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Battery Requirements for Plug-In Hybrid Electric Vehicles – Analysis and Rationale

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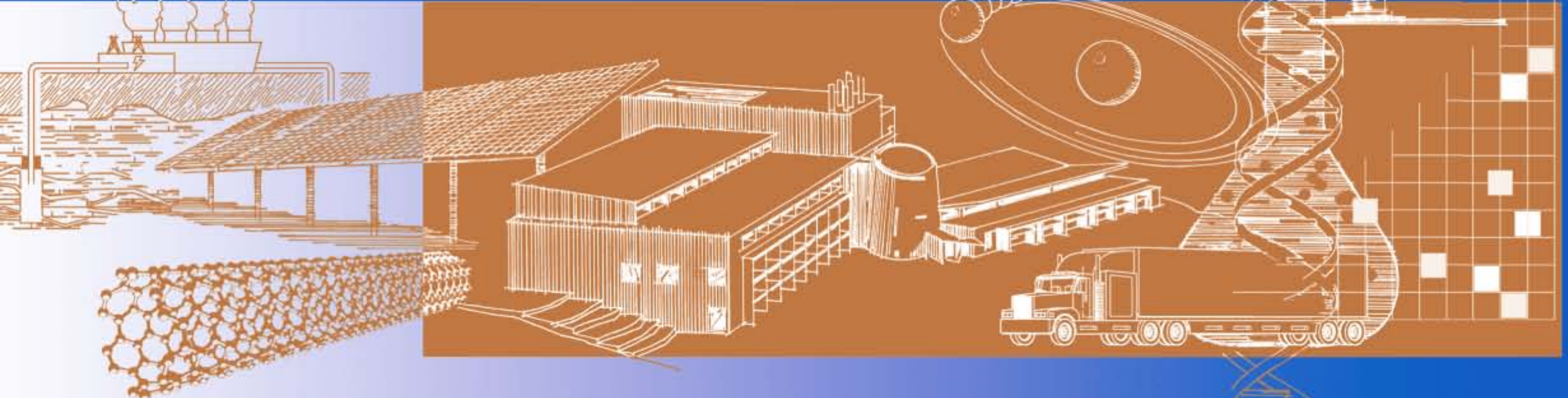

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Battery Requirements for Plug-In Hybrid Electric Vehicles – Analysis and Rationale

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Abstract

Plug-in hybrid electric vehicles (PHEVs) have the potential to displace a significant amount of petroleum in the next 10 to 20 years. The main barriers to the commercialization of PHEVs are the cost, safety, and life of batteries. Therefore, the U.S. Department of Energy and auto companies have embarked on a program to develop batteries for PHEVs. Defining battery targets or requirements to benchmark progress is essential. In support of the U.S. Advanced Battery Consortium (USABC), vehicle analysis and battery sizing studies were performed to recommend battery requirements. The analysis process included defining vehicle platforms, vehicle performance targets, the desired equivalent electric range operating strategy (all electric or blended), and the state-of-charge window. Based on the analysis, USABC members recommended two categories of batteries: one for a 10-mile equivalent electric vehicle (EV) range (high power/energy ratio) and one for a 40-mile EV range (high energy/power ratio). Four sets of requirements were defined: (1) system-level (range pack cost, calendar life, volume, weight, and energy efficiency); (2) charge-depleting hybrid EV (HEV) mode (2-second and 10-second discharge power, 10-second regenerative braking power, available energy at constant power, number of deep cycles, maximum recharge rate); (3) charge-sustaining HEV mode (available energy for charge-sustaining operation, cold cranking power, number of shallow charge-sustaining cycles); and (4) battery limits (maximum current, maximum and minimum voltage, operating and survival temperatures). In this paper, we present the assumptions, the analysis, discussions, and the resulting requirements adopted by USABC.

Keywords: Plug-in hybrid electric vehicles, PHEV, battery, EV range, charge-depleting

1. Introduction

A plug-in hybrid electric vehicle (PHEV) is a hybrid electric vehicle (HEV) with the ability to recharge its energy storage system with electricity from an off-board power source such as a grid. The key advantage of PHEV technology relative to hybrid electric and conventional vehicles is fuel flexibility. A PHEV uses stored electrical energy to propel the vehicle and reduce petroleum consumption by the combustion engine. This provides an opportunity to drive primarily in electric mode and reduce emissions in congested cities around the world.

A study by Simpson estimates that a PHEV with usable electrical energy storage equivalent to 20 miles of electric travel (PHEV20) would reduce petroleum consumption by 45% relative to that of a comparable conventional combustion engine vehicle [1]. Plug-in hybrid electric vehicles have the potential to displace a significant amount of petroleum in the next 10 to 20 years. Many believe that PHEVs could enter the passenger vehicle market much sooner than hydrogen fuel cell vehicles, since there is no need for a costly hydrogen fueling infrastructure and there are fewer technical barriers. As a result, a significant amount of activity has been initiated to advance the development of PHEVs and batteries suitable for them. For example, the U.S. Department of Energy's (DOE) Vehicle Technologies Program (which includes the FreedomCAR and Fuel Partnership) has developed a research and development (R&D) plan to evaluate the potential of PHEVs, and the program has proposed R&D activities to improve the batteries and power electronics that go into PHEVS while also improving vehicle efficiency technologies [2].

