U.S. Department of Energy
Energy Efficiency and Renewable Energy
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FreedomCAR & Vehicle Technologies Program

Plug-In Hybrid Electric Vehicle R&D Plan

External Draft
February 2007

Department of Energy
Washington, DC 20585

February 28, 2007

Open letter to readers of the Plug-In Hybrid Electric Vehicle (PHEV) R&D Plan

Plug-in hybrid electric vehicles are an important part of the Administration's Advanced Energy Initiative. With successful development and deployment of the critical propulsion system technologies, PHEVs could noticeably contribute to the "20 in 10" gasoline savings goal announced in the 2007 State of the Union Address. In fact, the President explicitly mentioned PHEVs as one element in the strategy to diversify America's energy supply, i.e., "*We need to press on with battery research for plug-in and hybrid vehicles, and expand the use of clean diesel vehicles and biodiesel fuel*".

Some of you participated in the PHEV Discussion Meeting held at DOE in mid-2006 and your contributions were extremely helpful. That meeting was instrumental in the DOE decision to rigorously assess technology development requirements and allocate resources for the critical components of PHEVs. Furthermore, the key challenges identified in the meeting and DOE experience with the supporting technologies were the basis of our PHEV planning activities. The FreedomCAR and Vehicle Technologies (FCVT) Program, in consultation with industry and other DOE offices, generated this plan to develop batteries, power electronics and electric machines for hybrid vehicles that meet the Administration's expectations. The plan addresses all aspects of the activity from benchmarking and requirements analysis through technology development and demonstration.

We are proud of our efforts to develop PHEV technology and it shows in the plan; the substantial effort and contributions of the FCVT technical staff and national laboratories should be recognized.

I am asking you to support our technology development efforts and invite your review of the Department's PHEV R&D Plan; it can be downloaded from the DOE website (www.eere.energy.gov/vehiclesandfuels). In keeping with the growing public and congressional interest, I have targeted an expeditious release of the plan by April 20. Therefore, I ask for your response by e-mail no later than March 28 (addressed to AAT@ee.doe.gov). I look forward to hearing from you.

Sincerely,

Edward J. Wall

Edward J. Wall
Program Manager, FreedomCAR and Vehicle Technologies
Energy Efficiency and Renewable Energy

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INTRODUCTION

The U.S. Department of Energy (DOE) is supporting the development of hybrid vehicles with the ability to operate in both electrical/mechanical and electric-only modes recharging from a standard electric outlet because of the potential national benefits of substantially shifting fuel from petroleum to electricity. The Advanced Energy Initiative (AEI) announced by the President in the 2006 State of the Union describes plug-in hybrid electric vehicles (PHEVs) as a way to dramatically increase energy efficiency and utilize spare electric generating capacity. President Bush reiterated his support in the 2007 State of the Union, stating *"We need to press on with battery research for plug-in and hybrid vehicles"*.

In announcing the AEI, the President posed to the Department and to industry a challenge to develop technology that would allow 40 miles electric range, enough to satisfy approximately 70 percent of the daily travel in the United States. This challenge necessitates a substantial improvement over today's hybrid vehicles that are capable at most of only a few miles electric range at reduced performance. In addition, consumers currently pay a premium for hybrids. Additional electric range, requiring a higher energy battery and higher power electric drive components, will have to be accomplished without further exacerbating the cost differential – to increase the likelihood of high volume sales and consequently the intended fuel savings.

The DOE Office of FreedomCAR and Vehicle Technologies (FCVT) conducts research and development targeting more energy-efficient and environmentally-friendly highway transportation technologies that enable America to use less petroleum. This research includes work on hybrid and electric propulsion technologies. The long-term aim is to develop "leap frog" technologies that improve vehicle energy efficiency and bolster energy security efforts at lower costs and with lower environmental impacts than currently-used vehicles. The program focuses its investments specifically on technologies with uncertain or long-term outcomes that may have significant public benefit, if achieved.

