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PLUG-IN HYBRID ELECTRIC VEHICLE HEV SYSTEM AND CHARGING TECHNOLOGY EVALUATION

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PREFACE

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ABSTRACT

Enhancing battery selection for plug-in hybrid vehicles is complex. The battery must meet the vehicle's energy storage and peak power requirements and fit into the space available. Various economic factors and safety issues must also be considered. A number of cells and modules of several lithium-ion chemistries were tested. Test data are presented for nickel cobalt (nickelate), iron phosphate, and lithium titanate oxide in the electrodes. The energy density of cells using nickelate in the positive electrode had the highest energy density. Cells using iron phosphate in the positive electrode had energy density between 80-110 watt hours per kilogram, and those using lithium titanate oxide in the negative electrode had energy density between 60-70 watt hours per kilogram. The power capability of the different chemistries was not as clear due to the energy density/power capability trade-offs inherent in battery design.

The combination of batteries and ultracapacitors can deliver high power and high energy, which is attractive for plug-in hybrid electric vehicles. This research modeled various combinations of advanced batteries and ultracapacitors in plug-in hybrid electric vehicles and compared performance against batteries alone. Vehicle performance improved using ultracapacitors. Results indicated that ultracapacitor batteries with a wide range of power characteristics could be used in plug-in hybrid electric vehicles and electric vehicles without sacrificing vehicle performance or subjecting the batteries to high stress that may shorten their life.

The high cost of batteries is one of the primary barriers to commercializing plug-in electric vehicles. There is considerable interest in secondary use of vehicle batteries after they are no longer suitable for use in vehicles. The primary barrier to implementing secondary use was demonstrating the economic viability in terms of the battery cost to second owners and guarantees that the used batteries would have satisfactory calendar and cycle life.

Keywords: Plug-in hybrids, lithium batteries, second-use, fast charging, simulations, PHEV, battery chemistry comparisons

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EXECUTIVE SUMMARY

Introduction

Plug-in hybrid-electric vehicles (PHEVs) are becoming increasingly available and the market for these vehicles is expected to grow significantly over the next several years. The key issue in the design of a PHEV is selecting the battery. The consensus view is that the battery will be of the lithium-ion type, but which of the lithium-ion chemistries to use is still a major question. The selection depends on a number of factors: useable energy density, useable power density, cycle and calendar life, safety (thermal stability), and cost. Another promising approach for PHEVs is combining batteries and ultracapacitors, which should be able to deliver high power and high energy. PHEV batteries also store a significant amount of energy, and information is needed on the viability of reusing these batteries for secondary applications once they can no longer be used in PHEVs.

Project Purpose

The goals of this project were characterizing the performance of lithium-ion batteries of various chemical chemistries for use in PHEVs, conducting simulations of PHEVs using advanced lithium batteries and ultracapacitors on various driving cycles, and examining potential secondary uses for PHEV batteries.

Project Results

The lithium-ion chemistry used in consumer electronics is the most developed. The chemistry involves carbon/graphite in the negative electrode and nickel cobalt and other metal oxides in the positive electrode. This chemistry yields the best performance (energy density and power density) but also has the greatest uncertainty concerning safety. The other chemistries being developed (iron phosphate in the positive and lithium titanate in the negative) have less favorable performance but also have less safety concerns and longer cycle life. This study evaluated these alternative chemistries were in detail.

Test data are presented for lithium-ion cells and modules using nickel cobalt, iron phosphate, and lithium titanate oxide in the electrodes. Cells with $NiCoO_2$ (nickelate) in the positive electrode had the highest energy density, in the range of 100-170 watt hours per kilogram (Wh/kg). Cells using iron phosphate in the positive electrode had energy densities between 80-110 Wh/kg, and those using lithium titanate oxide in the negative electrode had energy densities between 60-70 Wh/kg. The power density ranges varied significantly, even for a given chemistry. It is possible to design high-power batteries (500-1,000 W/kg at 90 percent efficiency) for all the chemistries if one is willing to sacrifice energy density and likely cycle life. The data indicated that high power iron phosphate cells could be designed without a significant sacrifice in energy density. When lithium-ion batteries have power densities greater than 2,000 W/kg, it is for low-efficiency pulses. For example, for an efficiency of 65 percent, the 15 Ampere hour (Ah) EIG iron phosphate battery had a pulse power of 2,330 W/kg rather than the 919 value for a 90 percent efficient pulse.

Cycle life data were not considered in this study. However, cell cycle life data reported by energy storage system provider Altairnano for its cells using lithium titanate oxide in the

negative electrode indicated cycle life in excess of 5000 cycles for charge and discharge rates of two and greater. It seemed likely that the cycle life of both titanate oxide and iron phosphate lithium batteries would be satisfactory for vehicle applications.

The cost of lithium batteries was high ($500-1000 /kWh) when purchased in relative small quantities. However, detailed cost modeling of batteries done at Argonne National Laboratory for the various chemistries indicated high production volumes (greater than 100,000 packs per year) for all chemistries can be in the range of $250-$400/kWh depending upon the battery size (kWh energy stored). The lithium titanate chemistry was projected to have the highest cost and the longest cycle life.

Research and development (R&D) efforts were continuing to increase the energy density of lithium-ion batteries. Prototype cells using layered metal oxides/spinels in the positive electrodes have energy densities in the range of 250-300 Wh/kg. Higher energy densities appeared to be likely when combining these electrodes with negative electrodes using composites of silicon oxides and carbon. R&D on electrically rechargeable zinc-air cells was also in progress. Energy densities in the range of 300-400 Wh/kg and 700-1000 volumetric energy density (Wh/L) appeared to be possible using the zinc-air chemistry. The power capability of these advanced batteries was uncertain.

It has been recognized for a number of years that combining batteries and ultracapacitors can offer advantages in PHEVs. Ultracapacitor refers to an electric double-layer capacitor that has an unusually high energy density when compared to common capacitors. Ultracapacitors can deliver very high power and respond in fractions of a second, but have limited storage capacity (100-200 Wh). Batteries have lower power capability but with high energy density can store relatively large kilowatt hours (kWh) of energy.

Ultracapacitors in PHEVs combined with high-energy-density lithium-ion and zinc-air batteries were simulated on various driving cycles in both the charge depleting and charge sustaining modes of vehicle operation. Battery energy density and power capability characteristics were assumed for use in new vehicle simulation models that included battery/ultracapacitor combinations for energy storage (two-energy storage systems and associated control strategies). The control strategies resulted in load leveling the batteries and the ultracapacitors accepting all the regenerative braking energy. The total weights of the cells in the lithium-ion batteries were 20-22 kg and in the zinc-air battery, 32 kg. The cell weight of the ultracapacitors was 20 kg. The all-electric ranges using the lithium batteries and the zinc-air battery were 20 miles and 40 miles, respectively.

Simulations were performed for the federal urban driving cycle (FUDS), Federal Highway, and US06 driving cycles with the PHEVs operating in both the charge depleting and charge sustaining modes. The US06 driving cycle was designed to test the exhaust emissions of vehicles at high speeds and aggressive driving conditions and is run at ambient temperature conditions of 68 degrees Farenheit (°F) to 86°F. The PHEVs were able to operate in the all-electric mode until the battery state of charge (SOC) equaled 30 percent on the FUDS and Federal Highway driving cycles using the batteries in combination with the ultracapacitors. The

vehicle had blended operation in the charge depleting mode in all cases for the US06 driving cycle.

The effects of load leveling of the power demand from the batteries using the ultracapacitors was clearly evident in the simulation results. Both the average currents and the peak currents from the batteries were lower by a factor of two to three using the ultracapacitors. The minimum voltages of the batteries were significantly higher using the capacitors and the voltage dynamics (fluctuations) were dramatically reduced, which reduced the stress on the battery and the resultant heating.

The simulation results indicated that by using ultracapacitors, batteries with a wide range of power characteristics could be used in PHEVs and electric vehicles (EVs) without sacrificing vehicle performance and subjecting the batteries to high stress and shorter life. This could be especially important in the future as high-energy-density batteries such as zinc-air and possibly lithium-air are developed.

PHEVs use batteries that store a significant amount of energy and thus offer the possibility of secondary use in utility-related applications such as residential and commercial backup systems and solar and wind generation systems. Cell tests on the performance of lithium-ion batteries of several chemistries suitable for use in PHEVs were conducted and these data were included in this report. The energy densities of cells using NiCo (nickelate) in the positive electrode had the highest energy density, in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive electrode had energy density between 80-110 Wh/kg, and those using lithium titanate oxide in the negative electrode had energy densities between 60-70 Wh/kg. Tests were performed for charging rates between one and six. The test results indicated that both iron phosphate and titanate oxide battery chemistries can be fast charged. However, the fast charge capability of the titanate oxide chemistry was superior to that of the iron phosphate chemistry with respect to both temperature rise during charging and the Ah capacity retention for charging up to the maximum voltage without taper.

The researchers concluded that there were a number of possible second-use applications for these batteries. Some of these applications were closely linked to utility operations, and others were connected to commercial and residential end-users. These applications were well suited for second use since the energy storage and power requirements for the end-user applications were comparable to those of the original vehicle applications and would require only minor reconfiguring of the packs. The applications closely related to utility operations did not seem well suited for second use. Those applications required megawatt (MW) power and megawatt hours (MWh) of energy storage, which were orders of magnitude larger than that of the vehicle applications. The primary barrier to implementing secondary use of PHEV batteries was demonstrating the economic viability in terms of the battery cost to second owners and guarantees that the used batteries would have satisfactory calendar and cycle life.

Project Benefits

Technology advancements in the chemistry of batteries used for PHEVs will help increase their market penetration. PHEVs benefit Californians by decreasing the use of gasoline-powered vehicles, which reduces vehicle emissions that produce air pollution.

CHAPTER 1:
Performance Characteristics of Lithium-ion Batteries of Various Chemistries for Plug-in Vehicles

1.1 Introduction

It is well recognized that the key issue in the design of a plug-in hybrid-electric vehicle is the selection of the battery. The consensus view is the battery will be of the lithium-ion type, but which of the lithium-ion chemistries to use is still a major question. The selection will depend on a number of factors: useable energy density, useable power density, cycle and calendar life, safety (thermal stability), and cost. The most developed of the lithium-ion chemistries is that used in consumer electronics – that is carbon/graphite in the negative electrode and nickel cobalt and other metal oxides in the positive electrode. That chemistry yields the best performance (energy density and power density), but also has the greatest uncertainty concerning safety. The other chemistries (iron phosphate in the positive and lithium titanate in the negative) being developed are known to have less favorable performance, but less concern regarding safety and longer cycle life. These latter chemistries have been evaluated in detail in the present study.

A number of companies world-wide are presently developing lithium-ion batteries utilizing the various electrode chemistries. Most of these companies are relatively small and are not well known in the battery business, but nevertheless their technologies are representative of the possibilities for the development of the emerging battery technologies. Hence a strong effort was made to obtain cells from a number of these companies for testing and evaluation. Reasonable success was achieved in obtaining lithium-ion cells from a number of sources for testing. This paper is concerned with analyzing the performance of the various cells/chemistries based on testing of the cells. In addition, simulation results are presented for a plug-in Prius-type vehicle using different battery technologies and their suitability for use in plug-in hybrids assessed.

1.2 Lithium-Ion Battery Chemistries

The lithium-ion battery technology used for consumer electronics applications is reasonably mature and in 2008 over one billion, small (18650) what is this number? cells were manufactured and sold. These cells utilized graphite/carbon in the negative and nickelate (LiNiCoAlO) in the positive. This is the baseline chemistry with which the other emerging chemistries are compared. The graphite/nickelate chemistry yields cells with the highest energy density and power capability of the chemistries being developed for vehicle applications primarily because the cell voltage and the specific charge (mAh/gm) of the positive electrode material are higher than for the other chemistries. The material and cell characteristics of the various chemistries are shown in Table 1. If performance of the cell was the only consideration, there would be little interest in developing cells/batteries with the other chemistries. However, cycle life and safety (thermal stability) as well as cost are important considerations in selecting batteries for vehicle applications. Unfortunately the graphite/nickelate chemistry has shown in

the consumer electronics applications to have safety and cycle life limitations, which can become even more serious for the large cells/batteries needed for vehicle applications. Hence development is underway using lithium manganese spinel and iron phosphate for the positive electrodes and lithium titanate oxide for the negative electrode. As indicated in Table 1, these chemistries have significantly lower performance than the graphite/nickelate chemistry, but longer cycle life and higher thermal stability. It is more difficult to compare the power capability of the different chemistries, because there is the inherent trade-off between energy density and power capability via the design of the electrodes and choice of material properties (primarily particle size and surface area). Nevertheless, the cells with the higher cell voltage tend to have higher power capability. The goal of the developments of the other chemistries is to minimize the penalty in performance without significant sacrifice of the inherent advantages of the respective emerging chemistries.

Most of the cells for the consumer electronics applications are spiral wound packaged in a rigid container. Some cells are prismatic (thin, flat) in shape, but they are also packaged in a rigid container. All these cells (Figure 1) are small (1-3 Ah) and can be used in vehicle applications only if larger cells/modules are assembled by placing many of the small cells in parallel. This can be done, but it requires special attention to safety issues. For vehicle applications, larger cells (up to 100 Ah) are being developed so it is not necessary to assemble parallel strings of the cells in the modules. In all cases, the modules consist of a number of cells in series to attain a reasonably high module voltage. In some cases, the larger cells (Ah > 10 Ah) are packaged in a soft laminated pouch (Figure 2), which are then placed in a rigid container to form a high voltage module. Some of the larger cells are spiral wound (Figure 3), but the trend in cell development seems to be toward soft packaging. Whether this proves to be a wise trend remains to be seen as there are strong, well founded concerns about the robustness and reliability of the soft packaging for vehicle applications.

Table 1: Characteristics of Lithium-ion Batteries Using Various Chemistries

Chemistry Anode/cathode	**Cell voltage ax/nom.**	**Ah/gmAnode/cathode**	**Energy density Wh/kg**	**Cycle life(deep)**	**Thermal stability**
Graphite/ $NiCoMnO_2$	4.2/3.6	.36/.18	100-170	2000-3000	fairly stable
Graphite/Mn spinel	4.0/3.6	.36/.11	100-120	1000	fairly stable
Graphite/ $NiCoAlO_2$	4.2/3.6	.36/.18	100-150	2000-3000	least stable
Graphite/iron phosphate	3.65/ 3.25	.36/.16	90-115	>3000	stable

Chemistry Anode/cathode	Cell voltage ax/nom.	Ah/gmAnode/cathode	Energy density Wh/kg	Cycle life(deep)	Thermal stability
Lithium titanate/Mn spinel	2.8/2.4	.18/.11	60-75	>5000	most stable

Figure 1: Small Spiral Wound Cells

Figure 2: Pouch Packaged

Figure 3: Spiral Wound Large Cells

44 Ah cell 7.5 Ah

1.3 Battery Testing

Test Procedures and the Batteries Tested

For each of the cells/modules, the following tests were performed:

- Constant current tests starting at C/1 and up to currents at which the Ah capacity of the cell begins to show a significant decrease with rate.
- Constant power tests starting at about 100 W/kg and up to powers (W/kg) at which the energy density (Wh/kg) begins to show a significant decrease with rate.
- 5 sec pulse tests at high currents (5-10C) at states of charge between 90 percent -10 percent to determine the open-circuit voltage and resistance from which the power capability of the cells can be calculated.

The power capability of the cells/modules was determined in the present study by determining the open-circuit voltage and resistance as a function of state-of-charge and calculating the pulse power using the following equation:

$$P = Eff\ (1-Eff)\ Voc\ 2\ /R$$

where Eff is the pulse efficiency, Eff= Vpulse /Voc

The power density is simply calculated as P/battery weight or volume. This method is not too different from that given in the USABC test manual for PHEV batteries and can be applied for cells/modules independent of the vehicle in which they would be used.