The chief barrier to the commercialization of PHEVs has been identified to be the battery, in terms of cost, combined shallow/deep cycle life, calendar life, volume, and safety. Therefore, DOE and U.S. auto companies, through the U.S. Advanced Battery Consortium (USABC), have embarked on a sizable program to develop batteries for PHEVs. Such a program needs to have battery targets or requirements to benchmark progress. In support of USABC, we have performed vehicle analysis and battery sizing studies to recommend battery requirements. USABC intends to use these requirements in soliciting proposals from potential battery developers.

The National Renewable Energy Laboratory (NREL) and Argonne National Laboratory (ANL) have conducted a number of analyses to help define these battery requirements. Researchers at ANL developed a battery model and a process for performing analyses for sizing energy storage systems for plug-in applications and investigated the impacts of all-electric range, drive cycle, and control strategy [3]. NREL researchers performed simulations to investigate the impacts of component sizes (engine power, motor power, and battery power and energy) in meeting performance constraints and energy consumption characteristics of vehicles over different driving profiles as a function of the equivalent electric range capability and the degree of hybridization [4, 5]. NREL also investigated component costs and impacts on benefits [1].

These definitions and terminologies will be helpful in the discussion that follows:

- Charge-depleting (CD) mode: An operating mode in which the energy storage state-of-charge (SOC) may fluctuate but, on average, decreases while the vehicle is driven.
- Charge-sustaining (CS) mode: An operating mode in which the energy storage SOC may fluctuate but, on average, is maintained at a certain level while the vehicle is driven. This is the common operating mode of commercial hybrids such as the Ford Escape hybrid, the Toyota Prius, the Chevy Tahoe hybrid, and the Dodge Durango hybrid.
- All-electric range (AER): After a full recharge, the total miles driven electrically (with the combustion engine off) before the engine turns on for the first time.
- Blended or charge-depleting hybrid (CDH) mode: An operating mode in which the energy storage SOC decreases, on average, while the vehicle is driven; the engine is used occasionally to support power requests.
- Zero-emission vehicle (ZEV) range: The same as the all-electric range (AER); there are no tailpipe emissions when the vehicle is in EV mode.

As part of the process of defining battery requirements, the USABC formed a PHEV Battery Work Group. As members of this Work Group, we obtained input from a number of organizations, engaged in discussions, made some assumptions for vehicle and expected performance attributes, and performed analyses. The results of the analysis were discussed in the Work Group and reported back to USABC and FreedomCAR Technical Teams (including Vehicle System Analysis) for guidance. Based on the discussions, questions, and feedback, we looked at the impact of battery and range assumptions as well as different strategies, drive cycles, and vehicle attributes. In this paper, we present the rationale behind selecting the assumptions, performing the analyses, and the resulting requirements.

2. Approach for Power and Energy

From previous analyses, it was understood that the energy storage requirements for PHEVs depend on the vehicle platform, vehicle performance, hybrid configuration, drive cycle, electric range, operating strategy, all-electric range capability, and level of electric performance on various drive cycles. The requirements were not intended to be specific nor to depend on a particular control strategy. Rather, they intended to be flexible enough to allow them to be applied to different vehicles and operating strategies.

The analysis process included defining vehicle platforms (mass, aerodynamic, and rolling resistance); vehicle performance targets (acceleration, top speed, grade); the desired equivalent electric range (10–60 miles); the operating strategy (all-electric and blended); and the usable SOC window. The analysis (including vehicle simulations and power/energy calculations) provided electric vehicle consumption (Wh/mile), peak power requirements for a particular drive cycle, and peak power requirements during charge-sustaining operation.

2.1 Vehicle Assumptions

The choice of a vehicle platform and performance characteristics strongly impacts component sizing and battery requirements. Cars make up a significant portion of the light-duty vehicle market, and midsize cars represent a large portion of the car market, so to represent this segment we studied a midsize car, similar to a Chevy Malibu. Another large portion of the light-duty vehicle market is captured by sport utility vehicles (SUVs), so a midsize SUV similar to the Ford Explorer was investigated. SUVs are popular with U.S. drivers, so it was important to consider a plug-in for this market segment. SUVs also consume more fuel than cars, so there is a greater opportunity to save petroleum with plug-in hybrid SUVs; however, the higher cost and volume differential were concerns. Because of the growing interest among U.S. consumers in crossover utility vehicles (UVs) (a vehicle somewhere between a traditional SUV and a car), a midsize crossover UV, similar to the Chrysler Pacifico, was also studied.

Research included several iterations on the mass, frontal area, rolling resistance, and aerodynamic drag coefficient. Table 1 shows the typical vehicle assumptions (midpoints) that were used for the requirement analysis and recommendations. A reasonable sensitivity around each parameter was considered and presented in [3]. The vehicle performance targets, selected based on today's vehicle performance and future trends, are given in Table 2.

