonstrates the many inherent tradeoffs in battery development. A single battery has yet to meet all relevant USABC PHEV goals: power, energy, life, safety, and cost. For instance, higher power battery chemistries have higher open circuit voltage, which also reduces life and safety. Chemistries with increased life and safety tend to limit cell voltage, which reduces power and energy capacity. The challenge is to find an appropriate balance for a particular application.

We summarize the current literature on Li-Ion battery technologies as follows:

> **LCO:** Lithium cobalt oxide (LCO) is the most common Li-Ion chemistry for non-vehicle consumer applications, but is generally not suitable for automotive applications due to concerns with safety, longevity and cost (Kromer and Heywood, 2007; Chu, 2007). Toyota delayed the use of this chemistry in electric-drive development due to safety concerns (Shirouzu, 2007).
>
> **NCA:** Lithium nickel, cobalt and aluminum (NCA) is currently being tested by JCS, GAIA, Matsushita and Toyota. NCA batteries perform quite well in terms of power density, energy density and longevity (Kalhammer et al., 2007; Nelson, Amine and Yomoto, 2007). However, this technology faces limitations in safety and cost (Nelson, Amine and Yomoto, 2007).
>
> **LFP**: Lithium iron phosphate (LFP) chemistries are in testing stages with A123, Valence and GAIA. LFP technologies are thought to perform similar to NCA batteries, but with a higher degree of safety due to a more stable electrode material with less susceptibility to thermal runway and other threats (Nelson et al., 2007; Chu, 2007) and potential for lower costs (Kromer and Heywood, 2007; Kalhammer et al., 2007). However, Kromer and Heywood (2007) and Anderman (2007) note there are still energy density challenges for PHEV applications.
>
> **NCM:** Lithium nickel, cobalt and manganese (NCM) chemistries are being tested by Litcel, Kokam, and NEC Lamillion. Kalhammer et al. (2007) indicate that NCM has lower performance than NCA and LFP batteries in terms of power, energy, safety, and life. Testing at UC Davis suggests that the high voltage of NCM holds potential for high energy density (e.g. Table 4).
>
> **LMS:** Lithium manganese spinel (LMS) is currently in development stages with GS Yuasa, Litcel, NEC and EnerDel. Although this chemistry has limitations in power and energy density, it holds high potential for safety, longevity and low cost (Nelson et al., 2007; Kalhammer et al., 2007).
>
> **LTO:** Lithium titanium (LTO) is in development stages with Altairnano and Enerdel. LTO holds potential for high safety and longevity, but is limited in power, energy, and affordability (Kalhammer et al., 2007).
>
> **MNS/MN:** Manganese titanium (MNS and MS) chemistries are still in early research stages. These chemistries are thought to hold potential for excellent power, energy density, and safety, at moderate costs (Nelson et al., 2007).