The cells tested in the present study are listed in Table 2. As indicated in Table 3, modules were available for some of the batteries. Testing of the modules is still in progress. Photographs of a few of the cells and modules are shown in Figures 1- 4.

Figure 4: Lithium-ion Battery Modules for Testing

V, 50 Ah modules from Altairnano

24

70V modules from EIG

Table 2: Batteries Tested -Manufacturers, Technology, and Characteristics

Manufacturer	Technology type	Ah	Voltage range	Weight kg/Volume L
K2	Iron phosphate	2.4	3.65-2.0	.083/.035

EIG	Iron phosphate	10.515.7	3.65-2.0	.325/.13.424/--
A123	Iron phosphate	2.1	3.6-2.5	.07/--
Lishen	Iron Phosphate	10.2	3.65-2.0	----
EIG	Graphite/ Ni CoMnO2	18	4.2-3.0	.45/--
GAIA	Graphite/LiNiCoO2	42	4.1-3.0	.32/--
Quallion	Graphite/Mn spinel	1.82.3	4.2-3.0	.043/.017.047/.017
Altairnano	Lithium Titanate	1152	2.8-1.5	.34/--1.6/--
EIG	Lithium Titanate	12.0	2.7-1.5	

Table 3: Lithium-ion Battery Modules Available for Testing

Chemistry Anode/cathode	Developer	Voltage	Ah	ResistancemOhm	Weightkgpack.fact.	VolumeLPack.fact.
Nickel Cobalt	EIG	72	20	60	13.4.67	11.3.41
Iron Phosphate	EIG	74	14	55	13.6.69	11.3.34
Lithium titanate	Altairnano	16V	11	2	16.3----	11.4----
Lithium titanate	Altairnano	24V	50	10	21.4.75	12.6

Test Data for Selected Cells and Modules

Detailed data were taken for all the cells listed in Table 2. Selected data for some of the cells are shown in Tables 3 through 8 as illustrations of the performance of the iron phosphate and lithium titanate oxide cells.

Table 4: Data for the 15 Ah EIG Iron Phosphate Cell

Iron Phosphate				
FO 15A	Weight .424kg	3.65-2.0V		
Power (W)	W/kg	Time (sec)	Wh	Wh/kg
62	142	2854	49.5	117
102	240	1694	48.0	113
202	476	803	45.1	106
302	712	519	43.5	103
401	945	374	41.7	98
Current (A)	Time (sec)	Ah	Crate	ResistancemOhm
15	3776	15.7	.95	
30	1847	15.4	1.95	2.5
100	548	15.2	6.6	

200	272	15.1	13.2	
300	177	14.8	20.3	

Table 5: Test Data for the Altairnano 11Ah lithium Titanate Oxide Cell

Constant Current Test Data (2.8-1.5V)

I(A)	nC	Time (sec)	Ah	Resistance mOhm
10	.8	4244	11.8	--
20	1.7	2133	11.9	--
50	4.5	806	11.2	2.2
100	9.2	393	10.9	2.1
150	15.3	235	9.8	--
200	---	116	6.4	--

Resistance Based on 5 Sec Pulse Tests

Constant Power Test Data (2.8-1.5V)

Power W	W/kg	Time sec	nC	Wh	Wh/kg
30	88	2904	1.2	24.2	71.2
50	147	1730	2.1	24.0	70.7
70	206	1243	2.9	24.2	71.0
100	294	853	4.2	23.7	69.7
150	441	521	6.9	21.7	63.8
170	500	457	7.9	21.6	63.5
260	764	255	14	18.4	54.2
340	1000	103	35.0	9.7	28.6

Mass: .34 Kg

Constant Current Discharges (2.8-1.5V)

Table 6:Test Data for the Altairnano 50Ah Lithium Titanate Oxide Cell

Current A	nC	Time sec	Ah	Resistance mOhm
50	.96	3773	52.4	
100	1.95	1847	51.3	1.0
200	4.0	904	50.2	.95
300	6.1	588	49.0	1.0

Constant Power Discharge (2.8-1.5V)

Power W	W/kg	Time sec	nC	Wh	Wh/kg
100	62	3977	.9	111	69
200	125	1943	1.85	108	67
300	188	1244	2.9	102	64
400	250	849	4.2	94	59
500	313	636	5.66	88	55
600	375	516	7.0	86	54

Weight: 1.6 kg

The resistance of the cells was determined from pulse tests performed at various states-of-charge. Pulse data for the EIG iron phosphate and NiCo cells are shown in Tables 6 and 7. A comparison of the power characteristics of the NiCo and iron phosphate cells is given in Table 8.

Table 7: Pulse Characteristics of the EIG 20Ah Nico Cell at Various States-of-Charge

Voc	DOD %	$V_{2\ sec}$	Effic. %	R mOhm	Power W	W/kg
4.12/250A	0	3.33	80.8	3.16	833	1850
3.98/250A	10	3.24	81.4	2.96	810	1800
3.88/250A	20	3.14	80.9	2.96	785	1744
3.78/250A	30	3.06	81.0	2.88	765	1700
3.72/250A	40	2.98	80.1	2.96	745	1655
3.67/250A	50	2.90	79.0	3.08	725	1611

3.63/250A	60	2.84	78.2	3.16	710	1578
3.59/250A	70	2.74	76.3	3.4	685	1522
3.54/100A	80	3.18	89.8	3.6	318	706
3.48/100A	90	2.96	85.1	5.2	296	658

Table 8: Pulse Characteristics of the EIG 14Ah Iron Phosphate Cell At

Voc	DOD %	$V_{2\ sec}$	Effic. %	R mOhm	Power W	W/kg
3.45/75A	0	3.08	89	4.9	231	711
3.3/75A	10	3.02	91.5	3.73	227	698
3.28/75A	20	3.0	91.5	3.73	225	692
3.26/75A	30	2.98	91.4	3.73	224	689
3.25/75A	40	2.96	91.0	3.87	222	683
3.25/75A	50	2.94	90.5	4.13	220	679
3.24/75A	60	2.91	89.8	4.4	218	672
3.21/75A	70	2.85	88.8	4.8	214	658
3.17/75A	80	2.74	86.4	5.7	206	632
2.58/75A	90	2.06	79.8	6.9	155	475

Table 9: Comparisons of the Power Characteristics of the EIG Nico And

90% Efficiency					80% Efficiency	
Cell	Wh/kg at C/1	10% DOD	80% DOD		10% DOD	80% DOD
NiCo20Ah	140	1056 W/kg	696 W/kg		1875 W/kg	1238 W/kg
Iron phosphate 14 Ah	90	808 W/kg	488 W/kg		1437 W/kg	670 W/kg

Test data for a 16V module of the Altairnano 11Ah cells are shown in Table 9. The characteristics of the module follow directly from the characteristics of the 11Ah cells.

Constant Current Discharge (8 Cells in Parallel, 6 in Series)

Table 10: Test Data for the Altairnano 16V Module

I(A)	Time (sec)	nC	Ah	Resistance mOhm
50	6908	.52	95.9	
100	3419	1.05	95.0	
200	1704	2.11	94.7	1.95
300	1113	3.23	92.8	2.0
400	833	4.32	92.6	2.0

Cell Mass: 16.3 Kg, Resistance Based on 5 Sec Pulses of the Module

90% Efficiency Pulse: 11.5 Kw, 706 W

Constant Power Discharges

Power (W)	(W/kg) cells	Time (sec)	kWh	(Wh/kg)cells
1000	61	4576	1.27	77.9
1500	92	2975	1.24	76.1
2000	122	2217	1.23	75.5
2500	250	1756	1.22	75.0
3000	184	1459	1.22	75.0
3500	215	1221	1.19	73.0
3600	221	1222	1.22	75.0

Charge at 88A to 16.3, Discharge from 16.3 to 9V

1.4 Comparisons of the Performance of Lithium-ion Cells of the Different Chemistries from Various Battery Developers

A summary of the data for the different chemistries is shown in Table 10. It is clear from the table that both the energy density and power capability of the cells vary over a wide range and that there are significant trade-offs between energy and power with all the chemistries. Energy density and power capability are discussed separately the following sections.

1.4.1 Energy Density

It is clear from Table 10 that the energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the negative electrode can have energy density between 60-70 Wh/kg. Hence in terms of energy density, the rankings of the different chemistries are clear and the differences are significant: 1. NiCo, 2. iron phosphate, 3. lithium titanate oxide. The question of what fraction of the energy density is useable in a specific vehicle application could decrease the relative advantage of the different chemistries.

Table 11: Summary of the Performance Characteristics of Lithium-ion Cells of Different Chemistries from Various Battery Developers

Manufacturer	Technology type	Ah	Voltage range	Wh/kg at 300 W/kg	$(W/kg)_{90\%eff.}$ 50% SOC
K2	Iron phosphate	2.4	3.65-2.0	86	667
EIG	Iron phosphate	10.515.7	3.65-2.0	83113	708919
A123	Iron phosphate	2.1	3.6-2.5	88	1146
Lishen	Iron Phosphate	10.2	3.65-2.0	82	161
EIG	Graphite/ Ni CoMnO2	18	4.2-3.0	140	895
GAIA	Graphite/LiNiCoO2	42	4.1-3.0	94	1742at 70%SOC
Quallion	Graphite/Mn spinel	1.8	4.2-3.0	144	491at 60%SOC
		2.3	4.2-3.0	170	379at 60%SOC
Altairnano	Lithium Titanate	1152	2.8-1.5	7057	684340
EIG	Lithium Titanate	12.0	2.7-1.5	43	584

1.4.2 Power Capability

The situation regarding the power capability (W/kg) of the different chemistries is not as clear as was the case for energy density because of the energy density/power capability trade-offs inherent in battery design. Further the question of the maximum useable power density is also application specific. In order to have a well-defined basis for comparing the different chemistries and cells, the power density (W/kg) for a 90 percent efficient pulse at 50 percent SOC is shown in Table 10 for most of the cells. The power densities can vary over a wide range even for a given chemistry. This is particularly true for the graphite/NiCoMn chemistry. In general, it seems possible to design high power batteries (500-1000 W/kg at 90 percent efficiency) for all the chemistries if one is willing to sacrifice energy density and likely also cycle life. The data in Table 10 indicate that high power iron phosphate cells can be designed without a significant sacrifice in energy density. When power densities greater than 2000 W/kg for lithium-ion batteries are claimed, it is for low efficiency pulses. For example, for an efficiency of 65 percent, the 15Ah EIG iron phosphate battery has a pulse power of 2330 W/kg rather than the 919 value for a 90 percent efficient pulse.

1.5 Considerations for Selecting Batteries/Energy Storage for Plug-in Hybrid Vehicles

The selection of the battery for plug-in hybrid vehicle is complicated process and depends on many factors. In simplest terms, the battery must meet the energy storage (kWh) and peak power (kW) requirements of the vehicle and fit into the space available. In addition, the battery must satisfy the cycle life requirements both for deep discharge cycles in the charge depleting mode and shallow cycling in the charge sustaining mode of operation. Further the battery unit must be designed to meet the thermal management, cell-to-cell monitoring, and safety requirements. The final considerations are concerned with the initial and life cycle costs of the battery.

This paper has dealt in detail with the performance of the lithium-ion batteries using different chemistries. Even though electrode chemistry has a significant effect on the performance of the battery, these differences alone are far from sufficient for selecting a battery for a PHEV. The other factors – cycle life and the effect on cycle life of depth-of-discharge, safety and thermal issues, and cost can be critical in influencing battery selection.

As indicated earlier in the paper, a primary reason for the present development of lithium-ion batteries of various chemistries is related to safety issues with the batteries using NiCo and other metal oxides in the positive electrode. There have been some instances in which those cells/batteries have experienced thermal runaway events and as a result, the NiCo based battery systems are treated with considerable caution. They incorporate extensive cell monitoring circuitry as protection against possible destructive thermal events.

Cells using iron phosphate in the positive electrode are thought to be much less prone to thermal runaway both because they are less energetic (significantly lower energy density) and do not produce oxygen on overcharge which can react exothermically with the graphite in the negative electrode. Cells using lithium titanate oxide (LTO) in the negative are even less

energetic (lower energy density) than cells using iron phosphate and in addition the LTO replaces the graphite in the negative electrode removing a combustible substance in the cell. Hence both the iron phosphate and lithium titanate chemistries are inherently safer than the NiCo chemistry.

Another important issue in evaluating lithium-ion battery chemistries is cycle life and calendar life. In a plug-in hybrid vehicle, a battery life of at least ten years is thought to be necessary. This means that the battery must be able to sustain about 3000 deep discharge cycles in the charge depleting mode and several hundred thousand shallow cycles at low states-of-charge in the charge sustaining mode. Hence a PHEV battery must have the life cycle characteristics of an EV battery and a HEV battery. Whether any of the lithium battery chemistries can meet these life cycle requirements has not yet been determined.

It is expected that both the iron phosphate and lithium titanate chemistries will have significantly longer cycle life than the NiCo chemistry. This is especially true of the lithium titanate chemistry. Life cycle testing of cells done by Altairnano as part of their development program have indicated a very long cycle life of greater than 5000 cycles even for fast charge and discharge rates (Reference 1).

Little information is available on the relative cost ($/kWh) of lithium-ion batteries of the different chemistries. Further it is difficult to get good information on the costs of the various materials used in the batteries. If such information were available, it is relatively simple to estimate the differences in the electrode material costs for the different chemistries. This could be done using the following equation to estimate the $/Wh for each chemistry:

$$\$/Wh = \{[(\$/gm)/Ah/gm]\ anode + [\$/gm)/Ah/gm]cathode\ \}/\ Vnom.$$

Values for the Ah/gm and Voc are given in Table 1. Calculated values for the electrode material costs ($/kWh) are shown in Table 11 for the assumed unit costs of the various materials. The material unit costs used in the calculations are based on inquiries made of several sources involved with the manufacture of lithium batteries (References 2 and 3). The results shown in Table 12 indicates the relative electrode material costs of the various chemistries and also that electrode material costs should not dominate the total battery cost. Note that in general the higher cost lithium battery chemistries have the potential for longer cycle life which on a life cycle cost basis can compensate for the higher initial cost of those chemistries. This is especially true of the lithium titanate chemistry.

Table 12: Relative Electrode Material Costs for Various Lithium Battery Chemistries

Chemistry Anode/cathode	Cell voltageMax/nom.	Electrode material $/kgAnode/cathode	Electrode material cost $/kWh	Cycle life(deep)
Graphite/ $NiCoMnO_2$	4.2/3.6	12/25	48	2000-3000
Graphite/Mn	4.0/3.6	12/8	30	1000

spinel				
Graphite/ $NiCoAlO_2$	4.2/3.6	12/25	48	2000-3000
Graphite/iron phosphate	3.65/ 3.25	12/20	49	>3000
Lithium titanate/Mn spinel	2.8/2.4	25/8	88	>5000

1.6 Plug-in Hybrid Vehicle Simulations Using Various Battery Chemistries

Simulations of Prius plug-in hybrids have been performed with Advisor utilizing lithium-ion batteries of the different chemistries (References 4 and 5). The UC Davis test data were used to prepare the battery input files needed in Advisor. Simulations were made for battery packs weighing 60 kg and 120 kg. The results of the simulations are given in Table 12. Note from Table 12 that plug-in hybrids can be designed using the various lithium-ion batteries as well as a nickel metal hydride battery. However, the charge depleted (CD) electric ranges of the various designs and their fuel economy in the CD mode are much different and the differences are highly dependent on the driving cycle. The CD ranges are larger for the batteries with the higher energy densities and the fuel economies in the CD mode are highest for the batteries that are capable of high peak power. High battery power capability permits the vehicle to operate in the all-electric mode (engine off) until the energy in the battery is depleted. The fuel economy in the charge sustaining (CS) mode is dependent on the driving cycle, but not significantly on the battery energy density and weight of the battery pack. The weight of the battery and its energy density has a large effect on CD operation as would be expected. The simulation results show that the selection of the battery chemistry for plug-in hybrids is closely linked to the details of the vehicle design and performance specifications and expected driving cycle. Economic factors such as cycle life and battery cost and battery management and safety issues must also be considered in selecting the most appropriate battery chemistry of plug-in hybrids.