Table 1. Vehicle assumptions used for simulations and component sizing

Parameter	Units	Midsize Car	Midsize Crossover UV	Midsize SUV
Approximate Glider Mass	kg	940	1100	1200
Approximate Vehicle Test Mass	kg	1600	1950	2000
Frontal Area	m^2	2.22	2.69	2.89
Drag Coefficient		0.308	0.417	0.42
Rolling Resistance		0.009	0.010	0.011
Accessory Electrical Load	W	800	1000	1200

Table 2. Vehicle performance parameters

Parameter	Value
Acceleration from 0 to 60 mph	9 s
Top Speed	100 mph
Grade at 55 mph	6%

2.2 Vehicle Simulations and Analysis

We used vehicle simulations (ANL's Powertrain Simulation Toolkit, or PSAT) and power flow calculations to size the various components, including the battery, engine, and motor. Component sizes were selected to satisfy the performance constraints listed in Table 2 for each of the vehicles identified in Table 1. Each vehicle's gasoline and electricity consumption over various driving cycles were calculated based on the model output. The vehicle's performance and energy use were coupled to vehicle mass, so the model was able to capture mass compounding in the sizing of components. PSAT simulations were completed using an electric vehicle model with a five-speed transmission and with slightly oversized power and energy inputs to a generic battery model. Spreadsheet calculations were used to determine the vehicle test mass for the simulations (accounting for variations in the mass of the engine and batteries to satisfy vehicle requirements).

The required electric drive sizing was based on completing the given distance of Urban Dynamometer Driving Schedule (UDDS) drive cycle repetitions all electrically while limiting the battery energy utilization to 60%–70% of the "available" total. Beginning battery power and energy were assumed to be oversized by 30% and 20%, respectively, to account for degradation over the life of the vehicle [6]. However, this was used only in estimating the initial mass of the battery pack, and thus the vehicle, for calculating fuel and electricity consumption. The useful SOC range and degradation factors were not defined in requirements since they are technology-specific and should be specified by battery suppliers. The required engine sizing was based on meeting a 6% grade requirement at 55 mph and two-thirds of peak power [6]. Iterations were performed to incorporate mass-compounding interactions between the component sizing and vehicle requirements.

2.3 PHEV Design Strategy

The PHEV Battery Work Group discussed the advantages and disadvantages of all-electric and blended operations and their impact on the size and cost of the energy storage system. In all-electric mode, the motor and energy storage provide all the power needed to move the vehicle. The power requirements depend on the drive cycle and the amplitude and duration of peak power, and the required energy depends on the distance driven on that drive cycle. With more aggressive cycles, the power requirements increase and the energy needed to drive the same distance also increases. In blended mode, the motor provides most of the power to move the vehicle, while the engine provides assist for peak pulses that are beyond the capability of the motor/energy-storage system. As a result, the power capability of the energy-storage system could be lower in blended operation; however, it could also be of longer duration, as shown by Markel [4].

The all-electric mode has the advantage of displacing more gasoline and reducing more vehicle emissions; however, aggressive drive cycles and longer electric ranges require larger and costlier energy-storage systems. To qualify for ZEV or Advanced Technology Partial ZEV (AT PZEV) credits, the California Air Resource Board (CARB) requires the minimum AER to be 10 miles during the UDDS drive cycle. The Work Group felt it was important for a PHEV to qualify for AT PZEV credits and recommended using the UDDS drive cycle in identifying the power and energy requirements for the all-electric mode. This meant that, during actual daily driving profiles that are more aggressive than UDDS, the vehicle would operate in blended mode with the engine turning on to provide an assist to the electric drive system during high-power peak demands. Real-world blended operation decreases the gasoline fuel economy and increases tailpipe emissions slightly, but it would keep the energy storage size and cost manageable. Note that the analysis showed that the energy needed to drive the equivalent electric range in either AER or blended mode is about the same.

3. Analysis Results for Power and Energy

The results of simulations for the platforms, range, strategy, and performance matrix are presented in Figures 1 and 2. These and other analysis results indicate the following:

- Increased vehicle mass leads to increased peak power and stored electrical energy requirements.
- Peak power was higher for the SUV studied than it was for the crossover UV, which in turn had a higher peak power than the car did.
- The electric energy consumption for propelling the vehicle a given distance over the UDDS drive cycle (Wh/mile) does not significantly depend on whether the operation is all-electric or blended.
- Electric energy consumption strongly depends on the vehicle platform and efficiency of the electric components; the energy consumption of the SUV was higher than that of the crossover UV, which in turn was higher than that of the car.
- Required motor/battery peak power (2-second) for all-electric operation is higher than the motor/battery peak power (10-second) for blended operation. The reason for the difference in duration of peaks is an artifact of the UDDS driving profile and the associated power need.