Table 5: Illustrative “Snapshot” of Li-Ion PHEV Battery Chemistries

Name	Description	Electrodes: Positive (Negative)	Companies	Automotive Status	Power	Energy	Safety	Life	Cost
LCO	Lithium cobalt oxide	$LiCoO_2$ (Graphite)	Various consumer applications (not automotive)	Limited auto applications (due to safety)	Good[4]	Good[4]	Low[2,4], Mod.[3]	Low[2,4]	Poor[2,3]
NCA	Lithium nickel, cobalt and aluminum	$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$ (Graphite)	JCI-Saft[3] GAIA[3] Matsuhita[3] Toyota[6]	Pilot[1]	Good[1,3]	Good[1,3]	Mod.[1]	Good[1]	Mod.[1,3]
LFP	Lithium iron phosphate	$LiFePO_4$ (Graphite)	A123[3] Valence[5] GAIA	Pilot[1]	Good[1]	Mod.[2,6]	Mod.[1,2,4]	Good[1,4]	Mod.[1], Good[2,3]
NCM	Lithium nickel, cobalt and manganese	$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ (Graphite)	Litcel (Mitsubishi) [3] Kokam[3] NEC Lamillion[3]	Pilot[3]	Mod.[3]	Mod.[3], Good[7]	Mod.[3]	Poor[3]	Mod.[3]
LMS	Lithium manganese spinel	$LiMnO_2$ or $LiMn_2O_4$ ($Li_4Ti_5O_{12}$)	GS Yuasa[3] Litcel (Mitsubishi) [3] NEC Lamillion[3] EnerDel	Devel.[1]	Mod.[2]	Poor[1,2,3]	Excel.[1], Good[2]	Excel.[1] Mod.[6]	Mod.[2]
LTO	Lithium titanium	$LiMnO_2$ ($LiTiO_2$)	Altairnano[3] EnerDel	Devel.[3]	Poor[3], Mod.[7]	Poor[3]	Good[3]	Good [3]	Poor [3]
MNS	Manganese titanium	$LiMn_{1.5}Ni_{0.5}O_4$ ($Li_4Ti_5O_{12}$)		Research[1]	Good[1]	Mod.[1]	Excel.[1]	Unkwn.	Mod.[1]
MN	Manganese titanium	$Li_{1.2}Mn_{0.6}Ni_{0.2}O_2$ (Graphite)		Research[1]	Excel.[1]	Excel.[1]	Excel.[1]	Unkwn.	Mod.[1]

Sources:

[1] Nelson, Amine and Yomoto (2007, p2)

[2] Kromer and Heywood (2007, p37)

[3] Kalhammer et al. (2007)

[4] Chu (2007)

[5] Kohler (2007)

[6] Anderman (2007)

[7] UC Davis Testing

6.0 Conclusion

Using the USABC's goals for PHEV batteries, we have summarized the state of various battery technologies. Four main highlights can be drawn from this discussion. First, the battery “goals” or “requirements” for a PHEV are contingent on many assumptions. We compared the goals of the USABC to two alternative studies published by researchers from MIT and EPRI. The three sets of goals differ greatly based on different assumptions about CD range, CD operation (all-electric vs. blended), drive cycle, vehicle mass, battery mass, and other issues. The “true” requirements of PHEV technology will depend on consumers’ driving and recharging behaviors as well as their valuation of different PHEV designs and capabilities. In turn, producer and consumer behavior alike can be shaped by government regulation, e.g., California’s ZEV mandate. Thus, while the USABC (and others) provides a useful benchmark for the future of PHEV battery technology, there may be a role for less ambitious PHEV designs, such as *blended* PHEV conversions, as well as Toyota’s demonstration of a PHEV Prius using NiMH. In other words, it may not be necessary that USABC’s goals be met by a specific battery technology before the commercial production or success of PHEVs can occur. However, such advances *will* be required for more ambitious PHEV designs, if proved necessary for market acceptance, such as GM’s Volt concept, which is promised to offer 40 miles of *all-electric* range.

Second, battery development is constrained by inherent tradeoffs among the five main battery attributes: power, energy, longevity, safety and cost. No battery currently meets all of the USABC’s PHEV goals for these attributes. Increasing power density requires higher voltage that reduces longevity and safety and increases cost. Increasing energy density tends to reduce power density. Attempts to simultaneously optimize power, energy, longevity, and safety will increase battery cost. Readers must be careful to understand the complex trade-offs among these attributes and among battery technologies. Certainly we must avoid assembling the best performances from different battery technologies on different drive cycles in different vehicles as an indication of the current state of battery technology.

Third, in meeting the USABC’s PHEV battery design goals, Li-Ion chemistries are better suited than NiMH. Only Li-Ion can meet the high power and energy density goals specified by USABC for vehicles with *all-electric* driving in charge depleting mode. Although a PHEV designed to operate in *blended* mode will have lower power and energy density goals than the USABC goals, Li-Ion technologies are still superior to NiMH in potential for lower cost. However, despite Li-Ion’s potential, the technology is not yet firmly established for automotive applications, and development must overcome issues of longevity and safety—and the resulting tradeoffs with performance—in order to achieve commercial success.