Because PHEVs appeared to have the potential to dramatically decrease petroleum fuel consumption and improve energy efficiency, FCVT convened a 2-day discussion meeting in May 2006, attended by over 120 experts representing the automotive and electric utility industries, government, national laboratories and academia to discuss potential benefits, technical challenges and economic issues. The attendees addressed vehicle technology, the electric power grid, consumer expectations and the role of the Federal government. Substantial agreement on the key challenges as well as the potential benefits was obtained. Based on this feedback and initial data, FCVT concluded that the potential national benefits of petroleum displacement from PHEVs did warrant further analysis and focused development of the relevant critical technologies.

FCVT expanded hybrid vehicle activities in fiscal year 2006 (FY06) to include PHEVs. Analytical studies and benchmarking activities were initiated to ascertain PHEV requirements and benefits. Competitive technology development solicitations for first generation PHEV components were developed. Multiple awards for power electronics and electric machines are anticipated in the second quarter of FY07 (Q2-FY07) with a battery solicitation to follow. Generation 1 hardware is expected to be delivered in FY09-10, with solicitations for second generation hardware targeting optimized designs for specific PHEV applications to follow soon thereafter.

Business-Oriented Approach

FCVT in consultation with industry and other appropriate DOE offices developed this R&D plan to accelerate the development and deployment of technologies critical for plug-in hybrid vehicles. This plan addresses all aspects of R&D from technology assessment through production readiness. The necessary development of batteries and electric drive components is described, including near- and mid-term R&D activities as well as long-term fundamental research. It also relies on analytical studies to quantify the potential national benefits of PHEVS, and the monitoring of global policy and technological developments to find opportunities for beneficial collaboration and stay aware of the latest advances from around the world.

This plan incorporates systems engineering and risk management to ensure that each activity progresses appropriately and resources are directed effectively. This process is summarized in the following major steps:

- Quantify the state-of-the-art (benchmark testing and global assessment),
- Determine component development requirements (vehicle simulation),
- Identify development paths to meet the requirements (gap analysis),
- Assess the risks (cost, technical and schedule) for each path, and
- Identify the best approaches and decision points (i.e., continue or redirect).

Collaboration

This plan includes collaboration among government, industry and academia on development, demonstration and the assessment of production readiness. FCVT will utilize its relationship with the automotive industry to ensure that its goals for PHEV technology are applicable and appropriate. Additional alliances with industry, including electric utilities, will be pursued as needed to meet the objectives of the activity.

The plan calls for extensive utilization of the DOE national laboratories and others that could provide additional expertise, e.g., the Commerce Department's National Institute of Standards and Technology (NIST). The national laboratories have well-developed capabilities and facilities to support the analytical and hardware development tasks to ensure a thorough assessment of the potential of PHEVs. Resources include specialized analytical tools for hybrid vehicle modeling and simulation, facilities for the development, testing and demonstration of components and/or vehicles and experienced personnel that work on a regular basis with industry on directly applicable technology.

Strategic Manufacturing Technology

The plan also includes manufacturing technology development, particularly directed at determining the feasibility of establishing a domestic source for the most critical component of PHEVs (and many other high efficiency vehicles of the future), the battery.

Section 1: Overview

1.1 External Assessment and Market Overview

The PHEV R&D Plan is driven by the desire to reduce dependence on foreign oil by diversifying the fuel sources of automobiles. Some universities, companies and entrepreneurs in the private sector also have promoted plug-in hybrids as a way to substantially realize the benefits of electric vehicles without the range limitation (the primary impediment to mass market electric vehicles). In addition, some electric utilities are interested due to the potential to utilize off-peak capacity and increase their long-term demand base. As a result, public and congressional awareness is high and increasing. However, automotive manufacturers have stated that technical barriers and cost premiums associated with dual propulsion systems capable of acceptable performance under all conditions and the lack of appropriate batteries that last the life of the vehicle have prevented them from committing to manufacture substantial numbers of PHEVs.