1.7 Summary and Conclusions

It is well recognized that the key issue in the design of a plug-in hybrid-electric vehicle is the selection of the battery. The consensus view is the battery will be of the lithium-ion type, but which of the lithium-ion chemistries to use is still a major question. The selection will depend on a number of factors: useable energy density, useable power density, cycle and calendar life, safety (thermal stability), and cost. This paper is concerned with the testing and evaluation of various battery chemistries for use in PHEVs. Test data are presented for lithium-ion cells and modules utilizing nickel cobalt, iron phosphate, and lithium titanate oxide in the electrodes. The energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the

negative electrode can have energy density between 60-70 Wh/kg. The situation regarding the power capability (W/kg) of the different chemistries is not as clear because of the energy density/power capability trade-offs inherent in battery design. The power densities can vary over a wide range even for a given chemistry. This is particularly true for the graphite/NiCoMn chemistry. In general, it seems possible to design high power batteries (500-1000 W/kg at 90 percent efficiency) for all the chemistries if one is willing to sacrifice energy density and likely also cycle life. The data indicate that high power iron phosphate cells can be designed without a significant sacrifice in energy density. When power densities greater than 2000 W/kg for lithium-ion batteries are claimed, it is for low efficiency pulses. For example, for an efficiency of 65 percent, the 15Ah EIG iron phosphate battery has a pulse power of 2330 W/kg rather than the 919 value for a 90 percent efficient pulse.

Simulations of Prius plug-in hybrids have been performed with Advisor utilizing lithium-ion batteries of the different chemistries. Simulations were made for battery packs weighing 60 kg and 120 kg. The simulation results show that the selection of the battery chemistry for plug-in hybrids is closely linked to the details of the vehicle design and performance specifications and expected driving cycle. Economic factors such as cycle life and battery cost and battery management and safety issues must also be considered in selecting the most appropriate battery chemistry of plug-in hybrids.

Table 13: Simulation Results for Prius Phevs Using Various Lithium-ion Batteries

		60 kg Battery			
		Varta (Ovonic)	LFP (A123)	NCM (Gaia)	LTO (Altairnano)
		Ni-MH	Li-Ion	Li-Ion	Li-Ion
(1) Power					
(Cell power density)	W/kg	333	1100	1700	680
Pack Power Density[a]	W/kg	250	825	1275	510
Battery Peak Power	kW	15	50	77	31
Motor peak power[b]	kW	**13**	**42**	**65**	**26**
(2) Energy Capacity					
(Cell Energy density)	Wh/kg	71	90	96	70
Pack Total Energy Density[a]	Wh/kg	54	68	72	53
Total Energy	kWh	3.21	4.05	4.32	3.15
Available Energy[c]	kWh	**2.57**	**3.24**	**3.46**	**2.52**
Cell Voltage	V	**13.4**	**3.2**	**3.6**	**2.3**
Cell Capacity	Ah	**15**	**19**	**20**	**15**
# of Cells	#	**16**	**67**	**60**	**94**
(3) PHEV performance (US06)					
CD electricity use	Wh/mile	171	225	175	157
CD range	miles	15	14	20	16
CD gasoline use	mpg	98	3000	inf	425
CS gasoline use	mpg	44	44	43	43
(3) PHEV performance (UDDS)					
CD electricity use	Wh/mile	149	126	97	93
CD range	miles	17	26	36	27
CD gasoline use	mpg	800	inf	inf	inf
CS gasoline use	mpg	67	73	69	71
(3) PHEV performance (HWFET)					
CD electricity use	Wh/mile	178	155	120	114
CD range	miles	14	21	29	22
CD gasoline use	mpg	1500	inf	inf	inf
CS gasoline use	mpg	66	67	64	66

[a] Assuming packing factor = 0.75

[b] Assuming motor efficiency equals = 0.85

[c] Assuming DOD = 0.8

Table 14: Simulation Results for Prius Phevs Using Various Lithium-ion Batteries

		120 kg Battery			
		Varta (Ovonic)	LFP (A123)	NCM (Gaia)	LTO (Altairnano)
		Ni-MH	Li-Ion	Li-Ion	Li-Ion
(1) Power					
(Cell power density)	W/kg	333	1100	1700	680
Pack Power Density[a]	W/kg	250	825	1275	510
Battery Peak Power	kW	30	99	153	61
Motor peak power[b]	kW	**25**	**84**	**130**	**52**
(2) Energy Capacity					
(Cell Energy density)	Wh/kg	71	90	96	70
Pack Total Energy Density[a]	Wh/kg	54	68	72	53
Total Energy	kWh	6.43	8.10	8.64	6.30
Available Energy[c]	kWh	**5.14**	**6.48**	**6.91**	**5.04**
Cell Voltage	V	**13.4**	**3.2**	**3.6**	**2.3**
Cell Capacity	Ah	**30**	**37**	**40**	**29**
# of Cells	#	**16**	**68**	**60**	**94**
(3) PHEV performance (US06)					
CD electricity use	Wh/mile	246	182	169	187
CD range	miles	21	36	41	27
CD gasoline use	mpg	329	inf	inf	inf
CS gasoline use	mpg	43	44	45	42
(3) PHEV performance (UDDS)					
CD electricity use	Wh/mile	146	104	97	104
CD range	miles	35	62	71	48
CD gasoline use	mpg	inf	inf	inf	inf
CS gasoline use	mpg	69	71	71	72
(3) PHEV performance (HWFET)					
CD electricity use	Wh/mile	171	127	118	126
CD range	miles	30	51	59	40
CD gasoline use	mpg	inf	inf	inf	inf
CS gasoline use	mpg	66	66	66	66

[a] Assuming packing factor = 0.75

[b] Assuming motor efficiency equals = 0.85

[c] Assuming DOD = 0.8

Chapter 2:
Simulations of Plug-in Hybrid Vehicles Using Advanced Lithium Batteries and Ultracapacitors on Various Driving Cycles

2.1 Introduction

Simulation models of hybrid-electric vehicles using ***Advisor*** have been prepared at the University of California-Davis, Institute of Transportation Studies. The hybrid-electric drivelines modeled included the Honda single-shaft, Toyota planetary, GM two-mode, and the VW/Borg Warner dual clutch transmission arrangements. Both charge sustaining HEV and plug-in hybrid vehicles have been simulated using nickel metal hydride and lithium-ion batteries. In the present study, the simulation models have been extended to include the cases of battery/ultracapacitor combinations for energy storage (2-energy storage systems and associated control strategies). These new models include DC/DC inverters to control the energy flow from the battery and/or the ultracapacitors. The control strategies result in load leveling the batteries and having the ultracapacitors accept all the regenerative braking energy. This paper is concerned with the application of the 2-energy storage models to plug-in hybrid vehicles (PHEV) using advanced lithium batteries having energy densities of 200-400 Wh/kg. These high energy density batteries often do not have commensurate high power capability and thus will benefit greatly by being combined with ultracapacitors or other very high power capability devices. This is especially true of PHEV designs which are intended for all-electric operation in the charge depleting mode. In this paper, simulation results are presented for mid-size PHEVs with all-electric ranges of 25-90 km. It is shown that high energy density, relatively low power batteries combined with ultracapacitors will provide good all-electric vehicle performance with much reduced stress on the batteries. This is expected to significantly enhance battery cycle life.

2.2 Battery and Ultracapacitor Characteristics

A number of lithium batteries and ultracapacitors have been tested in the laboratory at the University of California-Davis . A summary of the test results for the batteries is given in Table 1 and for the ultracapacitors in Table 2. For both energy storage technologies, the devices with the highest energy density typically have the lowest power capability. The pulse power capabilities shown in the tables were calculated using the following relationships:

Batteries: $P = EF(1-EF)\, V_{oc}^2/R$

Ultracapacitors: $P = 9/16(1-EF)\, V_{rated}^2/R$

where EF is the efficiency of the pulse ($EF = V_{pulse}/V_{oc}$).

The matched impedance power which is often cited for both battery and ultracapacitor devices is calculated as follows:

$$P_{match\ imped.} = V^2/4R$$

For charge sustaining hybrids, it seems reasonable to cite the power capability of devices for pulse power efficiencies of 90-95 percent. For PHEVs and EVs operating in charge depleting modes for the battery, it is reasonable to cite the power for efficiencies of 75-80 percent. In all instances, the power capability is proportional to V^2/R so that high power capability requires a low resistance R.

2.2.1 Batteries

The primary goal of this paper is to investigate via vehicle modeling the performance of combinations of advanced batteries and ultracapacitors in PHEVs and compare that performance with the batteries alone. Vehicle simulations are performed for batteries having a wide range of energy densities and power capabilities. The characteristics of some of the batteries are based on cell test data while the characteristics of others are those of projected (fictitious) cells of advanced chemistries. A summary of the characteristics of the batteries used in the vehicle simulations is given in Table 3. The batteries were projected to have energy densities between 200 and 400 Wh/kg and varying power capability.

Little direct information is given in the literature concerning the energy density of particular cell designs using advanced materials such as MnO2 composites and silicone carbon composites. Electrode material properties are given based on electrode test data , but as yet no test data on cells assembled using the materials seems to be available in the literature. Hence the cell performance values given in Table 3 are only estimates selected to show the effect of the cell performance on PHEV performance with and without the use of ultracapacitors. The resistances and power capabilities shown in Table 3 for the advanced lithium battery chemistries are based on extrapolating the Ah-mOhm values from the resistance test data shown in Table 1. The power densities for 95 percent and 75 percent pulses were calculated using the equation for battery power previously discussed.

Table 15: Summary of the Performance Characteristics of Lithium-ion Batteries of Various Chemistries

Battery Developer/ Cell type	Electrode chemistry	Voltage range	Ah	Resist. mOhm	Wh/kg	W/kg 90% effic.*	W/kg Match. Imped.	Wgt. (kg)	Density gm/cm3
Enerdel HEV	Graphite/ Ni MnO2	4.1-2.5	15	1.4	115	2010	6420	.445	----
Enerdel EV/PHEV	Graphite/ Ni MnO2	4.1-2.5	15	2.7	127	1076	3494	.424	----
Kokam prismatic	Graphite/ NiCoMnO2	4.1-3.2	30	1.5	140	1220	3388	.787	2.4
Saft Cylind.	Graphite/ NiCoAl	4.0-2.5	6.5	3.2	63	1225	3571	.35	2.1
GAIA Cylind.	Graphite/ NiCoMnO2	4.1-2.5	40 7	.48 3.6	96 78	2063	5446 3472	1.53 .32	3.22 ---
A123 Cylind.	Graphite/Iron Phosph.	3.6-2.0	2.2	12	90	1393	3857	.07	2.2
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	11	2.2	70	990	2620	.34	1.83
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	3.8	1.15	35	2460	6555	.26	1.91
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	1.8	60	144	577	1550	.043	2.6
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	2.3	72	170	445	1182	.047	2.8
EIG prismatic	Graphite/ NiCoMnO2	4.2-3.0	20	3.1	165	1278	3147	.41	----
EIG prismatic	Graphite/Iron Phosph.	3.65-2.0	15	2.5	113	1100	3085	.42	---
Panasonic EV prismatic	Ni Metal hydride	7.2-5.4	6.5	11.4	46	395	1093	1.04	1.8

* power density $P = Eff.*(1-Eff.)\ Voc^2/R$, $P_{match.\ imped.} = V^2/4R$

Table 16: Summary of Ultracapacitor Device Characteristics

Device	V rated	C (F)	R (mOhm)	RC (sec)	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped.	Wgt. (kg)	Vol. lit.
Maxwell*	2.7	2885	.375	1.08	4.2	994	8836	.55	.414
Maxwell	2.7	605	.90	.55	2.35	1139	9597	.20	.211
Skeleton Technologies	2.8	1600	1.3	2.1	5.8	800	7140	.22	.13
ApowerCap**	2.7	55	4	.22	5.5	5695	50625	.009	---
Apowercap**	2.7	450	1.3	.58	5.89	2766	24595	.057	.045
Ness	2.7	1800	.55	1.00	3.6	975	8674	.38	.277
Ness	2.7	3640	.30	1.10	4.2	928	8010	.65	.514
Ness (cyl.)	2.7	3160	.4	1.26	4.4	982	8728	.522	.379
Asahi Glass (propylene carbonate)	2.7	1375	2.5	3.4	4.9	390	3471	.210 (estimated)	.151
Panasonic (propylene carbonate)	2.5	1200	1.0	1.2	2.3	514	4596	.34	.245
EPCOS	2.7	3400	.45	1.5	4.3	760	6750	.60	.48
LS Cable	2.8	3200	.25	.80	3.7	1400	12400	.63	.47
BatScap	2.7	2680	.20	.54	4.2	2050	18225	.50	.572
Power Sys. (activated carbon, propylene carbonate) **	2.7	1350	1.5	2.0	4.9	650	5785	.21	.151
Power Sys. (graphitic carbon, propylene carbonate) **	3.3 3.3	1800 1500	3.0 1.7	5.4 2.5	8.0 6.0	486 776	4320 6903	.21 .23	.15 .15
JSR Micro (AC/graphitic carbon)	3.8	1000 2000	4 1.9	4 3.8	11.2 12.1	900 1038	7987 9223	.113 .206	.073 .132

(1) Energy density at 400 W/kg constant power, Vrated - 1/2 Vrated

(2) Power based on P=9/16*(1-EF)*V2/R, EF=efficiency of discharge

* Except where noted, all the devices use acetonitrile as the electrolyte

** All device except those with ** are packaged in metal containers

The resistance and thus the power capability of the rechargeable Zinc-air battery were estimated based on the resistance of a 10Ah cell being developed by Revolt Technology in Switzerland and assuming a large reduction (a factor of about three) in a the Ah-mOhm value of 20Ah cell. As indicated in Table 3, the Zinc-air battery is assumed to be a high energy density, relatively low power technology for vehicle applications. The low power capability of the Zinc-air battery is due to a large extent to its low cell voltage (1.35V) compared to the lithium cells.

2.2.2 Ultracapacitors

The characteristics of power devices are also shown in Table 3. The values shown for the ultracapacitors are for a device using activated carbon in both electrodes and acetronitrile as the electrolyte. The cell performance shown in Table 3 is the present state-of-the art for ultracapacitors based on test data for the ApowerCap 450F device, Table 2. Further improvements in power density are likely, but not assumed in the present study. Higher energy density ultracapacitors are available, but they have lower power capability. In addition to high power density, the carbon/carbon ultracapacitors have a cycle life of hundreds of thousands of deep discharge cycles. This long cycle life is essential for the present PHEV application.