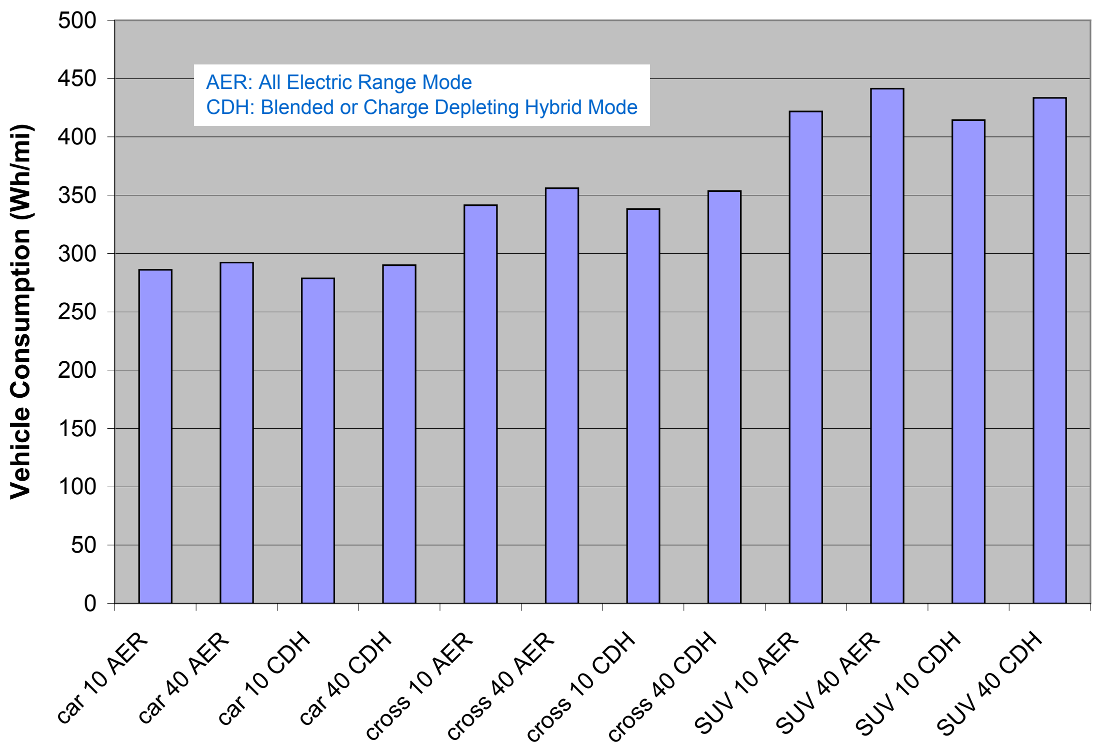

Figure 1. Electric energy consumed per mile for various vehicles and operating modes

For the simulation in Figures 1 and 2, it was assumed that the blended or CDH peak was about 50% of the AER peak power. Markel [4] has indicated that more than 85% of an AER fuel consumption reduction could be achieved at this power level. Consumption reductions drop more dramatically as peak power is reduced. The 50% value provided a balance between power reduction (battery size) and consumption goals.

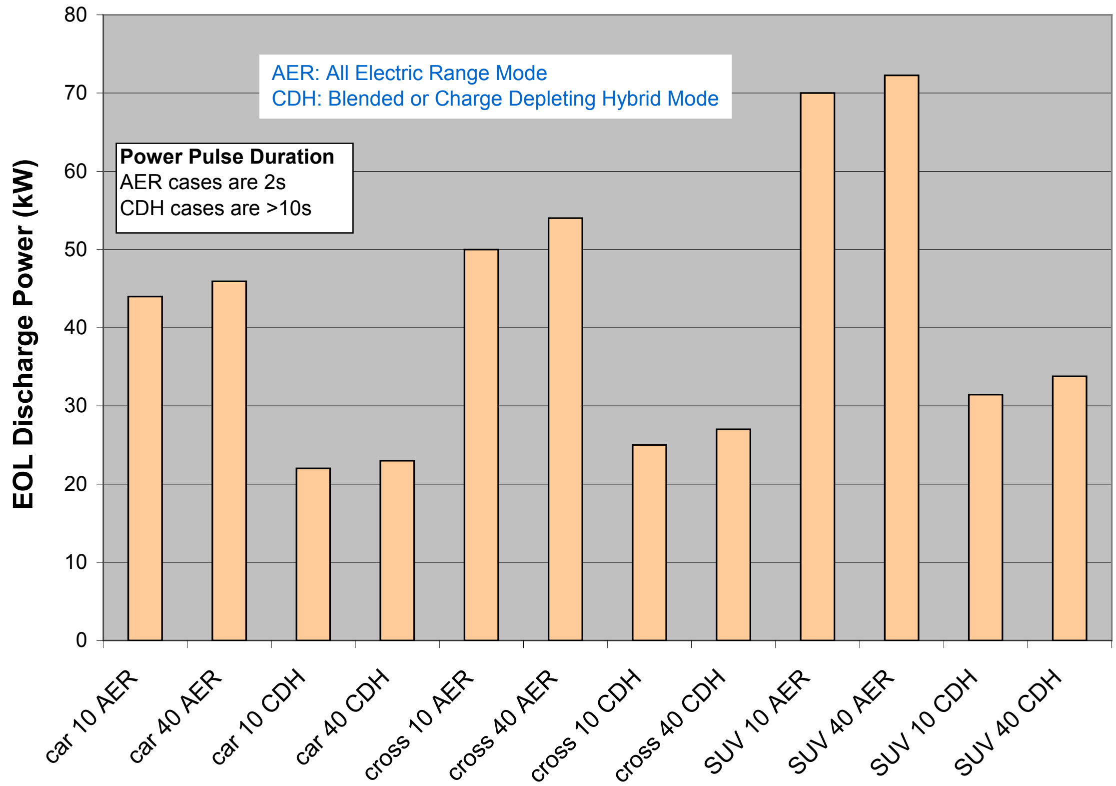

Figure 2. Peak power needed for various vehicles and operating modes over the UDDS drive cycle

The analysis showed that the midsize car consumed about 280-290 Whr/mile, the midsize crossover used about 340 Wh/mile, and the midsize SUV consumed about 420 Wh/mile. An example of the analysis results is shown in Table 3, generated by Gonder [6] for the PHEV Battery Work Group. The table shows specific numbers for electric range and pulse discharge power over the UDDS drive cycle and maximum regenerative braking (regen) pulse based on the US06 drive cycle for the crossover platform. Note that the (2-s) power to (available) energy ratio (P/E) decreases with an increase in the electric range for the same class of vehicle. P/E increases with the mass of the vehicle for the same electric range. Power-assist HEVs have batteries with a P/E ratio of more than 15 to 20; batteries for electric vehicles have a P/E ratio of less than 2 to 3.