Fourth, Li-Ion technology continues to follow multiple paths of development. Table 5 illustrates eight such directions, each using different electrode materials in efforts to optimize power, energy, safety, life, and cost performance. In particular, we must not generalize the attributes of one battery, e.g. Toyota’s concerns about safety with its LCO battery, to all Li-Ion batteries. Table 5 shows how these attributes can vary substantially among different chemistries. In addition, Table 5 also demonstrates the complexity and uncertainty of selecting a single technological “winner” among advanced automotive battery chemistries.

In summary, electric-drive interest groups, including researchers, policymakers, companies, advocates and critics, should be aware of these fundamental battery issues to facilitate more grounded debates about the present and future of electric-drive vehicles, including plug-in hybrid vehicles.

7.0 References

Anderman, M. (2007). *Gap Analysis for Li-Ion Batteries in Automotive Applications,* Advanced Automotive Batteries Conference 2007, Long Beach, California, May, 14-18, 2007.

Anderman, M. (2008). *PHEV: A step forward or a detour?* Presentation at SAE 2008 Hybrid Vehicle Technologies Symposium, San Diego, California, February 12-14, 2008.

CalCars (2008). *All About Plug-In Hybrids (PHEVs)*, http://www.calcars.org/vehicles.html (accessed April 17th, 2008).

California Air Resources Board – CARB (2003). Final Regulation Order: The 2003 Amendments to the California Zero Emission Vehicle Regulation, California Environmental Protection Agency. http://www.arb.ca.gov/regact/zev2003/fro.pdf (accessed May 9th, 2008).

California Air Resources Board – CARB (2008a). *ARB Passes New ZEV Amendment: Measures could produce 65,000 cleaner vehicles by 2012*, Press Release, March 27th, 2007, http://www.arb.ca.gov/newsrel/nr032708b.htm (accessed April 17th, 2008).

California Air Resources Board – CARB (2008b). *2008 Proposed Amendments to the California Zero Emission Vehicle Program Regulations,* Staff Report: Initial Statement of Reasons, February 8th, 2008, http://www.arb.ca.gov/regact/2008/zev2008/zevisor.pdf (accessed April 17th, 2008).

Chu, A. (2007). *Nanophosphate Lithium-Ion Technology for Transportation Applications*, 23rd International Electric Vehicle Symposium and Exposition (EVS-23), Anaheim, California, December 2-5, 2007.

Doughty, D. and C. Crafts (2005). *FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications*, Sandia National Laboratories, 2005-3123, June, 2005

Electric Power Research Institute – EPRI (2007). *The Power to Reduce* CO_2 *Emissions: The Full Portfolio*, Discussion Paper, Prepared for the EPRI 2007 Summer Seminar Attendees, August 2007.

Fahey, J. (2006). Remember the pinto? *Forbes*, 178(8), October 16th, 2006.

Graham et al., (2001). *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options* EPRI, Palo Alto, CA: 2001. 1000349, Duvall, M. et al., (2002). *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles*, EPRI, Palo Alto, CA: 2002. 1006892.

Gondor, J. and A. Simpson (2007). Measuring and Reporting Fuel Economy of Plug-In Hybrid Electric Vehicles, *WEVA Journal*, Vol.1.

Kalhammer, F.R., B.M. Kopf, D. Swan, V.P. Roan, and M.P. Walsh (2007). *Status and Prospects for Zero Emissions Vehicle Technology: Report of the ARB Independent Expert Panel 2007*, Prepared for State of California Air Resources Board, Sacramento, California, April 13 2007.

Kohler, M. (2007). *Lithium Phosphate Batteries used Successfully in PHEV Applications*, Advanced Automotive Batteries Conference 2007, Long Beach, California, May, 14-18, 2007.

Kromer, M. and J. Heywood (2007). *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*, LFEE 2007-03 RP. Sloan Automotive Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

Kurani, K., R. Heffner and T. Turrentine (2007). *Driving Plug-In Hybrid Electric Vehicles: Reports from U.S. Drivers of HEVs Converted to PHEVs, Circa 2006-2007*, Institute of Transportation Studies, University of California, Davis, October 16th, 2007.