Table 17: Characteristics of Present and Future Battery Cell Technologies for EVs and PHEVs

Chemistry Anode/cathode	Cell voltage Max/nom.	Ah	Wgt.kg	Rm Ohm	EV Wh/kg	HEV W/kg95 %	EV W/kg75 %	Cycle life(deep)	Thermal stability
Present technology batteries									
Graphite/ $NiCoMnO_2$	4.2/3.6	30	.787	1.5	140	521	2060	2000-3000	fairly stable
Graphite/ Mn spinel	4.0/3.6	15	.424	2.7	127	540	2120	1500	fairly stable
Future technology batteries									
Graphite/ composite MnO_2	4/3.6	5	.09	20	200	250	1350	----	fairly stable
Silicon carbon composites/ composite MnO_2	4/3.6	20	.24	4.5	295	621	2250	---	fairly stable
Rechargeable Zinc-Air	1.3/1.15	20	60	6.6	385	156	616	----	very stable
Present Technology									

Power devices									
supercapacitor Activated carbon/activated carbon	2.7/1.35	500F	.068	1.3	5.5	2320	11600	500K	Very stable
Power battery Lithium titanate oxide	2.8/2.5	4	.23	1.15	40	1310	5170	20-50K	Very stable

Another possible power device technology is a lithium-ion battery using lithium titanate oxide (LTO) in the negative electrode. As indicated in Table 1, cells using LTO have lower energy density than lithium batteries using other chemistries, but they can have significantly higher power and much longer cycle life. Hence for vehicle applications for which energy storage requirements exceed those doable with ultracapacitors, the LTO lithium battery should be considered. The characteristics of LTO cells are included in Table 3, but PHEV simulations using those cells were not done as part of the present study.

2.2.3 Combinations of Batteries and Ultracapacitors

When considering the combination of high energy density batteries with ultracapacitors in PHEVs, it will be assumed that the battery is sized by the energy requirement to achieve a specified all-electric range (AER) in the charge depletion mode of operating the vehicle. The energy storage and battery weight for AER between 10 and 40 miles (16-60 km) are shown in Table 4 for battery energy densities between 100-300 Wh/kg. The corresponding power density requirements for 50 and 70 kW electric drivelines in the vehicles are also shown in the table. The power density values shown are high –several kW/kg in some cases- indicating that it is unlikely the high energy density batteries alone will be able to satisfy the power requirements. Hence it seems appropriate to consider combining the batteries with ultracapacitors for the PHEV designs. The results of utilizing a 100 Wh useable energy ultracapacitor pack (20 kg of cells) are shown in Table 5. In these designs, the ultracapacitors can provide a high fraction of the peak power and the batteries the average power that is much lower. This approach to load leveling of the batteries is followed in the vehicle simulations discussed in the next section. Note in Table 5 that for a given AER, the combined weight of the batteries and ultracapacitors is the lowest using the highest energy density batteries which would not be possible without incorporating the ultracapacitors in the system.

Table 18: Battery Sizing and Power Density for Various Ranges and Motor Power

				BATTERY ENERGY DENSITY							
				300 Wh/kg			200 Wh/kg			100Wh/kg	
Range miles	kWh *needed	kWh **	** k	50 kWkW	70kWkW/kg	kg	50kWkW/kg	70kWkW/kg	kg	50kW kW/k	70kWkW/kg

	d	store d	g	/kg						g	
10	2.52	3.6	12	4.17	5.83	18	2.78	3.89	36	1.39	1.94
15	3.78	5.4	18	2.78	3.89	27	.1.85	2.59	54	.92	1.30
20	5.04	7.2	24	2.08	2.92	36	.1.39	1.94	72	.69	.97
30	7.56	10.8	36	.1.39	1.94	54	. 93	1.30	108	.46	.65
40	10.1	14.4	48	1.04	1.46	72	. .69	.97	144	.35	.49

***** Vehicle energy usage from the battery: 250 Wh/mi

** Useable state-of-charge for batteries: 70%, weights shown are for cells only

Table 19: Storage Unit Weights Using a Combination of Batteries and Ultracapacitors for Various All-Electric Ranges

Wh/kg: 5 300 200 100

Range miles	Ultra capkg *	BatteryKg**	Combination kg	Battery kg	Combination kg	Battery kg	Combination kg
10	20	12	32	18	38	36	56
15	20	18	38	27	47	54	74
20	20	24	44	36	56	72	92
30	20	36	56	54	74	108	128
40	20	48	68	72	92	144	164

* The ultracapacitor unit stores 100 Wh useable energy

** Weights shown are for cells only, packaging into modules not included

2.3 Modeling of PHEVs Combining Batteries and Ultracapacitors

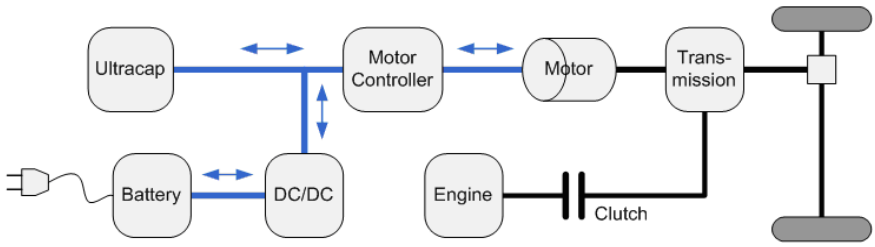
It has been recognized for a number of years that combining batteries and ultracapacitors can offer advantages in hybrid vehicles. Ultracapacitors can deliver very high power and respond in fractions of a second, but have limited storage capacity (100-200 Wh). Batteries have lower power capability, but with high energy density can store relatively large kWh of energy. The combination of batteries and ultracapacitors can deliver high power and high energy and is ideal for PHEVs in term of extending the battery life and downsizing battery pack.

Simulation models of hybrid-electric vehicles using ***Advisor*** have been prepared at the University of California-Davis, Institute of Transportation Studies. The hybrid-electric drivelines modeled included the Honda single-shaft, Toyota planetary, GM two-mode, and the VW/Borg Warner dual clutch transmission arrangements. Both charge sustaining HEV and

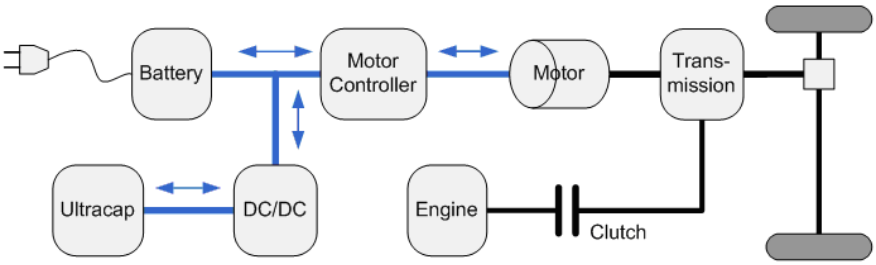
plug-in hybrid vehicles have been simulated using nickel metal hydride and lithium-ion batteries. As discussed in this section of the paper, the simulation models are extended to include the cases of battery/ultracapacitor combinations for energy storage (2-energy storage systems and associated control strategies). These new models include DC/DC inverters to control the energy flow from the battery and/or the ultracapacitors. The control strategies result in load leveling the batteries and having the ultracapacitors accept all the regenerative braking energy.

Figure 5 shows topologies of interfacing batteries and ultracapacitors with the motor drive dc-link using a bi-directional dc-dc converter. Figure 5(a) has ultracapacitors directly coupled with the motor drive dc-link. The battery interfaces with the dc-link via a bi-directional dc/dc converter. This topology is well suited for blending ultracapacitors with optimal engine operation. There is a relatively wide variation of the dc-link voltage, but it can be handled by the motor electronics. Figure 5(b) directly interfaces batteries with the motor drive dc-link. Ultracapacitors take over the transient power via a bi-directional dc/dc converter. This configuration is best suited for battery powered electric vehicles. In this paper, the configuration (a) is modeled in detail. The use of two bi-directional dc/dc converters to control the power flow in/out of the battery and ultracapacitor is possible and is the most flexible, but it is the most costly with likely minimal gain in system performance.

Figure 5: Driveline Configurations of PHEVs Combining Batteries and Ultracapacitors



(a)

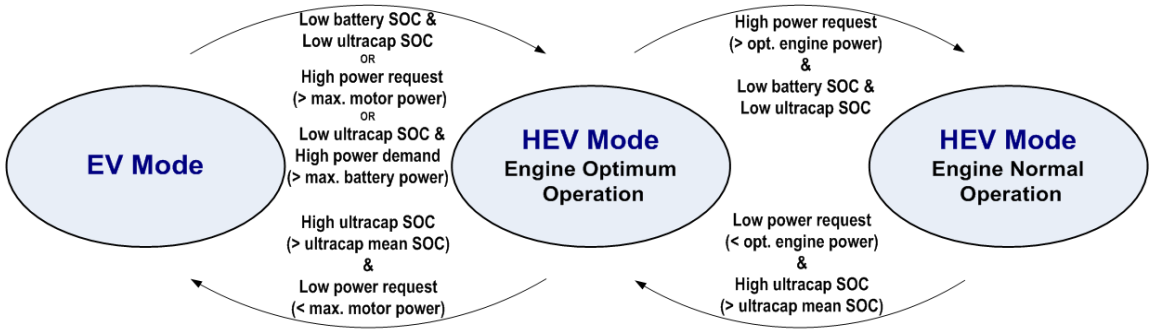


(b)

In the PHEV model with two energy storage units, there are three basic driveline operating modes: (1) EV mode (electric drive only), (2) HEV mode with optimal engine operation, and (3) HEV mode with normal engine operation. These various modes are shown in Figure 6. In terms of the batteries, there are two modes: (1) a charge depleting mode in which the battery

state-of-charge is decreasing to a specified minimum value, (2) a charge sustaining mode that maintains the minimum state-of-charge of the battery utilizing the engine and motor/generator as in the Toyota Prius and Honda hybrid Civic.

Figure 6:Modes of Operation of the PHEV with Two Energy Storages



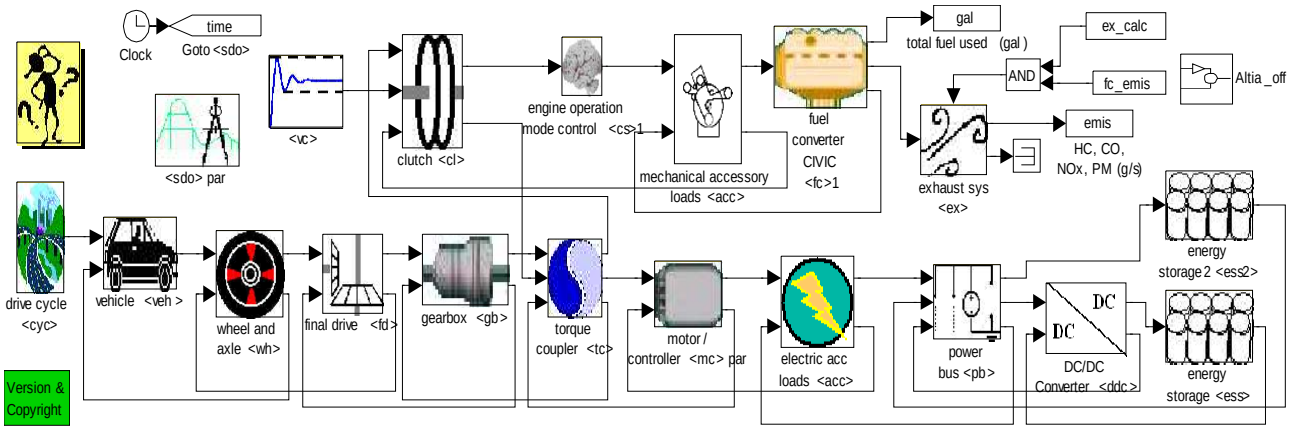
In the EV mode, only the traction motor powers the vehicle. Batteries and/or ultracapacitors supply or absorb power up to the limits of the traction motor. Batteries provide the time-averaged power and the ultracapacitor provides the remainder of the power needed by the vehicle. This reduces stress on the battery and extends battery life. For a PHEV, most of this operation takes place in the battery charge depleting mode at vehicle ranges less than AER. The ultracapacitor is controlled to be within its appropriate voltage limits via charging from the battery when needed and it accepts all the regenerative braking energy.

In this mode, a 90sec moving average is used to smooth the battery power. The maximum power of the battery is limited to one third of the maximum power of the traction motor. To limit the voltage swing of ultracapacitors (traction motor dc-link), the minimum voltage of the ultracapacitor is set to 50 percent of the maximum, rated voltage (The usable energy is 75 percent of the total energy stored in the capacitor), and the ultracapacitor *SOC* is controlled between 0.2 and 0.9.

In HEV mode with optimal engine operation, the engine runs near maximum efficiency at all engine speeds and provides the resultant optimum power regardless of the power demand of the vehicle. In order to balance the engine output power with that required by the vehicle, the difference via the motor/generator is either absorbed or provided by the ultracapacitor. This mode of operation occurs most frequently in the battery charge sustaining mode near minimum battery state-of-charge. In this mode, the intent is to provide all electrical power from the ultracapacitors and have them accept all the regenerative braking energy. The battery is not used unless the ultracapacitor would happen to be completely depleted.

In HEV mode with normal engine operation, the engine provides the required vehicle propulsion power as in a conventional vehicle and charges the ultracapacitor if needed.

Figure 7:Advisor Vehicle Block Diagram



The block diagram for the PHEV vehicle simulation in ***Advisor*** is shown in Figure 7. As indicated by the previous discussion of the various operating modes of the vehicle, the control of the PHEV is quite complex as it involves minimizing the stress on the battery and optimizing the efficiency of engine operation using the high power, high efficiency ultracapacitor as an electrical energy buffer and for recovery of energy from regenerative braking. In addition, the control strategy must be applicable to the various driving cycles (FUDS, Federal Highway, and US06) that vary significantly in their power demand characteristics. The simulation results of the next section will show large differences as to how the energy storage units respond to vehicle operation on the various driving cycles.

2.4 Simulation Results for PHEVs Using Batteries and Ultracapacitors

2.4.1 Vehicle design parameters and electric and engine characteristics

All the simulations were performed using the following vehicle inputs:

C_D =.27, A_F = 2.2 m^2, f_r =.008, test weight = 1650 kg (approx.)

Engine: Honda 1.3L, iVTEC engine map, scaled to 90 kW

Electric motor: Honda hybrid Civic AC PM 2006 efficiency map, scaled to 70 kW

DC/DC inverter: constant efficiency 0.96

Transmission: 5-speed manual (3.11, 2.11, 1.55, 1.0, .71, FD=3.95), automatically shifted in the model, but future models would incorporate the DCT (dual clutch transmission) as a convenient means to have smooth, fast shifting and to decouple the engine when it is not needed to provide power.

2.4.2 Batteries and Ultracapacitors

Simulations were performed using batteries and ultracapacitors with the characteristics shown in Table 3. The weights of the energy storage units are given in terms of the weights of the cells in the various units. The weights of the complete units would be higher due packaging and

unit management considerations, but the performance of the unit is dependent on the cell weights. The energy storage unit cell weights used in the simulations are the following:

Lithium-ion batteries				
EIG $NiCoMnO_2$	30 kg	20 Ah cells	60 in series	3.5 kWh useable
Composite MnO_2	32 kg	40 Ah cells	60 in series	4.6 kWh useable
Silicone composite	22 kg	30 Ah cells	60 in series	4.6 kWh useable
Zinc-air batteries				
Zn-air	32 kg	60Ah cells	180 in series	9.5 kWh useable
Carbon/carbon ultracapacitors				
Symmetric C/C	20 kg	1350F cells	110 in series	100 Wh useable

The nominal energy storage unit voltage was 240V (approx.) in all cases with the maximum currents limited to about 300A even in the cases of the batteries alone. In all cases, the batteries were depleted to 30 percent SOC from 100 percent SOC.