Table 3. Results of simulations for midsize crossover UV [6]

Characteristics	Units	10 Miles AER	20 Miles AER	40 Miles AER
Pulse Discharge Power (2 s), UDDS	kW	50	51	54
Pulse Discharge Power (10 s)*	kW	37	39	40
Max Regen Pulse (2 s), US06	kW	36	37	39
Max Regen Pulse (10 s)*	kW	27	28	29 2
Available Energy for CD Mode	kWh	3.36	6.7	13.9
Electrical Energy Consumption	Wh/mile	336	340	348
(discharge 2 s) Power / (available) Energy Ratio	W/Wh	14.9	7.6	3.9

*The 10-second pulse is 75% of the 2-second pulse representing state-of-the-art high-energy lithium ion cells.

4. Selection of Battery Requirements

4.1 Power and Energy for the Charge-Depleting AER Mode

Following discussions of the results of the analysis with the Work Group, FreedomCAR Tech Teams, and the USABC, two sets of requirements for two types of batteries were selected: one with a high power/energy ratio for larger vehicles, such as a crossover UV, and one with a high energy/power ratio for midsize cars. Having more than two sets of targets and requirements would have created an unnecessary burden and confusion for all involved in the development, evaluation, and testing of the batteries. These two sets of battery requirements could cover the majority of batteries for various types of PHEVs. In addition, for the mid-term (by 2012), the targets are more achievable for batteries in vehicles with a 10-mile AER [the minimum range for obtaining the CARB Advanced Technology-Partial Zero-Emission Vehicle (AT-PZEV) credits].

The crossover vehicle platform and associated power and energy requirements were found to be valuable and feasible for the mid-term, 10-mile AER pathway (high P/E ratio battery). The initial incremental cost of the battery and the PHEV when compared with fuel savings (even with gasoline at $3/gallon) did not justify the higher AERs and other vehicle scenarios. The mid-term, 10-mile batteries have requirements similar to the batteries for power-assist HEVs that USABC developers are already working on. So power, energy, and cost requirements for mid-term were believed to be more achievable. For the long-term (2016), the battery targets were selected to be more challenging with a 40-mile AER to meet the range stated in President Bush's 2006 State of the Union Address. The Wh/mile and peak power characteristics of the midsize car were found to be more attractive for the long-term, 40-mile AER (high E/P battery).

For the high power/energy case (mid-term, 10 mile AER), the vehicle energy consumption assumed was 340 Wh/mile, and the 2-second peak power discharge assumed was 50 kW. The 10-second discharge and regen powers for this case were 45 kW and 30 kW, respectively. Therefore, for the 10-mile AER, the available energy needed was 3.4 kWh. For the high energy/power case (long-term, 40-mile AER), the vehicle energy consumption was assumed to be 290 Wh/mile, and the 2-second peak power discharge was set to 46 kW. The 10-second discharge and regen powers for this case were 38 kW and 25 kW, respectively. Therefore, for the 40-mile AER, the available energy needed was 11.6 kWh. Note that the selection of these values was based on the results of the analysis and on input from car company representatives who have significant experience with the operation of HEVs and EVs. At times the values were increased to err on the conservative side. The power capabilities of the batteries must be provided over the entire range of the SOC in which the operation is expected to be AER.

Two questions came up for setting the energy requirements:

1. At what rate should the battery be discharged during the CD mode?
2. What should the SOC window be for the battery?

The responses to those questions were as follows:

1. The rate should be 10 kW (roughly one-fourth of peak power), which approximates the power needed to propel either of the vehicles at a constant speed of 25 to 30 mph.
2. The SOC window was left to the battery developer or supplier to decide, based on the limits of the technology considering the trade-off between weight and life. However, in most of the Work Group discussions, a 70% SOC window was assumed.

Table 4 summarizes the power and energy requirements. Note that a battery must meet these requirements at 30°C and at the end of life (EOL), which is discussed later. This means that the battery developer/supplier has to set a margin for the beginning of life to account for battery degradation, or fade in energy and power. This is usually about 20% or 30%, but it was left to the developer/supplier since each technology can be different. USABC has used a standard temperature of 30°C for other HEV and EV battery life requirements.

Table 4. PHEV power and energy requirements (at 30°C) for two battery categories

Characteristics at EOL (End of Life)	Units	High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Technology Readiness Target	year	2012	2016
Reference Equivalent Electric Range	miles	10	40
Peak Pulse Discharge Power - 2 s	kW	50	46
Peak Pulse Discharge Power - 10 s	kW	45	38
Peak Regen Pulse Power - 10 s	kW	30	25
Available Energy for CD (Charge Depleting) Mode, 10 kW Rate	kWh	3.4	11.6

4.2 Battery Power and Energy for the Charge-Sustaining HEV Mode

A PHEV operates like an HEV when the battery is depleted, that is, discharged to a certain SOC. Most HEVs operate in a charge-sustaining mode around a predefined SOC. During CS HEV operation, the battery has to meet the discharge and regen power with available energy around this SOC. USABC and the FreedomCAR partnership have previously set battery requirements and targets for charge-sustaining power-assist HEVs [7]. For a minimum power-assist HEV, the targets are 25 kW 10-second discharge and 20 kW 10-second regen with 300 Wh available energy at 30°C. For a maximum power-assist HEV, the targets are 40 kW 10-second discharge and 35 kW 10-second regen with 500 Wh available energy at 30°C. The AER power requirements for the 10-mile and 40-mile ranges discussed above are higher than the targets set for maximum and minimum power-assist HEVs, respectively.