PHEV discussion meeting - To identify and better understand the critical issues, FCVT invited a group of over 120 experts from the automotive and electric utility industries, government, national laboratories and academia to a 2-day meeting in May 2006 to openly discuss the technology and economics of PHEVs. The attendees largely agreed on the potential benefits of PHEVs and the primary impediments. The major points of consensus among the attendees, as summarized in the executive summary, are as follows:

- PHEVs can substantially reduce petroleum consumption, but cost is the primary impediment and battery technology is a potential show stopper for production.
- Electric power generation efficiency and the environmental impact of automobiles can be improved by shifting to electricity from gasoline; off-peak power can handle a large number of PHEVs, i.e., power from the electric grid is not a barrier.
- Fuel economy, rather than all-electric range (AER) is the key vehicle efficiency metric for the public; all other vehicle aspects must be competitive, including vehicle purchase and operating costs, for a PHEV to be marketable. An AER requirement would drive cost up and decrease the likelihood of production.
- Federal government is expected to set policy, support pre-competitive research, act as a trusted source of information and minimize market barriers for PHEVs.

Decision to proceed – Based on the results of the May 2006 meeting and initial data, FCVT remains convinced that the merits of PHEVs, in particular the perceived national benefits of petroleum displacement, warrant further analysis and focused development of the critical technologies to overcome the substantial technical and economic challenges.

Thorough assessment of market potential needed – Promotional activities raise public and congressional awareness, but rigorous efforts are required to understand the market drivers and accurately quantify market potential. FCVT plans a rigorous analytical approach to determine the key attributes of PHEVs (from consumer and manufacturer perspectives) and quantify the value proposition for all the stakeholders in an attempt to gain insight into market potential.

1.2 Relevant DOE Activities and Technology

FCVT has ongoing activities to develop batteries, power electronics and electric machines that are directly applicable to plug-in hybrids. However, PHEVs are still in the concept development phase and several designs are being considered. Configurations range from electric vehicles with engines used only for long trips (the most demanding for batteries and electric drives) to evolutionary designs based on today's hybrids (i.e., substituting a better battery). Therefore, it is premature to select one set of development goals at this time.

The vehicle design and control strategy choices have a tremendous influence on the component requirements and the resulting vehicle economics (i.e., higher power and energy electric propulsion systems cost more). Choosing all-electric range (i.e., no engine operation until the battery energy is depleted) versus charge-depleting range (i.e., power demand is shared between the electric motor and engine until the battery is depleted) makes a tremendous difference in the requirements for the battery and electric drive components. Compared to today's hybrids, useable battery energy will have to increase an order of magnitude to provide 40 miles electric range and electric drive power will have to double to provide equal (full) performance capability in both electric and hybrid modes. These factors further exacerbate the higher cost of today's hybrid propulsion systems, leading to the conclusion that there is no optimum (economic) solution for PHEV design without technology breakthroughs that reduce cost. Current research activities are applicable to these challenges:

- Lithium-ion batteries: developments targeting cost reduction (e.g., materials and processing, cell and module packaging), improved specific energy, life and abuse tolerance. The Office of Science is a contributor to this effort with advanced materials development activities.
- Power electronics and electric machines: developments targeting cost reduction and volumetric efficiency (packaging).
- Vehicle efficiency technologies: low-cost lightweight materials and efficient ancillary systems (e.g., climate control) to reduce power and energy requirements.
- Grid interactions: vehicle-utility interface and regional impact analysis. The Office of Electricity sponsors/conducts the majority of utility impacts analysis, including specific regional studies.