Nelson, P., K. Amine, and H. Yomoto (2007). *Advanced Lithium-Ion Batteries for Plug-in Hybrid-Electric Vehicles,* 23rd International Electric Vehicle Symposium and Exposition (EVS-23), Anaheim, California, December 2-5, 2007.

Pesaran, A., T. Market, H. Tataria, and D. Howell (2007). *Battery Requirements for Plug-In Hybrid Electric Vehicles: Analysis and Rationale*, 23rd International Electric Vehicle Symposium and Exposition (EVS-23), Anaheim, California, December 2-5, 2007.

Shirouzu, N. (2007). Toyota Puts Off New Type of Battery for Next Prius, *The Wall Street Journal*, June 14th, 2007.

Turrentine, T. and K. Kurani (1996) *Advances in Electric Vehicle Technology from 1990 to 1995: The Role Of California's Zero Emission Vehicle Mandate*, EPRI Report TR-106274, February 1996.

8.0 Acronyms and Glossary

All-Electric Operation: A type of operation in charge-depleting (CD) mode that uses only grid electricity to power the vehicle.

Available Energy Capacity: The amount of energy (in kWh or kWh/kg) stored in a battery that can be used in regular operation. Equal to the *total* battery energy multiplied by the usable depth of discharge (DOD).

Blended Operation: A type of operation in charge-depleting (CD) mode that uses grid electricity *and* gasoline to power the vehicle—energy from the engine and the battery are "blended" together through the electro-mechanical drivetrain.

Calendar Life: The ability of the battery to withstand degradation over time, which may be independent of how much or how hard the battery is used.

CARB – California Air Resources Board: An environmental regulation agency in California.

CD Mode – Charge Depleting: Energy stored in the battery is used to power the vehicle, gradually *depleting* the battery's state of charge (SOC).

CD Range: The distance a PHEV can drive in charge depleting (CD) mode before switching to charge sustaining (CS) mode.

Cell: A single battery unit.

CS Mode – Charge Sustaining: The battery's state of charge (SOC) is *sustained* by relying primarily on the gasoline engine to drive the vehicle, only using the battery and electric motor to increase the efficiency of the gasoline engine (like an HEV).

Deep Cycle Life: The number of complete discharge-recharge cycles the battery can perform in charge-depleting (CD) mode.

DOD – (Usable) Depth of Discharge: The differences between the battery's maximum and minimum states of charge (SOC) – not usually equal to 100%.

Drive Cycle: A driving pattern used to test vehicle fuel economy, as well as battery performance, often made up of one or more *drive schedules*.

Drive Schedule: A driving pattern that simulates a particular driving pattern, such as city (UDDS) or highway (HWFET) driving.

Energy Density (Wh/kg): The amount of energy stored per kg of a battery *pack* or *cell*.

EPA – Environmental Protection Agency: A U.S. government agency whose goal is to protect human health and the environment.

EPRI – Electric Power Research Institute: A non-profit organization that conducts research and development on technology for the electric power sector.

EV – Electric Vehicle: An electric drive vehicle that is only powered by grid electricity.

HEV – Hybrid Electric Vehicle: An electric drive vehicle that is primarily powered by a heat engine (e.g. an internal combustion engine), but uses an electric motor and energy storage system (e.g. an advanced battery) to improve engine efficiency.

HWFET – Highway Fuel Economy Test Schedule: A drive schedule established by the EPA to simulate highway driving conditions.

ICE – Internal Combustion Engine: An engine that converts the energy in a fuel into motion through combustion.

JCS – Johnston Controls-Saft: A manufacturer of advanced batteries (among other things).

kW – Kilowatt: A measure of power (1000 watts), where 1 kW = 1.34 horsepower.

kWh – Kilowatt-hour: A measure of energy use or capacity, where 1 kWh = 1,000 Watts provided for 1 hour.

LCO – Lithiated Cobalt Oxide: A Li-Ion chemistry currently being explored for PHEV applications. Although very common in consumer applications, there are concerns with safety, longevity and cost.