2.4.3 Simulation Results and Their Interpretation

Computer runs were performed for PHEVs using the batteries shown above with and without the ultracapacitors. Simulations were made for the FUDS, Federal Highway, and US06 driving cycles. For each of the driving cycles, runs were made for selected numbers of cycles to represent driving in the charge depleting and charge sustaining modes of operation. The all-electric range (AER) and electric energy use (Wh/mi) were determined for the charge depleting mode and the fuel economy (mpg) was determined for all cases/modes in which the engine was operating. The simulation results are summarized in Table 6 for the battery and ultracapacitor combinations and in Table 7 for the cases of batteries alone without ultracapacitors.

With the batteries in combination with the ultracapacitors, the PHEVs were able to operate in the all-electric mode until the battery SOC=30 percent on the FUDS and Federal Highway driving cycles. In all cases for the US06 driving cycle, the vehicle had blended operation (engine and electric drive both needed) in the charge depleting mode. The use of the ultracapacitors with the batteries permits all-electric operation of the vehicle have a wide range of driving conditions and higher Wh/mi for all the driving cycles. Hence in the charge depleting mode, the fuel economy (mpg) is higher by 50-100 percent using the ultracapacitors for all the batteries. The fuel economy in the charge sustaining mode is also higher for all the driving cycles using the ultracapacitors, but only by 15-40 percent in most cases. The acceleration times of the vehicle were lower using the ultracapacitors than for the batteries alone. With the ultracapacitors, the acceleration times were 2.7 sec for 0-30 mph and 6.9 sec for 0-60 mph. For the batteries alone, the acceleration times varied somewhat with the battery used ranging from 2.9-3.2 sec for 0-30 mph and 8.6-9.8 sec for 0-60 mph. Hence in all respects, vehicle performance was improved using the ultracapacitors for all the batteries studied.

The current and voltage responses of the batteries with and without the ultracapacitors are shown in Figures 8-11 for the silicone carbon lithium-ion and the Zinc-air batteries for the FUDS and US06 driving cycles. The effects of the load leveling of the power demand from the batteries using the ultracapacitors are clearly evident in the figures. Both the average currents and the peak currents from the batteries are lower by a factor of 2-3 using the ultracapacitors. The minimum voltages of the batteries are significantly higher using the capacitors and the voltage dynamics (fluctuations) are dramatically reduced. Hence the stress on the battery and resultant heating are much reduced. The simulation results in Figures 8-11 also show that the ultracapacitors are utilized over a wide voltage range indicating that a large fraction of their usable energy storage (100 Wh) is being used to load level the batteries. This is only possible using a DC/DC converter between the battery and the DC- bus.

The simulation results also indicate that using ultracapacitors, batteries with a wide range of power characteristics can be used in PHEVs and also EVs without sacrificing vehicle performance and subjecting the batteries to high stress and resultant shorter cycle life. This could be especially important in the future as high energy density batteries such as Zinc-air and possibly lithium-air are developed. It is likely that those battery types will not have commensurate increases in useable power density and without ultracapacitors, the battery unit in PHEVs and EVs would be sized by the maximum power requirement (kW) rather than the range (mi)/energy requirement (kWh). This would significantly increase weight, volume, and the cost of the battery unit. It is also unlikely that the air electrode will have charge acceptance capability and thus regenerative braking performance approaching that of ultracapacitors or even lithium-ion batteries. This is another advantage of the use of ultracapacitors with the air-electrode batteries.

Table 20: Simulation Results for the Advanced Batteries with Ultracapacitors

Battery Type (1)	cycle	Range mi.	kW max.control	kW maxbat.	Eff.Bat.	kW max.Cap.	Eff. Cap.	Wh/miBat.	Operat.mode	mpg20mi	mpg40mi	Ch. Sus.HEVmpg
Compos. MnO2	FUD	22	40	18	.94	40	.97	215	AE	none	97	52.8
32kgbat	HW	20	45	18	.91	45	.96	227	AE	none	109	56.3
20kgcap	US06	30	68	21	.91	68	.94	180	blended	71.9	56	38.3

Battery Type (1)	cycle	Range mi.	kW max.control	kW maxbat.	Eff.Bat.	kW max.Cap.	Eff. Cap.	Wh/miBat.	Operat.mode	mpg20mi	mpg40mi	Ch. Sus.HEVmpg
Si Carb/Compos. MnO2	FUD	20	40	18	.94	40	.97	220	AE	none	99	52.8
22kgbat	HW	20	45	19	.91	45	.97	225	AE	none	110	56.8
20kgcap	US06	30	68	21	.91	68	.94	190	blended	71.1	52	38.4
Rech.Zn-air	FUD	40	45	19	.87	45	.97	228	AE	none	none	54.5
32kgbat	HW	38	45	19	.81	45	.97	242	AE	none	none	57.7
20kgcap	US06	66	68	21	.82	68	94	149	blended	62.4	60	38.8

(1) weight of cells only

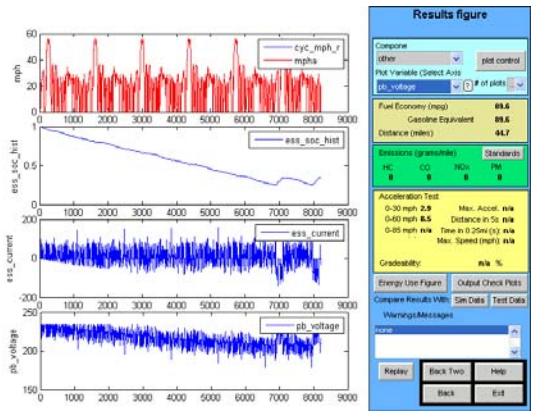
Table 21: Simulation Results for the Batteries Alone

Battery Type (1)	cycle	Range mi.	kW max.control.	kW max. bat.	Eff. Bat.	Wh/mi Bat.	Operat. mode	mpg20mi .	mpg40mi	Mpg Ch. sus.HEV
EIGNiCoMn	FUD	27	30	30	.94	125	blended	134	85	47
30 kg	HW	24	20	20	.93	137	blended	110	87	47
	US06	57	58	58	.88		blended	48	45	37

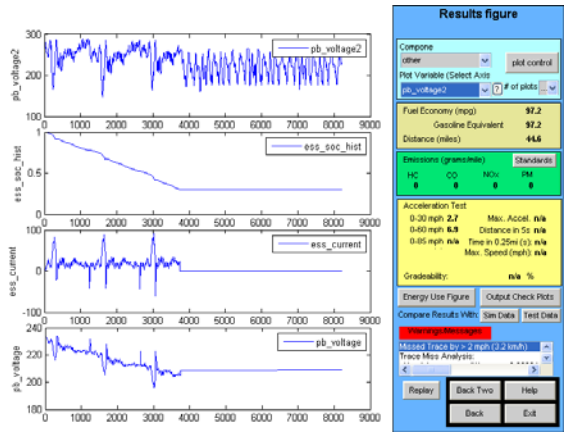
Battery Type (1)	cycle	Range mi.	kW max.control.	kW max. bat.	Eff. Bat.	Wh/mi Bat.	Operat. mode	mpg20mi .	mpg40mi	Mpg Ch. sus.HEV
Compos. MnO2	FUD	36	30	30	.92	135	blended	134	104	46.9
32kgbat	HW	31	20	20	.91	147	blended	167	113	46.6
	US06	64	58	58	.87	92	blended	48	48	34.1
Si Carb/Compos. MnO2	FUD	35	30	30	.93	138	blended	138	106	46.9
22kgbat	HW	32	20	20	.92	148	blended	169	114	46.9
	US06	64	58	58	.88	87	blended	48	48	35.7
Rech.Zn-air	FUD	66	30	30	.84	139	blended	139	137	39.4
32kgbat	HW	63	20	20	.83	156	blended	169	169	41.1
	US06	93	36	36	.72	101	blended	48.5	48.5	30.1

(1) weight of cells only

Figure 8: The Si Carbon Lithium Battery on the FUDS With and Without Ultracapacitors

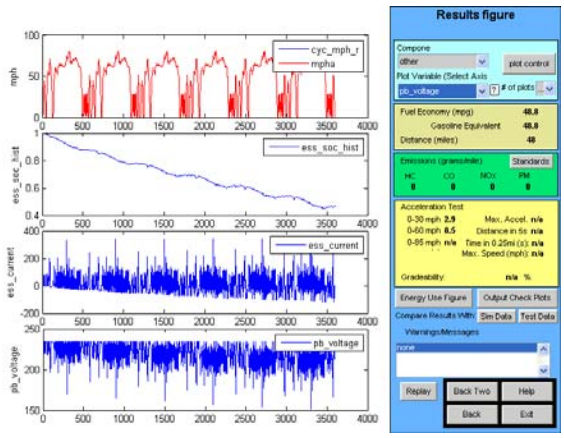


FUDS without ultracapacitors

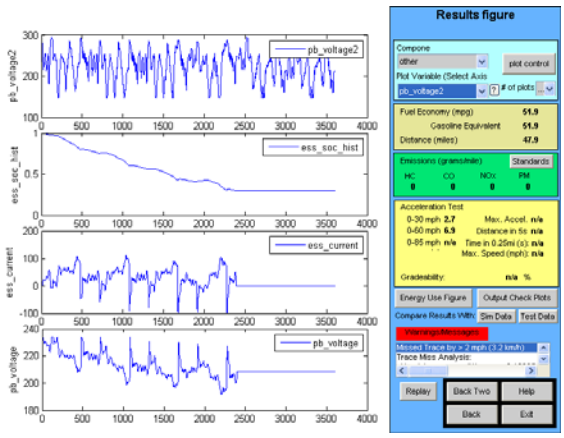


FUDS with ultracapacitors

Figure 9: The Si Carbon Lithium Battery on the US06 with and without Ultracapacitors

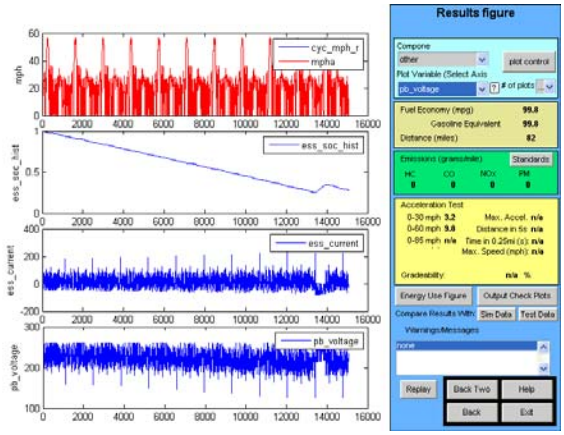


FUDS without ultracapacitors

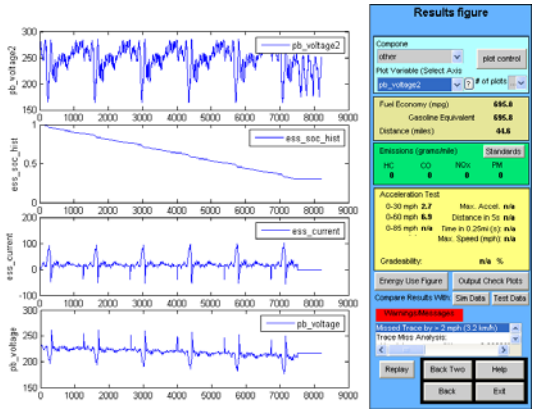


FUDS with ultracapacitors

Figure 10:The Zinc-Air Battery on the FUDS With and Without Ultracapacitors

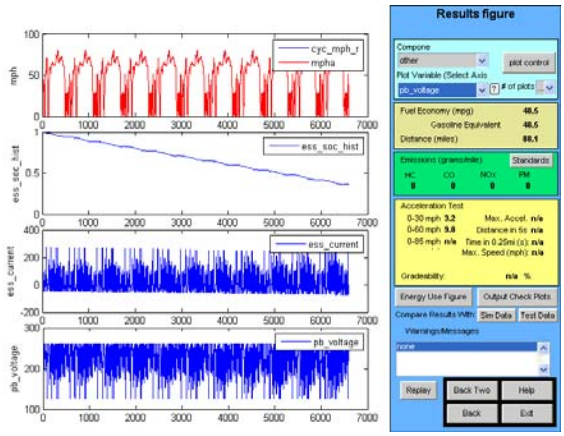


Zinc-air on the FUDS without ultracapacitors

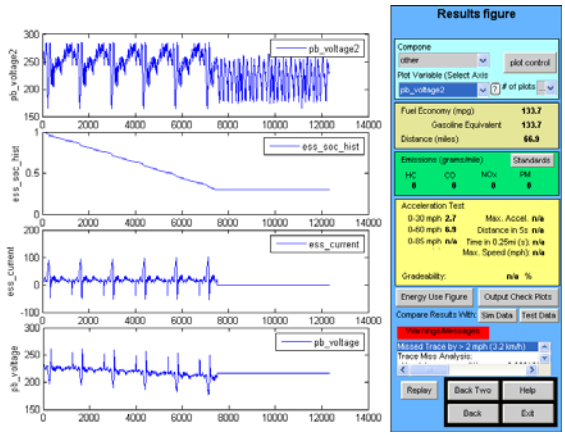


Zinc-air on the FUDS with ultracapacitors

Figure 11: Zinc-Air Battery on the US06 with and without Ultracapacitors



Zinc-air on the US06 without ultracapacitors



Zinc-air on the US06 with ultracapacitors

2.4.4 Summary and Conclusion

This paper is concerned with the use of ultracapacitors in plug-in hybrid vehicles (PHEVs) in combination with high energy density lithium-ion (200-300 Wh/kg) and zinc-air batteries (400 Wh/kg). Battery energy density and power capability characteristics are assumed for use in new vehicle simulation models that include battery/ultracapacitor combinations for energy storage (2-energy storage systems and associated control strategies). These new models include a DC/DC inverter to control the energy flow from the battery and/or the ultracapacitors. The control strategies result in load leveling the batteries and having the ultracapacitors accept all the regenerative braking energy. The ultracapacitor characteristics used in the simulations are those of a symmetric, activated carbon device using acetonitrile as the electrolyte. The total weights of the cells in the lithium-ion batteries were 20-22 kg and in the zinc-air battery, 32 kg.

The cell weight of the ultracapacitors was 20 kg. The all-electric range using the lithium batteries was 20 miles and 40 miles using the zinc-air battery.

Simulations were performed for the FUDS, Federal Highway, and US06 driving cycles with the PHEVs operating in both the charge depleting and charge sustaining modes. With the batteries in combination with the ultracapacitors, the PHEVs were able to operate in the all-electric mode until the battery SOC=30 percent on the FUDS and Federal Highway driving cycles. In all cases for the US06 driving cycle, the vehicle had blended operation in the charge depleting mode. In the charge depleting mode, the fuel economy (mpg) is higher by 50-100 percent using the ultracapacitors for all the batteries. The fuel economy in the charge sustaining mode is also higher for all the driving cycles using the ultracapacitors, but only by 15-40 percent in most cases. The acceleration times of the vehicle were lower using the ultracapacitors than for the batteries alone. With the ultracapacitors, the acceleration times were 2.7 sec for 0-30 mph and 6.9 sec for 0-60 mph. For the batteries alone, the acceleration times varied somewhat with the battery used ranging from 2.9-3.2 sec for 0-30 mph and 8.6-9.8 sec for 0-60 mph.

The effects of the load leveling of the power demand from the batteries using the ultracapacitors are clearly evident in the simulation results. Both the average currents and the peak currents from the batteries are lower by a factor of 2-3 using the ultracapacitors. The minimum voltages of the batteries are significantly higher using the capacitors and the voltage dynamics (fluctuations) are dramatically reduced. Hence the stress on the battery and resultant heating are much reduced. The simulation results also show that the ultracapacitors are utilized over a wide voltage range indicating that a large fraction of their usable energy storage (100 Wh) is being used to load level the batteries. This is only possible using a DC/DC converter between the battery and the DC- bus.