The supporting tools and facilities for analysis and development are being adapted for the unique requirements of PHEVs, including:

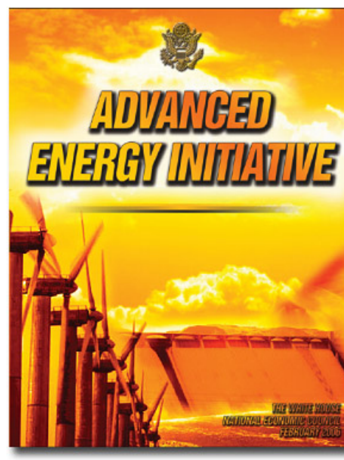
- Vehicle modeling & simulation software: control strategy modifications
- Standard battery bench testing: PHEV-specific procedures being developed
- Battery Hardware-In-the-Loop (HIL) testing: higher power, faster emulator being installed; PHEV-specific procedures being developed
- Vehicle dynamometer testing: PHEV-specific procedures being developed

1.3 Program Justification and Federal Role

The potential for petroleum displacement and the national benefits justify FCVT attempts to develop technology and quantify the potential. One of the topics discussed at the PHEV meeting in May 2006 was the role of government and there was substantial agreement on this topic. It was expressed that the Federal government should be involved where societal/national benefits are concerned, i.e., energy security, reducing emissions and maintaining mobility. In particular, the Federal government should facilitate cooperation among various constituencies and Federal agencies, promote national competitiveness, develop a consistent national energy strategy and clarify policy regarding the expected contribution of the automobile.

Specific recommendations for DOE included setting policy, supporting pre-competitive R&D and acting as an impartial broker of PHEV information (testing, analysis, codes, standards, etc.). Considering the analytical capabilities at the national laboratories, it was felt that DOE should analyze PHEVs technically and economically vis-à-vis other alternatives to displace petroleum (alternate fuels, etc.) and quantify the value proposition for automotive manufacturers, electric utilities, consumers and the nation. If warranted, DOE should promote PHEVs with consumer education and learning demonstrations.

1.4 Goals and Approach



Mandate/expectations – The Administration has expressed ambitious goals for PHEVs in the Advanced Energy Initiative and the intent is clear – dramatically reduced petroleum consumption. Quoting the White House press release following the 2006 State of the Union Address,

"A 'plug-in' hybrid can run either on electricity or on gasoline and can be plugged into the wall at night to recharge its batteries. These vehicles will enable drivers to meet ***most of their urban commuting needs with virtually no gasoline use****."*

Goals – FCVT has established technical goals that allow for flexibility in vehicle design and do not unduly constrain automotive manufacturers. The goals encompass vehicle designs with exclusive electric operation before the engine turns on as well as configurations that utilize the power sharing strategies of today's hybrids, but allow the battery to discharge over the day to reduce fuel consumption. Phased development is planned to deliver results and quantify benefits as soon as possible:

- Near-term focus on adapted technology; electric range of 10-20 miles (reduced performance) or charge-depleting (hybrid) range of 20 miles (full performance)
- Mid-term (3-5 years) development for PHEV-specific designs; electric range of 20+ miles or charge-depleting (hybrid) range of 40 miles (both full performance)
- Long-term (5-10 years) development projects will target components/capabilities to meet the 40+ miles electric range target.

Approach – Average daily travel varies across the country (averaging about 30 miles) and preliminary analyses have shown that a PHEV user would benefit most when the electric range matched their daily trip length. Since there is not a "one size fits all" solution, FCVT will quantify the potential benefits and technological implications of PHEVs capable of various electric and charge-depleting ranges.

Due to the flexibility in PHEV design, control strategy and fuel source (i.e., liquid or gaseous fuel and/or electricity), DOE will use standard (non-regulatory) definitions to ensure precise communication and unambiguous results with respect to these goals:

- **Operating modes**

  Electric mode – Propulsion and accessories powered by the electric drive and onboard electric energy storage (i.e., engine off)

  Hybrid mode – Propulsion and accessories powered by the electric drive and/or engine, encompassing all power sharing/blending strategies

- **Control strategies**

  Charge-depleting strategy (hybrid) – Operation in hybrid mode with a net decrease in battery state-of-charge (SOC)

  Charge-sustaining strategy (hybrid) – Operation in hybrid mode with a relatively constant battery state-of-charge

- **Range**

  All-electric range (AER) – Distance traveled in electric mode (engine off) on standard driving cycles

  Charge-depleting range (CDR) – Distance traveled in hybrid mode with a charge-depleting strategy until the vehicle transitions to the charge-sustaining strategy

- **Fuel consumption/economy**

  Electric consumption – Electrical energy consumed in electric or hybrid mode

  Liquid or Gaseous consumption – Liquid (e.g., gasoline or diesel) or gaseous (e.g., CNG) consumed on standard driving cycles

  Fuel economy – Distance traveled per unit of total fuel consumed (electric, liquid and/or gaseous) on standard drive cycles.