After looking at the power capabilities of tested lithium-ion batteries at various SOCs, the Work Group determined that if a battery system meets the AER peak power targets, it also would meet the CS HEV needs, so no additional peak power target for a CS HEV was selected. The available energy requirements for the CS HEV mode were selected to be 500 Wh for a 10-mile (high P/E ratio) battery (the same as maximum power-assist) and 300 Wh for a 40-mile (high E/P ratio) battery. The total EOL energy is the available energy/SOC window and depends on the battery technology.

For setting cold cranking power requirements, the following scenario was assumed: the PHEV is driven in CS HEV mode (SOC at lowest nominal CD value) in the last part of a trip and then parked without being plugged into the grid. The vehicle is kept at -30°C for a few days so the internal temperature of the batteries reached -30°C. In this scenario, the vehicle will be started as a CS HEV at -30°C, so the battery should support the engine cranking. This scenario is considered the worst for cold cranking since, if the battery is plugged in or at higher SOC, then the cold cranking capability of the battery would be higher.

The USABC cold cranking power requirements of a maximum power-assist HEV at -30°C is three 2-second, 7 kW pulses with a 10-second rest between each pulse. The same cold cranking power requirements were selected for both the PHEV battery categories. The purpose of cold cranking is to be able to start the engine at worst conditions.

Table 5 summarizes the cold cranking power and available energy requirements for the CS HEV mode at end of life.

Table 5. PHEV available energy and cold cranking power requirements for the CS HEV mode

Characteristics at EOL (End of Life)	Units	High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Available Energy for CS (Charge Sustaining) Mode	kWh	0.5	0.3
Cold Cranking Power at -30°C, 2 s, 3 pulses (10 s rest between)	kW	7	7

4.3 Calendar and Cycle Life

The USABC/FreedomCAR calendar life target for power-assist HEVs is 15 years [7]. This is a research target based on the expected average life of passenger cars, which is around 14 years. The same calendar life was selected for PHEVs for either battery type. However, since the PHEV battery gets plugged in and is fully charged often, its temperature may be generally higher than that of the HEV battery over its life; so 35°C was selected as the temperature for measuring the calendar life of PHEV batteries, versus 30°C for HEV batteries.

The cycle life for the CS HEV mode of PHEV for both high P/E and high E/P batteries was selected to be the same as maximum power-assist HEVs, as defined by USABC/FreedomCAR, which is 300,000 cycles of 50 Wh profile. This is equivalent to about 150,000 miles (the life expectancy of emission control devices set by CARB). For CD HEV operation, it was assumed that both 10-mile and 40-mile batteries are deep-discharged once a day—charged fully at the beginning of the day to the maximum SOC, according to the battery supplier, and discharged fully to the minimum SOC, according to the supplier. The number of deep discharges was calculated using 1 cycle per day, 330 days per year - accounting for some weekends with no deep discharging - and 15 years per battery, or about 5000 CD cycles. The CD discharge energy throughput was calculated using the number of deep discharges multiplied by the CD available energy: 5000*3.4 kWh = 17 MWh for the 10-mile battery and 5000*11.6 kWh = 58 MWh for the 40-mile battery. Table 6 provides a summary of calendar and cycle life requirements.

Table 6. Calendar and cycle life requirements for PHEV batteries

Characteristics at EOL (End of Life)	Units	High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Calendar Life, 35°C	year	15	15
Charge Depleting (CD) Cycle Life	cycles	5,000	5,000
Discharge Throughput Energy through CD Cycles	MWh	17	58
CS HEV Cycle Life, 50 Wh Profile	cycles	300,000	300,000

4.4 System-Level Requirements

Price. A reasonable battery system cost is critical to the success of PHEVs. Although, as with HEVs, early adaptors of the technology could be willing to pay higher prices for PHEVs, for mass-market penetration the initial incremental cost of a PHEV should be offset by savings on gasoline costs in a reasonable amount of time. The price targets selected for the battery system were set to be very challenging to push the technology. The battery system price target (cells, packaging, electronics, and thermal control) was set to $1,700 for the 10-mile (high P/E) battery and $3,400 for the 40-mile (high E/P) battery. The battery cost targets reflect the mid- and long-term R&D cost goals of $500/(available)kWh in 2012 and $300/(available) kWh in 2016. The production volume for the target system price is 100,000 units per year. In terms of price per EOL total energy, this corresponds to \$305/kWh for the mid-term, 10-mile battery and about \$200/kWh for the long-term, 40-mile battery. A 70% SOC window was assumed. Currently, high-energy batteries cost from \$800/kWh to \$1,000/kWh.

Volume and Mass. The battery system must fit in the vehicle with minimum adverse impact on the cabin or cargo space. Loss of cabin and cargo space could dissuade potential buyers of PHEVs from purchasing them, so it must be kept to a minimum. The maximum volume selected as targets were 40 liters for the 10-mile battery and 80 liters for the 40-mile battery. Assuming 70% for the SOC range and 20% for the fade factor, these correspond to roughly 145 Wh/liter for the 10-mile battery and 250 Wh/liter for the 40-mile battery, all at beginning of life (BOL). The mass of the battery system should be small enough to not have an adverse impact on the fuel economy and structure of the vehicle. The maximum weight selected as targets were 60 kg for the 10-mile battery and 120 kg for the 40-mile battery. These correspond to 95 Wh/kg for the 10-mile battery and 165 Wh/kg for the 40-mile battery, all at BOL. The mass and volume of cells, structure, packaging, electronics, and thermal control are included in the system mass and volume. These goals are very challenging, particularly the ones for long-term, 40-mile, high E/P ratio batteries.