The simulation results also indicate that using ultracapacitors, batteries with a wide range of power characteristics can be used in PHEVs and also EVs without sacrificing vehicle performance and subjecting the batteries to high stress and resultant shorter cycle life. This could be especially important in the future as high energy density batteries such as Zinc-air and possibly lithium-air are developed. It is likely that those battery types will not have commensurate increases in useable power density and without ultracapacitors, the battery unit in PHEVs and EVs would be sized by the maximum power requirement (kW) rather than the range (mi)/energy requirement (kWh). This would significantly increase weight, volume, and the cost of the battery unit. It is also unlikely that the air electrode will have charge acceptance capability and thus regenerative braking performance approaching that of ultracapacitors or even lithium-ion batteries. This is another advantage of the use of ultracapacitors with the air-electrode batteries.

CHAPTER 3:
Performance, Charging, and Second-use Considerations for Lithium Batteries for Plug-in Electric Vehicles

3.1 Introduction

This chapter is concerned with batteries for use in plug-in electric vehicles and the possibility of their second-use in stationary utility applications. By plug-in vehicles is meant hybrid-electric vehicles and battery-powered electric vehicles that depend on charging from the grid to obtain all/or a significant fraction of the energy they use for propulsion. These vehicles use batteries that store a significant amount (kWh) of energy and thus will offer the possibilities for second use in utility related applications such as residential and commercial backup systems and solar and wind generation systems.

The batteries used in the plug-in vehicles are likely to be one of the lithium-ion chemistries. Results from testing a number of lithium-ion batteries in the Hybrid Vehicle Propulsion System Lab at the University of California-Davis will be discussed in terms of their performance (energy density and power density). In addition, fast charging characteristics of the different lithium battery chemistries are presented and how those differences could relate to the manner in which the batteries would be charged by consumers in the field.

A final topic considered in the paper is the potential second use of the plug-in vehicle batteries in utility related applications. A review will be given of what factors should be considered in assessing the likelihood that the vehicle batteries will find a market after their performance has degraded such that they are no longer suitable for use in the plug-in electric vehicles. These batteries will retain a large fraction (at least 75 percent) of their initial energy storage capacity, but likely a smaller fraction of their initial power capability. The factors to be considered include extended calendar life and cycle life and how to relate these characteristics to the condition of the batteries when removed from the plug-in vehicles.

3.2 Plug-in Vehicle/Battery Design Considerations

3.2.1 Battery sizing and selection

The selection of the battery for plug-in vehicles is a complicated process and depends on many factors. In simplest terms, the battery must meet the energy storage (kWh) and peak power (kW) requirements of the vehicle and fit into the space available. In addition, the battery must satisfy cycle life requirements both for deep discharge in the charge depleting mode and shallow cycling in the charge sustaining mode of operation. Further the battery unit must be designed to meet thermal management, cell-to-cell monitoring, and safety requirements. The final considerations are concerned with the initial and life cycle costs of the battery. The battery size and cost will vary markedly depending on the all-electric range of the vehicle.

It is convenient to start the discussion of the batteries for plug-in electric vehicles with consideration of battery-powered vehicles which depend completely on battery stored electricity for propulsion. The batteries in those vehicles are sized by the energy storage requirement and not the power required by the electric motor. The characteristics of battery-powered vehicles of various types are given in Table 22. For a range of 100 miles, the batteries in those vehicles store 20-40 kWh and are relatively heavy weighing 170-320 kg. The pulsed power density required of the batteries is 400-500 W/kg, which is modest for the lithium-ion batteries.

Table 22: Characteristics of Battery-Powered Electric Vehicles (EV) of Various Types

Vehicle type	Vehicle test weight kg	BatteryWgt. kg(1)	Battery kWhstored(2)	Electric motor kW(3)	RequiredBattery pulse power W/kg(4)	Wh/mi from battery (5)	0-60 mphSec
Cars							
Compact	**1373**	**168**	**20.2**	**65**	**387**	**202**	**11.3**
Mid-size	**1695**	**208**	**24.9**	**102**	**490**	**249**	**8.9**
Full	**1949**	**238**	**28.5**	**122**	**513**	**285**	**8.6**
SUV							
Small	**2103**	**266**	**31.9**	**128**	**481**	**319**	**9.6**
Mid-size	**2243**	**278**	**33.3**	**143**	**514**	**333**	**9.3**
Full	**2701**	**317**	**38.0**	**160**	**501**	**380**	**9.6**

(1) Lithium-ion battery with an energy density of 120 Wh/kg
(2) All vehicles have a range of 100 miles
(3) Peak motor power
(4) Peak pulsed power required from the battery at 90% efficiency
(5) Average energy consumption on the FUDS and FHWAY drive cycles.

In the case of plug-in hybrid vehicles, there is much design flexibility in selecting the battery size and the electric motor and engine powers, because the all-electric range is a design variable and the power demand of the vehicle can be met by a combination (blending) of motor and engine output even when the battery is being depleted. Typical design combinations for all-

electric ranges between 10-40 miles are shown in Table 23 for a mid-size passenger car. The increased weight and decreasing power density

Table 23: Battery Sizing Ad Power Density for Plug-in Hybrid Vehicles for Various all-Electric Range and Electric Motor Power (Mid-Size Passenger Car)

Range miles	Electric motor kW	Engine power kW	BatterykWh *needed	BatterykWh** stored	Battery kg***	BatterykW/kg
10	50	100	2.52	3.6	30	1.66
15	55	100	3.78	5.4	45	1.22
20	60	75	5.04	7.2	60	1.0
30	75	60	7.56	10.8	90	.83
40	100	50	10.1	14.4	120	.83

* Vehicle energy usage from the battery: 250 Wh/mi

** Useable state-of-charge for batteries: 70%, weights shown are for cells only

*** Battery energy density 120Wh/kg

Requirement of the battery with increasing all-electric (battery depletion) range of the vehicle is typical of plug-in hybrid designs. The battery in a plug-in hybrid vehicle with a short all-electric range (<20 miles) will experience a deep discharge cycle almost every day and hence must be designed for more deep discharge cycles than the battery in a vehicle with a long all-electric range. It is clear from Table 23 that the requirements for batteries used in vehicles with short all-electric range are more demanding than those in other hybrid vehicles. This will result in those batteries being more expensive on a $/kWh basis than batteries in vehicles with long all-electric range and less likelihood that those batteries will be suitable for second-use recycling.

3.2.2 Battery/Grid Considerations

The batteries in plug-in hybrid vehicles are intended to be recharged off the grid either at the home of the vehicle owner or at a public charging station. For vehicles with short all-electric range (< 20 miles), the charging can be done off a standard 120V plug in 3-4 hours or less. For vehicle storing more than 10 kWh, a higher voltage charger (208V) will be needed unless the charging is done overnight. If the battery has fast charging capability (charging in 10 minutes or less), a high voltage, high power charger will be needed. This would in most cases be a public charging station built for the convenience of plug-in hybrid vehicle owners. For example, to charge the battery in the vehicle with a 30 mile range in 10 minutes requires a charger power of at least 50 kW.

The time of day for charging batteries in plug-in vehicles is somewhat uncertain. It seems likely that most of the charging of batteries in EVs will occur at night because the capacity of the

batteries is relatively large and the owners expect that most charging will take place at home using a high voltage charger. For plug-in hybrids, the time of charging is more uncertain as significant charging can be done with 120V chargers and the owners are likely to take advantage of limited time recharging as a means of attaining higher effective fuel economy with their hybrid vehicles. In addition, there is the possibility that some owners of vehicles with a longer all-electric range will utilize fast charging stations as a means of extending all-electric operation of their vehicle. In either case, the result could be that the plug-in vehicles will be charged occasionally when the utilities power demand is high during mid-day and the afternoon. This could be the case even if the electrical rates were high during those periods.

3.2.3 Batteries for Plug-in Vehicles

It is well recognized that the key issue in the marketing of plug-in vehicles is the availability of batteries with sufficient performance (energy and power) and low enough initial cost and long enough cycle/calendar life to permit the design of vehicles attractive to prospective vehicle buyers. The consensus view is the battery will be of the lithium-ion type, but which of the lithium-ion chemistries to use is still a major question. The selection will depend on a number of factors: useable energy density, useable power density, cycle and calendar life, safety (thermal stability), and cost. The most developed of the lithium-ion chemistries is that used in consumer electronics – that is carbon/graphite in the negative electrode and nickel cobalt and other metal oxides in the positive electrode. That chemistry yields the best performance (energy density and power density), but also has the greatest uncertainty concerning safety. The other chemistries (iron phosphate in the positive and lithium titanate in the negative) being developed are known to have less favorable performance, but less concern regarding safety and longer cycle life. These latter chemistries have been evaluated in detail in the present **study.**

The lithium-ion battery technology used for consumer electronics applications is reasonably mature and in 2008 over one billion, small (18650) cells were manufactured and sold. These cells utilized graphite/carbon in the negative and nickelate (LiNiCoAlO) in the positive. The graphite/nickelate chemistry yields cells with the highest energy density and power capability of the chemistries being developed for vehicle applications primarily because the cell voltage and the specific charge (mAh/gm) of the positive electrode material are higher than for the other chemistries. The material and cell characteristics of the various chemistries are shown in Table 3. If performance of the cell was the only consideration, there would be little interest in developing cells/batteries with the other chemistries. However, cycle life and safety (thermal stability) as well as cost are important considerations in selecting batteries for vehicle applications. Unfortunately the graphite/nickelate chemistry has shown in the consumer electronics applications to have safety and cycle life limitations, which can become even more serious for the large cells/batteries needed for vehicle applications. Hence development is underway using lithium manganese spinel and iron phosphate for the positive electrodes and lithium titanate oxide for the negative electrode. As indicated in Table 3, these chemistries have significantly lower performance than the graphite/nickelate chemistry, but longer cycle life and higher thermal stability. It is more difficult to compare the power capability of the different chemistries, because there is the inherent trade-off between energy density and power capability via the design of the electrodes and choice of material properties (primarily particle

size and surface area). Nevertheless, the cells with the higher cell voltage tend to have higher power capability. The goal of the developments of the other chemistries is to minimize the penalty in performance without significant sacrifice of the inherent advantages of the respective emerging chemistries. A number of companies world-wide are presently developing lithium-ion batteries utilizing the various electrode chemistries. Most of these companies are relatively small and are not well known in the battery business, but nevertheless their technologies are representative of the possibilities for the development of the emerging battery technologies.

A number of cells/chemistries were tested in the lab at UC Davis to assess their use in plug-in vehicles. Most of the cells for the consumer electronics applications are spiral wound packaged in a rigid container. Some cells are prismatic (thin, flat) in shape, but they are also packaged in a rigid container. All these cells (Figure 12) are small (1-3 Ah) and can be used in vehicle applications only if larger cells/modules are assembled by placing many of the small cells in parallel. This can be done, but it requires special attention to safety issues. For vehicle applications, larger cells (up to 100 Ah) are being developed so it is not necessary to assemble parallel strings of the cells in the modules. In all cases, the modules consist of a number of cells in series to attain a reasonably high module voltage. In some cases, the larger cells (Ah > 10 Ah) are packaged in a soft laminated pouch (see Figure 13), which are then placed in a rigid container to form a high voltage module. Some of the larger cells are spiral wound (see Figure 14), but the trend in cell development seems to be toward soft packaging. Whether this proves to be a wise trend remains to be seen as there are strong, well founded concerns about the robustness and reliability of the soft packaging for vehicle applications. The large format cells/modules are clearly of prime interest for consideration for second use applications.

Table 24: Characteristics of Lithium-ion Batteries Using Various Chemistries

Chemistry Anode/cathode	**Cell voltageMax/nom.**	**Ah/gmAnode/cathode**	**Energy density Wh/kg**	**Cycle life(deep)**	**Thermal stability**
Graphite/ $NiCoMnO_2$	4.2/3.6	.36/.18	100-170	2000-3000	fairly stable
Graphite/Mn spinel	4.0/3.6	.36/.11	100-120	1000	fairly stable
Graphite/ $NiCoAlO_2$	4.2/3.6	.36/.18	100-150	2000-3000	least stable
Graphite/iron phosphate	3.65/ 3.25	.36/.16	90-115	>3000	Stable
Lithium titanate/Mn spinel	2.8/2.4	.18/.11	60-75	>5000	most stable

Figure 12: Pouch Packaged Cells

Figure 13: Small, Spiral Wound Cells

Figure 14: Spiral Wound Large Cells

44 Ah cell **7.5 Ah**

In order to determine the performance of the cells/modules, the following tests were performed:

1) Constant current tests starting at C/1 and up to currents at which the Ah capacity of the cell begins to show a significant decrease with rate.
2) Constant power tests starting at about 100 W/kg and up to powers (W/kg) at which the energy density (Wh/kg) begins to show a significant decrease with rate.

3) 5 sec pulse tests at high currents (5-10C) at states of charge between 90 percent -10 percent to determine the open-circuit voltage and resistance from which the power capability of the cells can be calculated.

The power capability of the cells/modules was determined in the present study by determining the open-circuit voltage and resistance as a function of state-of-charge and calculating the pulse power using the following equation:

$$P = Eff\ (1-Eff)\ V_{oc}^{2}/R$$

where Eff is the pulse efficiency, $Eff = V_{pulse}/V_{oc}$

The power density is simply calculated as P/battery weight or volume. This method is not too different from that given in the USABC test manual for PHEV batteries and can be applied for cells/modules independent of the vehicle in which they would be used.

Test data for the 15Ah EIG iron phosphate cell and the Altairnano 11Ah titanate oxide cell are given in Tables 25 and26.

Table 25: Test Data for the 15 Ah EIG Iron Phosphate Cell

Iron Phosphate				
FO 15A	**Weight .424kg**	**3.65-2.0V**		
Power (W)	**W/kg**	**Time (sec)**	**Wh**	**Wh/kg**
62	142	2854	49.5	117
102	240	1694	48.0	113
202	476	803	45.1	106
302	712	519	43.5	103
401	945	374	41.7	98
Current (A)	**Time (sec)**	**Ah**	**Crate**	**Resistance mOhm**
15	3776	15.7	.95	
30	1847	15.4	1.95	2.5
100	548	15.2	6.6	

200	272	15.1	13.2	
300	177	14.8	20.3	

Table 26: Test Data for the Altairnano 11Ah Lithium Titanate Oxide Cell

Constant Current Test Data (2.8-1.5V)

I(A)	nC	Time (sec)	Ah	Resistance mOhm
10	.8	4244	11.8	--
20	1.7	2133	11.9	--
50	4.5	806	11.2	2.2
100	9.2	393	10.9	2.1
150	15.3	235	9.8	--
200	---	116	6.4	--

Resistance Based on 5 Sec Pulse Tests

Constant Power Test Data (2.8-1.5V)

Power W	W/kg	Time sec	nC	Wh	Wh/kg
30	88	2904	1.2	24.2	71.2
50	147	1730	2.1	24.0	70.7
70	206	1243	2.9	24.2	71.0
100	294	853	4.2	23.7	69.7
150	441	521	6.9	21.7	63.8
170	500	457	7.9	21.6	63.5
260	764	255	14	18.4	54.2
340	1000	103	35.0	9.7	28.6

The iron phosphate cell could be used in a plug-in hybrid with an all-electric range of 20-40 miles and the titanate oxide cell would be better suited for vehicles with a short all-electric range of 10-15 miles.

3.3 Comparisons of the Performance of Lithium-ion Cells of the Different Chemistries from Various Battery Developers

A summary of the data for the different chemistries is shown in Table 28. It is clear from the table that both the energy density and power capability of the cells vary over a wide range and that there are significant trade-offs between energy and power with all the chemistries. Energy density and power capability are discussed separately.