LFP – Lithiated Iron Phosphate: A Li-Ion chemistry currently being explored for PHEV applications. In the testing stage, this chemistry uses a more stable electrode material and has potential for lower costs.

Li-Ion – Lithium Ion: A class of advanced battery using lithium-ion chemistry.

LMS – Lithium Manganese Spinel: A Li-Ion chemistry currently being explored for PHEV applications. Hold high potential for safety, longevity and low cost, but with limitations in power and energy density.

LTO – Lithiated Titanium: A Li-Ion chemistry currently being explored for PHEV applications. Holds potential for safety and longevity, but limited prospects for power, energy, and affordability.

MNS - Manganese Titanium: A Li-Ion chemistry currently being explored for PHEV applications. Still in early research stages and thought to hold potential for high power, energy and safety at moderate costs.

MS – Manganese Titanium: A Li-Ion chemistry currently being explored for PHEV applications. Still in early research stages and thought to hold potential for high power, energy and safety at moderate costs.

NCA – Lithiated Iron Phosphate: A Li-Ion chemistry currently currently being explored for PHEV applications. Performs well in power density, energy density and longevity, but faces limitations in safety and cost.

NCM – lithiated nickel, cobalt and manganese: A Li-Ion chemistry currently being explored for PHEV applications. Has potential for high energy density, but faces limitations in power, life, safety and cost.

NiMH – Nickel-Metal Hydride: A class of advanced battery using nickel-metal hydride chemistry. Generally has lower power and energy density than Li-Ion chemistries.

Pack: A battery system, made up of several *cells*, and potentially a cooling system, inter-cell connectors, cell monitoring devices, safety circuits, and other components not included at the *cell* level.

Packaging Factor: A factor used to convert the attributes of a battery *cell* to a battery *pack* (or vice versa). For energy capacity, this factor is the ratio between the combined weights of the *cells* to the weight of the entire battery *pack* (ranging from 0.6 to 0.8). The factor is typically smaller for converting power density.

Parallel Architecture: A PHEV drivetrain that allows a direct connection between the engine and the wheels, as well as between the engine and battery and motor via a generator. The vehicle can be powered by electricity and gasoline simultaneously, electricity only, or by gasoline only. The battery is charged from an electrical outlet, or by the gasoline engine via a generator (e.g. Toyota Prius PHEV conversions).

PHEV – Plug-In Hybrid Electric Vehicle: An electric drive vehicle that can be powered by a heat engine (e.g. an internal combustion engine), an electric motor using grid electricity (e.g. stored in a battery), or both.

Power Density (W/kg): The amount of power that can be provided per kg of battery *pack* or *cell*.

Ragone Plot: A plot showing energy density versus power density for batteries and other energy-storing devices.

Series Architecture: A PHEV drivetrain that powers the vehicle only by an electric motor using electricity from a battery. The battery is charged from an electrical outlet, or by the gasoline engine via a generator (e.g. GM's Volt concept)

Shallow Cycle Life: The number of shallow cycles (state of charge variation of only a few percent) the battery can perform in charge-depleting (CD) and charge-sustaining (CS) modes.

SOC – State of Charge: The ratio of energy currently stored in a battery to the battery's maximum capacity.

Total Energy Capacity: The amount of total energy (in kWh or kWh/kg) that can be stored in a battery. Not all of this energy is usable, as operation is limited to using the assigned depth of discharge (DOD) to preserve battery life and safety.

UDDS – Urban Dynamometer Driving Schedule: A drive schedule established by the EPA to simulate city driving conditions.

US06 – Supplemental Driving Schedule: A more aggressive, and potentially more realistic, drive schedule than UDDS or HWFET.

USABC – U.S. Advanced Battery Consortium: a partnership between the U.S. Department of Energy (DOE) and US auto companies.

ZEBRA: A sodium-nickel chloride battery.

ZEV – Zero Emission Vehicle: A vehicle that produces zero tailpipe emissions.