Recharge Rate. To recharge the battery, the Work Group considered the time to recharge the battery and the availability of grid power. Charging overnight in 10 hours or less seemed reasonable. According to a Southern California Edison (SCE) Work Group member, the nominal distribution voltage for U.S. residential buildings is standardized at 240 VAC, resulting in a typical residential receptacle to be rated for 120 VAC (line to neutral). Normally, during the generation and distribution of electricity, there are natural losses in the system. Hence, most U.S. utilities guarantee their voltage at 120 +/- 5%, or between 114 V and 126 V. In some instances, depending on the location, some utilities may in fact set their tolerance to +/- 10%, or between 108 V and 139 V. Household receptacles in residential housing are rated for 15 A. Using outlets with power ratings of 120 V/20 A or 220 V/20 A increases the cost of installation, so they were not deemed desirable. In the United States, according to the National Electrical Code, the continuous power rating of an electrical outlet is 80% of the name plate, so the maximum recharge rate was set to 80% of 15 A. With nominal line at 120 VAC, the power was 1440 VA, or about 1.4 kW.

System Efficiency. The battery system should be of relatively high efficiency so that the vehicle powertrain efficiency, and thus energy consumption, will be low. Similar to the power-assist HEV, we selected a minimum round-trip battery system efficiency of 90% over the USABC HEV efficiency cycle.

The system-level requirements are summarize in Table 7.

Table 7. PHEV battery system-level requirements

Characteristics at EOL (End of Life)	**Units**	**High Power/Energy Ratio Battery**	**High Energy/Power Ratio Battery**
Maximum System Production Price @ 100,000 units/year	\$	\$1,700	\$3,400
Maximum System Weight	kg	60	120
Maximum System Volume	liter	40	80
System Recharge Rate at 30°C	kW	1.4 (120 V/15 A)	1.4 (120 V/15 A)
Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%	90	90

4.5 System-Level Limits

Voltage and Current. In order to integrate the battery system with other electrical components in electric drive systems (motors, converters), the maximum battery voltage was set at less than 400 V, the minimum voltage at 55% of maximum voltage, and the maximum current at 300 A. These are similar to targets for power-assist HEVs.

Maximum Self-Discharge Rate. In order to ensure that the high-voltage battery has sufficient energy and power for CS HEV operation after a long parking period (normally 30 days) without being connected to a plug, the maximum self-discharge rate was set at 50 Wh/day (at 30°C).

Temperatures. The unassisted operating and charging temperature range for the vehicle, and thus the battery, was set to between -30°C and +52°C. This is where most vehicles in the United States will operate. The survival (nonoperating) temperature range was set to between -46°C and +66°C. These are similar to those set for power-assist HEV batteries.

Table 8 summarizes the system-level limits for PHEV energy storage.

Table 8. System-level limits for PHEV batteries

Characteristics at EOL (End of Life)	Units	High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Max. Current (10 sec pulse)	A	300	300
Maximum Operating Voltage	Vdc	400	400
Minimum Operating Voltage	Vdc	>0.55 x Vmax	>0.55 x Vmax
Maximum Self-Discharge	Wh/day	50	50
Unassisted Operating & Charging Temperature Range	°C	-30 to +52	-30 to +52
Survival Temperature Range	°C	-46 to +66	-46 to +66

4.6 Combined Requirements

Table 9 summarizes the combined set of battery requirements from Tables 4 through 8. Note that all requirements/targets must be met at the same time. Table 9 is organized in four categories: system level, CD HEV mode, CS HEV mode, and battery system limits.

Table 9. Battery requirements for PHEVs – organized in four categories

Characteristics at EOL (End of Life)		High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Technology Readiness Target	year	2012	2016
Reference Equivalent Electric Range	miles	10	40
Maximum System Production Price @ 100,000 units/year	$	$1,700	$3,400
Calendar Life, 35°C	year	15	15
Maximum System Weight	kg	60	120
Maximum System Volume	liter	40	80
Peak Pulse Discharge Power - 2 s / 10 s	kW	50/ 45	46/ 38
Peak Regen Pulse Power (10 s)	kW	30	25
Available Energy for CD (Charge Depleting) Mode, 10 kW Rate	kWh	3.4	11.6
CD Life / Discharge Throughput	cycles/MWh	5,000 / 17	5,000 / 58
System Recharge Rate at 30°C	kW	1.4 (120V/15A)	1.4 (120V/15A)
Available Energy for CS (Charge Sustaining) Mode	kWh	0.5	0.3
Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%	90	90
Cold Cranking Power at -30°C, 2 s - 3 pulses (10 s rest between)	kW	7	7
CS HEV Cycle Life, 50 Wh Profile	cycles	300,000	300,000
Maximum Operating Voltage	Vdc	400	400
Minimum Operating Voltage	Vdc	>0.55 x Vmax	>0.55 x Vmax
Maximum Self-Discharge	Wh/day	50	50
Unassisted Operating & Charging Temperature Range	°C	-30 to +52	-30 to +52
Survival Temperature Range	°C	-46 to +66	-46 to +66

In addition to these requirements, the Work Group also set performance requirements for battery power at various temperatures, similar to those set for power-assist HEVs. Table 10 identifies the required power (discharge, regen, and recharge) at various temperatures as a percentage of 30°C power targets. Performance degradation is allowed at lower temperatures and is linear with temperatures below 30°C.