3.3.1 Energy density

It is clear from Table 28 that the energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the negative electrode can have energy density between 60-70 Wh/kg. Hence in terms of energy density, the rankings of the different chemistries are clear and the differences are significant: 1. NiCo, 2. iron phosphate, 3. lithium titanate oxide. The question of what fraction of the energy density is useable in a specific vehicle application could decrease the relative advantage of the different chemistries.

Table 27: Summary of the Performance Characteristics of Lithium-ion Cells of Different Chemistries from Various Battery Developers

Manufacturer	Technology type	Ah	Voltage range	Wh/kgat 300 W/kg	(W/kg)$_{90\%eff.}$ 50% SOC
K2	Iron phosphate	2.4	3.65-2.0	86	667
EIG	Iron phosphate	10.515.7	3.65-2.0	83113	708919
A123	Iron phosphate	2.1	3.6-2.5	88	1146
Lishen	Iron Phosphate	10.2	3.65-2.0	82	161
EIG	Graphite/ Ni CoMnO2	18	4.2-3.0	140	895
GAIA	Graphite/LiNiCoO2	42	4.1-3.0	94	1742at 70%SOC
Quallion	Graphite/Mn spinel	1.8	4.2-3.0	144	491at 60%SOC
		2.3	4.2-3.0	170	379at 60%SOC

Manufacturer	Technology type	Ah	Voltage range	Wh/kgat 300 W/kg	(W/kg)$_{90\%eff.}$ 50% SOC
Altairnano	**Lithium Titanate**	**1152**	**2.8-1.5**	**7057**	**684340**
EIG	**Lithium Titanate**	**12.0**	**2.7-1.5**	**43**	**584**

3.3.2 Power capability

The situation regarding the power capability (W/kg) of the different chemistries is not as clear as was the case for energy density because of the energy density/power capability trade-offs inherent in battery design. Further the question of the maximum useable power density is also application specific. In order to have a well-defined basis for comparing the different chemistries and cells, the power density (W/kg) for a 90 percent efficient pulse at 50 percent SOC is shown in Table 28. The power densities can vary over a wide range even for a given chemistry. This is particularly true for the graphite/NiCoMn chemistry. In general, it seems possible to design high power batteries (500-1000 W/kg at 90 percent efficiency) for all the chemistries if one is willing to sacrifice energy density and likely also cycle life. The data in Table 6 indicate that high power iron phosphate cells can be designed without a significant sacrifice in energy density. When power densities greater than 2000 W/kg for lithium-ion batteries are claimed, it is for low efficiency pulses. For example, for an efficiency of 65 percent, the 15Ah EIG iron phosphate battery has a pulse power of 2330 W/kg rather than the 919 value for a 90 percent efficient pulse.

3.3.3 Fast charging characteristics of lithium-ion batteries

There is presently considerable interest in fast charging of batteries in both battery- powered and plug-in hybrid vehicles. It is claimed that both the lithium titanate oxide and iron phosphate chemistries can be fast charged in about ten minutes. A series of tests have been performed using the 11Ah titanate oxide cell and the 15Ah iron phosphate cell whose characteristics were discussed previously. Tests were performed for charging rates between 1C and 6C. The cells were charged to a maximum (clamp) voltage and then the current was tapered to 1/10 the initial charge current. For all the tests, the cells were discharged at the 1C rate (1hr.) to determine the effect of charging rate on cell Ah capacity. The test results, which are summarized in Table 28, indicate that both battery chemistries can be fast charged. However, the fast charge capability of the titanate oxide chemistry is superior to that of the iron phosphate chemistry both with respect to temperature rise during charging and the Ah capacity retention for charging up to the maximum voltage without taper. For example, in the case of the lithium titanate oxide cell charged at 66A in 620 sec, the 1C capacity was 11.2 Ah compared to 12.0 Ah for a 1C (1 hr) charge.

Both cells were also fast charged for five repeated cycles to investigate the effect on the temperature rise and Ah capacity. In these tests, the cells were not actively cooled. The results

for the lithium titanate oxide cell are shown in Table 29 and in Figure 15. The charge time to the maximum voltage (cut-off of charge) was 614 sec with a temperature rise during charging of 4.5 deg C. However, the temperature decreased back to ambient during the discharge so that the temperature remained stable during the five cycles. The capacity of the cell was 11.2Ah for each cycle.

These tests indicate that fast charging of the lithium batteries should be possible without great difficulty if high power charging stations are available. Recent life cycle data (see Figure 16) taken by Altairnano indicate that the 11 Ah cells have long cycle life under fast charge (x C) conditions so the effect of fast charging on cycle life should not be a concern for the lithium titanate oxide batteries.

Table 28: Fast Charge Test Data for Lithium-ion Chemistries

EIG iron phosphate 15 Ah cell								
							Temp Rise During Cha	
Charge		Time to	Taper	Charge to	Total		Initial	Temp
Current		Cutoff	Time	Cutoff	Charge	Discharge	Temp	Change
(Amps)		(secs)	(secs)	(Amp-hrs)	(Amp-hrs)	(Amp-hrs)	(C)	(C)
15		3630	210	15.2	15.4	15.50	22.5	0
30		1770	210	14.7	15.4	15.45	22.5	1.5
45		1140	199	14.2	15.4	15.38	22.5	3
60		840	172	13.9	15.3	15.30	23.5	4.5
75		630	184	13.1	15.3	15.29	25.5	5.5
90		480	219	11.9	15.2	15.17	23	7
120		240	316	7.9	15.2	15.16	25	9
No Taper								
60		780.4		12.9		12.99		
90		464.8		11.6		11.60		
Altairnano titanate oxide 11 Ah cell								
							Temp Rise During Cha	
Charge		Time to	Taper				Initial	Temp
Current		Cutoff	Time		Charge	Discharge	Temp	Change
(Amps)		(secs)	(secs)		(Amp-hrs)	(Amp-hrs)	(C)	(C)
11		3920	81	11.9	12.0	12.00	22.5	0
22		1950	68.5	11.9	12.0	12.00	22	0.5
33		1300	57.7	11.9	12.0	12.00	22.5	1.5
44		970	59.2	11.8	12.0	12.01	23	2.5
55		760	74.8	11.6	12.0	11.97	21.5	4
66		620	83	11.3	12.0	11.97	22.5	4.5
88		440	103.1	10.7	12.0	11.97	24	6.5

Table 29: Repeated Fast Charging Cycles for the 11 Ah Lithium Titanate Oxide Cell

66 Amps	charge to 2.8V		12A discharge to 1.5V		no active cooling	
		Time to			Initial	Highest
	Charge or	Cutoff	charge	Discharge	Temp	Temp
Cycle	Discharge	(secs)	Amp-hrs	Amp-hrs	(C)	(C)
1	Chg	614.4	11.26		21.5	26
2	Dischg			11.19	24	22
2	Chg	614.7	11.27		21.5	26.5
3	Dischg			11.18	24	22
3	Chg	614.5	11.27		21.5	26
4	Dishcg			11.18	24	22
4	Chg	614.1	11.26		21.5	26
5	Dischg			11.17	23.5	22
5	Chg	614.1	11.26		21.5	26

Figure 15: Five Fast Charge Cycles for the Altairnano 11Ah Lithium Titanate Cell

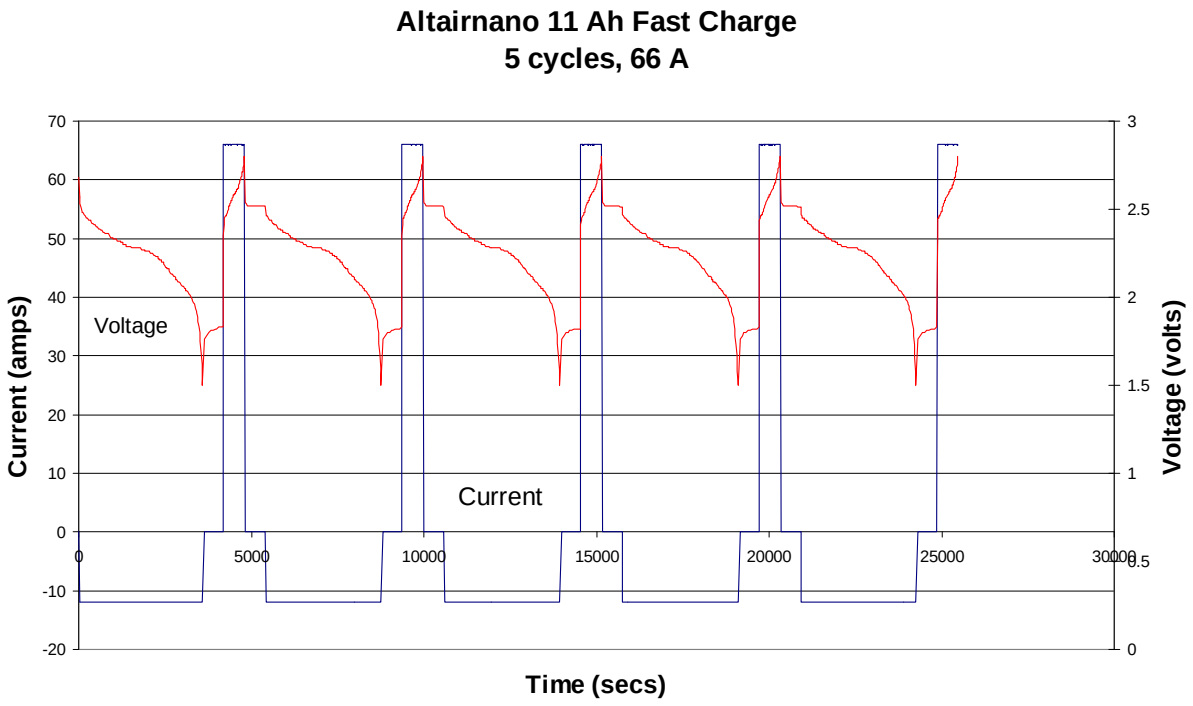
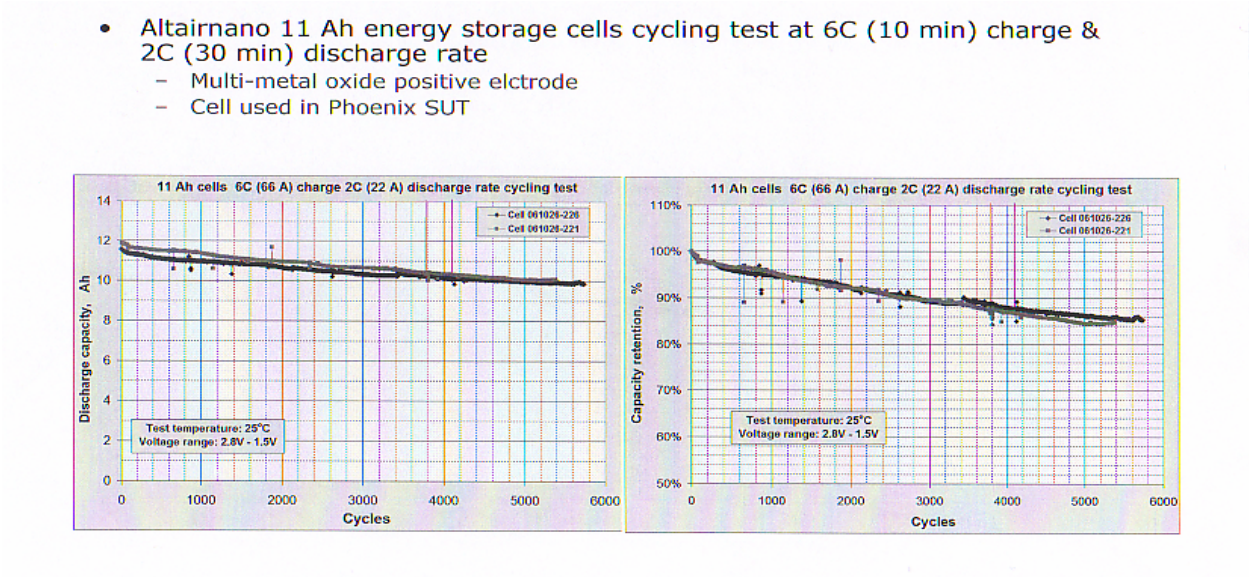


Figure 16: Life Cycle Data from Altairnano for the 11 Ah Cell Under Fast Charging



3.4 Plug-In Hybrid Vehicle Simulations Using Various Battery Chemistries

Simulations of Prius plug-in hybrids have been performed with ***Advisor*** utilizing lithium-ion batteries of the different chemistries. The UC Davis test data were used to prepare the battery input files needed in ***Advisor***. Simulations were made for battery packs weighing 60 kg and 120 kg. The results of the simulations are given in Table 30 and Table 31. Table 31 shows that plug-in hybrids can be designed using the various lithium-ion batteries as well as a nickel metal hydride battery. However, the charge depleted (CD) electric ranges of the various designs and their fuel economy in the CD mode are much different and the differences are highly dependent on the driving cycle. The CD ranges are larger for the batteries with the higher energy densities and the fuel economies in the CD mode are highest for the batteries that are capable of high peak power.

High battery power capability permits the vehicle to operate in the all-electric mode (engine off) until the energy in the battery is depleted. The fuel economy in the charge sustaining (CS) mode is dependent on the driving cycle, but not significantly on the battery energy density and weight of the battery pack. The weight of the battery and its energy density have a large effect on CD operation as would be expected. The simulation results show that the selection of the battery chemistry for plug-in hybrids is closely linked to the details of the vehicle design and performance specifications and expected driving cycle. Economic factors such as cycle life and battery cost and battery management and safety issues must also be considered in selecting the most appropriate battery chemistry of plug-in hybrids.

Table 30: Simulation Results for Prius Phevs Using Various Lithium-ion Batteries

		60 kg Battery			
		Varta (Ovonic)	LFP (A123)	NCM (Gaia)	LTO (Altairnano)
		Ni-MH	Li-Ion	Li-Ion	Li-Ion
(1) Power					
(Cell power density)	W/kg	333	1100	1700	680
Pack Power Density[a]	W/kg	250	825	1275	510
Battery Peak Power	kW	15	50	77	31
Motor peak power[b]	kW	**13**	**42**	**65**	**26**
(2) Energy Capacity					
(Cell Energy density)	Wh/kg	71	90	96	70
Pack Total Energy Density[a]	Wh/kg	54	68	72	53
Total Energy	kWh	3.21	4.05	4.32	3.15
Available Energy[c]	kWh	**2.57**	**3.24**	**3.46**	**2.52**
Cell Voltage	V	**13.4**	**3.2**	**3.6**	**2.3**
Cell Capacity	Ah	**15**	**19**	**20**	**15**
# of Cells	#	**16**	**67**	**60**	**94**
(3) PHEV performance (US06)					
CD electricity use	Wh/mile	171	225	175	157
CD range	miles	15	14	20	16
CD gasoline use	mpg	98	3000	inf	425
CS gasoline use	mpg	44	44	43	43
(3) PHEV performance (UDDS)					
CD electricity use	Wh/mile	149	126	97	93
CD range	miles	17	26	36	27
CD gasoline use	mpg	800	inf	inf	inf
CS gasoline use	mpg	67	73	69	71
(3) PHEV performance (HWFET)					
CD electricity use	Wh/mile	178	155	120	114
CD range	miles	14	21	29	22
CD gasoline use	mpg	1500	inf	inf	inf
CS gasoline use	mpg	66	67	64	66

[a] Assuming packing factor = 0.75

[b] Assuming motor efficiency equals = 0.85

[c] Assuming DOD = 0.8

Table 31: Simulation results for Prius PHEVs Using Various Lithium-ion Batteries

		120 kg Battery			
		Varta (Ovonic)	LFP (A123)	NCM (Gaia)	LTO (Altairnano)
		Ni-MH	Li-Ion	Li-Ion	Li-Ion
(1) Power					
(Cell power density)	W/kg	333	1100	1700	680
Pack Power Density[a]	W/kg	250	825	1275	510
Battery Peak Power	kW	30	99	153	61
Motor peak power[b]	kW	**25**	**84**	**130**	**52**
(2) Energy Capacity					
(Cell Energy density)	Wh/kg	71	90	96	70
Pack Total Energy Density[a]	Wh/kg	54	68	72	53
Total Energy	kWh	6.43	8.10	8.64	6.30
Available Energy[c]	kWh	**5.14**	**6.48**	**6.91**	**5.04**
Cell Voltage	V	**13.4**	**3.2**	**3.6**	**2.3**
Cell Capacity	Ah	**30**	**37**	**40**	**29**
# of Cells	#	**16**	**68**	**60**	**94**
(3) PHEV performance (US06)					
CD electricity use	Wh/mile	246	182	169	187
CD range	miles	21	36	41	27
CD gasoline use	mpg	329	inf	inf	inf
CS gasoline use	mpg	43	44	45	42
(3) PHEV performance (UDDS)					
CD electricity use	Wh/mile	146	104	97	104
CD range	miles	35	62	71	48
CD gasoline use	mpg	inf	inf	inf	inf
CS gasoline use	mpg	69	71	71	72
(3) PHEV performance (HWFET)					
CD electricity use	Wh/mile	171	127	118	126
CD range	miles	30	51	59	40
CD gasoline use	mpg	inf	inf	inf	inf
CS gasoline use	mpg	66	66	66	66

[a] Assuming packing factor = 0.75

[b] Assuming motor efficiency equals = 0.85

[c] Assuming DOD = 0.8

3.5 Second-Use of Plug-in Vehicle Batteries

3.5.1 General Considerations

The high cost of batteries continues to be one of the primary barriers to the commercialization of plug-in electric vehicles. In addition, vehicle applications are more demanding on batteries than most other applications in terms of performance and cycle life. Hence there is considerable interest in the possibility that vehicle batteries could be used in other applications after they are no longer suitable for use in vehicles. If this second use of vehicle batteries is feasible, it could defray part of the high initial cost of the batteries to the original vehicle owner. In this paper, batteries to be used in plug-in electric vehicles are of particular interest along with second applications of interest to electric utilities. The present study is concerned with lithium-ion batteries, but the considerations are closely related to those discussed in the earlier study. There have been recent studies of electrical energy storage in utility applications which are pertinent to the present second use study. The results of those studies are also relevant to the present study.

As shown in Tables 22 and 23, the requirements for batteries to be used in vehicle applications vary markedly with the application in terms of energy stored, peak power, and size (kg). These differences are highlighted in Table 32 for plug-in hybrids and battery powered vehicles of various ranges. As a result of these differences, the cell size (Ah) and module/pack characteristics of batteries available to be recycled from plug-in electric vehicles will vary over a wide range.

Table 32: Battery and Cell Characteristics for Plug-in Electric Vehicles

Electric range mi	System voltage	Weight of cells kg *	Energy stored kWh **	Ah/cell	Peak power kW	P/E ratio	Peak W/kg
10	150	30	3.6	24	50	13.9	1666
15	200	45	5.4	27	55	10.2	1222
20	250	60	7.2	29	60	8.3	1000
30	300	90	10.8	36	75	6.9	833
40	300	120	14.4	48	100	6.9	833
50	300	150	18	60	100	5.6	667
100	300	208	25	83	105	4.2	505

* energy density of the cells 120 Wh/kg

** useable fraction of stored energy 70%

The batteries in the hybrid vehicles presently being marketed in California are warranted for 10 years or 120,000 miles by the vehicle manufacturer. These warranties are set in regulations of the California Air Resources Board. It is expected that the same warranties would apply to the

batteries in the plug-in vehicles. For deep-discharge batteries, end-of-life is usually defined as when the battery capacity decreases by 20 percent from the rated value and/or the peak (pulse) power capability decreases by 25 percent from the initial value due to an increase in battery resistance. It is easier for the vehicle owner to discern a decrease in battery capacity (decrease in range) than a decrease in power capability. Hence it can be expected there would be some variability in the condition of the batteries when it is determined their performance is no longer satisfactory for the vehicle application. Clearly properly assessment of the condition of the batteries made available for reuse is essential and will require careful attention.

Since the energy and power requirements of the batteries in the second-use application would be expected to be significantly less demanding than in the vehicle application, it will be necessary to determine the calendar and cycle life of the partially expended batteries in the new application. This will require careful testing of the used vehicle batteries both to determine their condition and the life remaining, which is likely to vary for different second-use applications.

3.5.2 Potential Second-Use Applications

There are a number of possible second-use applications. These include the following:

(a) Transmission quality
(b) Spinning reserve
(c) Regional regulation
(d) Load leveling base generation
(e) Load leveling renewable generation
(f) Peak reliability and peak shaving
(g) UPS systems
(h) Light commercial load leveling
(i) Telecommunications backup
(j) Residential load leveling

The energy storage system requirements for the various applications are summarized in Table 33.

Table 33: Energy Storage System Requirements for Various Applications

Application	Duration	Energy storage	Power
Transmission quality	**10-100 secpulses**	**<1 MWh**	**100 MW**
Spinning reserve	**15 minutes**	**7.5 MWh**	**20 MW**
Regional regulation	**Continuous**	**2 MWh**	**10-20 MW**

	cycling		
Load leveling base generation	**>5 hrs**	**50 MWh**	**10 MW**
Load level renewable generation	**1-10 hrs**	**1-10 MWh**	**1-5 MW**
Peak reliabilityPeak shavingUPS	**-4 hrs.**	**3-4 MWh**	**1-2 MW pulses**
Light commercial load leveling	**3 hrs.**	**75-100 kWh**	**200 kW pulses25 kW average**
Telecommunicationsbackup	**5-10 hrs.**	**25-50 kWh**	**5 kW**
Residential load leveling	**3 hrs.**	**3-4 kWh**	**10 kW peak1 kW average**

The system requirements in Table 33 seem to indicate that the second-use of batteries from plug-in vehicles are best suited for the last three applications. The energy storage and power requirements for those applications are comparable to those of the original application in vehicles and would require only minor reconfiguring of the packs. In addition, the cell size (Ah) of the plug-in vehicle batteries would be appropriate resulting in the need to series/parallel relatively few packs in these applications. It seems unlikely that the battery packs from Prius-type charge sustaining hybrids presently be sold in large numbers would be appropriate for second-use applications, because their cell size is so small (<5 Ah using lithium-ion cells) and the packs will store less than 1 kWh. The applications closely related to utility operations require MW power and MWh of energy storage which are orders of magnitude larger than that of the vehicle applications. Configuring battery packs for the utility applications would require packs from hundreds of vehicles which would be expensive and difficult to maintain uniform quality of performance of the large packs.

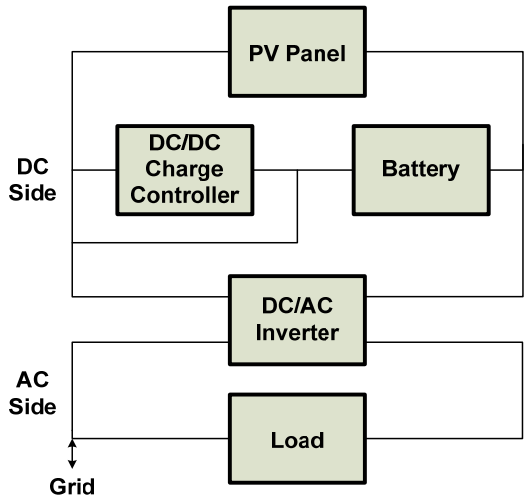
3.5.3 Residential/Commercial Applications with PV

Batteries can be used in grid-connected residential and commercial PV systems either for load leveling the demand and/or storing energy for later use when electricity is higher price or because the installation is in a remote area, off-grid. The voltage of the DC side of the residential systems is in the range of 24-150V and that of large commercial systems in the range of 500-600V. The peak power of the residential systems is 3-5 kW and that of the commercial systems 100-200 kW. A schematic of these systems is shown in Figure 17. Battery charging is done using by a battery charge controller that usually chops the PV panel voltage down to that needed to charge the battery. Electrical energy to the DC/AC inverter can be provided by the PV panel or battery alone or the PV panel and battery in combination. For crystalline silicone cells, a standard 1.5 ft x 5 ft panel can provide 40V and 200W. These panels or sub-sizes of the

panels would be arranged in series and parallel to get the voltage and current required by the system.

The energy stored in the batteries could be relatively small. For example in a residential system, the batteries could be 60Ah and the voltage 96V resulting in about 6 kWh of storage. For a commercial system, the corresponding values could be 300 Ah, 400V, and 120 kWh. These battery system requirements are certainly doable with batteries from plug-in vehicles especially those with a reasonably long electric range.

Figure 17: PV/Battery System Schematic



3.5.4 Prospects and barriers

In principle, it would seem that implementation of the second-use of plug-in electric vehicle batteries in the small scale applications that seem most appropriate should not be overly difficult. These applications could be essentially local to the vehicles from which the batteries are taken and require only relatively short transportation of the used batteries for processing and distribution to the new customers. The primary barrier to implementation would be demonstrating the economic viability of the reuse of the batteries in terms of the cost of the batteries to the second owners and a guarantee that the used batteries would have satisfactory calendar and cycle life. It would be necessary to convince potential customers of the recycled batteries that their use is more cost effective for them than purchasing new batteries, which could include low cost lead-acid batteries.

There are several ways in which reuse of the batteries could be utilized to reduce the cost of plug-in vehicle batteries either initially or over time as the vehicle is used. In any case, the purchasers of plug-in vehicles would have to benefit from the value of the second-use of the batteries. This could be done by subtracting some fraction of the sale price of the reused batteries from the initial cost of the new plug-in vehicle batteries. This could be done most easily if the same company owned the batteries over their complete life, including second-use. Another approach is for the plug-in vehicle owner to lease the batteries or pay for the batteries as they used electricity stored in the batteries. In either case, the cost of the batteries would be paid over their life time significantly reducing the initial cost of the plug-in vehicle.

One of the barriers to implementing the second-use battery market is the difficulty in establishing a business case for second-use company. Over a period of time this will require information regarding the performance, cycle life, and price of new plug-in vehicle batteries and the likely condition of the batteries when they would be removed from the vehicle at end of life after at least 5-10 years of service. The second-use company would also need sufficient information regarding the condition of the batteries and the second-use application to be able to set a reliable warranty for the batteries. In addition, they would need a good indication of the size of the markets they would be involved with. The end result would have to be a price for the reused batteries that would foster both the markets for the plug-in vehicles and the second-use batteries. An analysis of these markets should be undertaken as soon as the needed input information becomes available.

CHAPTER 4:
Summary and Conclusions

This paper advances the available data and evaluation of batteries for use in plug-in electric vehicles. These vehicles use batteries that store a significant amount (kWh) of energy and thus will offer the possibilities for second-use in utility related applications such as residential and commercial backup systems and solar and wind generation systems. Lithium-ion batteries for plug-in hybrid vehicles with all-electric ranges of 10-40 miles and battery-powered vehicles with a range of 100 miles are characterized in terms of cell size (Ah), energy storage (kWh), and power (kW) and are used for various discussions in this paper.

Cell test data are presented for the performance of lithium-ion batteries of several chemistries suitable for use in plug-in vehicles. The energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the negative electrode can have energy density between 60-70 Wh/kg. The question of what fraction of the energy density is useable in a specific vehicle application can decrease the relative advantage of the different chemistries. The situation regarding the power capability (W/kg) of the different chemistries is not as clear as was the case for energy density because of the energy density/power capability trade-offs inherent in battery design. The power densities can vary over a wide range even for a given chemistry. This is particularly true for the graphite/NiCoMn chemistry. In general, it is possible to design high power batteries (500-1000 W/kg at 90 percent efficiency) for all the chemistries if one is willing to sacrifice energy density and likely also cycle life.

There is presently considerable interest in fast charging of batteries in both battery- powered and plug-in hybrid vehicles. A series of tests were been performed using the 11Ah titanate oxide cell and the 15Ah iron phosphate cell. Tests were performed for charging rates between 1C and 6C. The test results indicate that both battery chemistries can be fast charged. However, the fast charge capability of the titanate oxide chemistry is superior to that of the iron phosphate chemistry both with respect to temperature rise during charging and the Ah capacity retention for charging up to the maximum voltage without taper. Both cells were also fast charged for five repeated cycles to investigate the effect on the temperature rise and Ah capacity. In these tests, the cells were not actively cooled. These tests indicate that fast charging of the lithium batteries will be is possible without great difficulty if high power charging stations are available.

Simulations of Prius plug-in hybrids have been performed with Advisor utilizing lithium-ion batteries of the different chemistries. Simulations were made for battery packs weighing 60 kg and 120 kg. Plug-in hybrids can be designed using the various lithium-ion batteries as well as a nickel metal hydride battery. However, the charge depleted (CD) electric ranges of the various designs and their fuel economy in the CD mode are much different and the differences are highly dependent on the driving cycle. The CD ranges are larger for the batteries with the higher energy densities and the fuel economies in the CD mode are highest for the batteries that

are capable of high peak power. High battery power capability permits the vehicle to operate in the all-electric mode (engine off) until the energy in the battery is depleted. The fuel economy in the charge sustaining (CS) mode is dependent on the driving cycle, but not significantly on the battery energy density and weight of the battery pack. The simulation results show that the selection of the battery chemistry for plug-in hybrids is closely linked to the details of the vehicle design and performance specifications and expected driving cycle. Economic factors such as cycle life and battery cost and battery management and safety issues must also be considered in selecting the most appropriate battery chemistry of plug-in hybrids.

The high cost of batteries continues to be one of the primary barriers to the commercialization of plug-in electric vehicles. If the second-use of vehicle batteries is feasible, it could defray part of the high initial cost of the batteries to the original vehicle owner. There are a number of possible second-use applications. Some of these applications are closely linked to utility operations and others are connected to commercial and residential end-users. Since the energy storage and power requirements for the end-user applications are comparable to those of the original vehicle applications and would require only minor reconfiguring of the packs, these applications are well suited for second-use. The applications closely related to utility operations do not seem well suited for second-use. Those applications require MW power and MWh of energy storage which are orders of magnitude larger than that of the vehicle applications. Configuring battery packs for a utility application would require packs from hundreds of vehicles which would be expensive and be difficult to maintain uniform quality of performance of the large packs.

The primary barrier to implementation of the second-use is demonstrating the economic viability of the reuse of the batteries in terms of the cost of the batteries to the second owners and a guarantee that the used batteries would have satisfactory calendar and cycle life. It would be necessary to convince potential customers of the recycled batteries that their use is more cost effective for them than purchasing new batteries, which could include low cost lead-acid batteries.

Establishing the business case for second-use will require information regarding the performance, cycle life, and price of new plug-in vehicle batteries and the likely condition of the batteries when they are removed from the vehicle at end of life after 5-10 years of service. The second-use enterprise will need sufficient information regarding calendar and cycle life expectancy to be able to set a reliable warranty for these batteries. In addition, they would need a reliable indication of the size of potential markets for second-use batteries. If a secondary use market could be successfully established, then the price for the reused batteries would foster the markets for both the plug-in vehicles and also the second-use batteries. An analysis of these markets should be undertaken once the necessary input information becomes available.

GLOSSARY

CD	Charge Depleted
CS	Charge Sustaining
EV	Electric Vehicle
PHEV	Plug-in Hybrid Vehicle

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