Table 10. Required battery power capability (as a percent of 30°C value) at various temperatures

Characteristics at EOL (End of Life)	Units	High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Unassisted Operating & Charging Temperature Range	°C	-30 to +52	-30 to +52
30°-52°	%	100	100
0°	%	50	50
-10°	%	30	30
-20°	%	15	15
-30°	%	10	10

5. Summary

In support of the U.S. Advanced Battery Consortium, vehicle analysis and battery sizing studies were performed to recommend battery requirements. The analysis process included defining vehicle platforms, vehicle performance targets, the desired equivalent electric range operating strategy (all-electric or blended), and state-of-charge window. Based on the analysis, USABC members recommended two categories of batteries, one for a 10-mile EV range (high power/energy ratio) and one for a 40-mile EV range (high energy/power ratio). Four sets of requirements were defined: (1) system-level (all-electric range, pack cost, calendar life, volume, weight, and energy efficiency); (2) charge-depleting hybrid EV (HEV) mode (2-second and 10-second discharge power, 10-second regenerative braking power, available energy at constant power, number of deep cycles, maximum recharge rate); (3) charge-sustaining HEV mode (available energy for charge-sustaining operation, cold cranking power, number of shallow charge sustaining cycles); and (4) battery limits (maximum current, maximum and minimum voltage, operating and survival temperatures).

The USABC adopted the requirements proposed by the PHEV Battery Work Group and included them as goals in a request for proposals to developers of PHEV batteries. Table 11 is the final version of the PHEV battery requirements, targets, and goals as posted on the USABC Web site (please see http://www.uscar.org/commands/files_download.php?files_id=118).

Table 11. USABC goals for advanced batteries for plug-in hybrid electric vehicles

Characteristics at EOL (End of Life)		High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Reference Equivalent Electric Range	miles	**10**	**40**
Peak Pulse Discharge Power - 2 Sec / 10 Sec	kW	**50 / 45**	**46 / 38**
Peak Regen Pulse Power (10 sec)	kW	**30**	**25**
Available Energy for CD (Charge Depleting) Mode, 10 kW Rate	kWh	**3.4**	**11.6**
Available Energy for CS (Charge Sustaining) Mode	kWh	**0.5**	**0.3**
Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%	**90**	**90**
Cold cranking power at -30°C, 2 sec - 3 Pulses	kW	**7**	**7**
CD Life / Discharge Throughput	Cycles/MWh	**5,000 / 17**	**5,000 / 58**
CS HEV Cycle Life, 50 Wh Profile	Cycles	**300,000**	**300,000**
Calendar Life, 35°C	year	**15**	**15**
Maximum System Weight	kg	**60**	**120**
Maximum System Volume	Liter	**40**	**80**
Maximum Operating Voltage	Vdc	**400**	**400**
Minimum Operating Voltage	Vdc	**>0.55 x Vmax**	**>0.55 x Vmax**
Maximum Self-discharge	Wh/day	**50**	**50**
System Recharge Rate at 30°C	kW	**1.4 (120V/15A)**	**1.4 (120V/15A)**
Unassisted Operating & Charging Temperature Range	°C	**-30 to +52**	**-30 to +52**
Survival Temperature Range	°C	**-46 to +66**	**-46 to +66**
Maximum System Production Price @ 100k units/yr	$	**$1,700**	**$3,400**

6. List of Abbreviations

AER: all-electric range
AT-PZEV: advanced technology, partial zero-emission vehicle
BOL: beginning of life
CD: charge-depleting
CDH: charge-depleting hybrid (blended)
CS: charge-sustaining
E/P: energy to power ratio
EOL: end of life
EV: electric vehicle
HEV: hybrid electric vehicle
P/E: power to energy ratio
PHEV: plug-in hybrid electric vehicle
SOC: state-of-charge
UDDS: Urban Dynamometer Driving Schedule
USABC: U.S. Advanced Battery Consortium
ZEV: zero-emission vehicle

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14. ABSTRACT *(Maximum 200 Words)*
Plug-in hybrid electric vehicles (PHEVs) could displace a significant amount of petroleum in the next 10 to 20 years. The main barriers to commercializing PHEVs are the cost, safety, and life of batteries. Therefore, the U.S. Department of Energy and auto companies embarked on a program to develop batteries for PHEVs. Defining battery targets or requirements to benchmark progress was essential. The DOE-industry U.S. Advanced Battery Consortium (USABC) sponsored analysis and battery sizing studies to recommend battery requirements. This included defining vehicle platforms, performance targets, an equivalent electric range operating strategy (all electric or blended), and the state-of-charge window. The studies recommended two battery categories: one for a 10-mile equivalent electric vehicle (EV) range (high power/energy ratio) and one for a 40-mile EV range (high energy/power ratio). This paper presents the assumptions, analysis, discussions, and resulting requirements adopted by the USABC.

15. SUBJECT TERMS
plug-in hybrid electric vehicles; hybrid electric vehicles; PHEV; battery, EV range, charge-depleting

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