  [Note: Unlike conventional or current production hybrid vehicles, the fuel economy of PHEVs can vary substantially as a function of distance traveled (e.g., by a factor of 2 or more) and the results can be misleading without precise standard procedures and reporting protocols. An activity is underway to identify the needed changes to standard test procedures and protocols to measure and fairly report PHEV fuel economy.]

Development strategy – Two generations of technology development actions are proposed in addition to long-term R&D. The resulting component developments, when integrated and validated in a vehicle environment, are expected to produce necessary data for technology transfer and production readiness decisions by industry.

Solicitations for the first generation of power electronics and electric machines were initiated in Q4-FY06 and will be awarded in Q2-FY07, targeting the adaptation of available technology for PHEVs. The first battery solicitation targets designs by FY08, upon which contracts for battery fabrication will be awarded. The second generation of technology development is expected to be solicited in FY09-10 and will focus on specific PHEV designs to be determined later in the project.

System Integration, Validation and Demonstration – The national laboratories, with extensive hybrid vehicle technology development experience, will analyze, specify, aid development, integrate, test and validate the battery and electric propulsion components in this activity. The initial approach is to demonstrate PHEV technologies in research vehicle platforms capable of various electric and charge-depleting hybrid ranges up to 40 miles. Specific roles of the applicable national laboratories are addressed in Section 2 and capabilities/facilities are summarized in Appendix A.

For additional validation, a solicitation for several small, strategically located demonstration fleets (e.g., 10 to 20 vehicles in 3 to 5 cities) is being considered for the 2008-2010 timeframe.

Manufacturing Technology Development – The ultimate benefits of PHEVs cannot be realized without suitable batteries. FCVT proposes to facilitate the domestic production of high energy automotive lithium-ion batteries by supporting the development and demonstration of manufacturing technology. The FCVT Energy Storage R&D activity has been instrumental in developing fundamental Lithium-ion (Li-ion) technology and fostering relationships to move the technology to the marketplace (e.g., Johnson Controls and SAFT). The success of Cobasys, who with DOE support for manufacturing technology became a supplier of Nickel Metal Hydride (NiMH) batteries to GM, is compelling evidence of what can be accomplished.

1.5 Collaboration

DOE works with OEMs, suppliers, other agencies and academia to bring the best talent and expertise together to address the PHEV challenges:

Industry – FCVT will continue its relationship with the automotive industry to ensure that PHEV technology is applicable and appropriate. This includes the long-standing successful partnership, the US Advanced Battery Consortium (USABC), which focuses on development and assessment of the critical battery technologies. FCVT, through the national laboratories, is already working with the Society of Automotive Engineers (SAE) regarding the development of PHEV-specific test procedures/protocols and holding discussions with many OEMs and suppliers.

Government – FCVT has discussed and is coordinating PHEV activities with relevant offices in DOE, including the Office of Electricity (OE) regarding electric power generation/distribution and the Office of Science, who plans a coordinated workshop in Q2-FY07 focused on materials R&D for batteries. The Biomass Program will be consulted regarding domestic fuels utilization (e.g., ethanol) as well as the HFCIT Program regarding fuel cells in plug-in hybrid applications. In addition, DOE is exploring with Environmental Protection Agency (EPA) the development of PHEV-specific test procedures/protocols and will explore with NIST manufacturing technology to accelerate the introduction and market adoption of PHEV technologies. Other DOE offices and government agencies will be approached as needed.

Academia – Exploratory research focusing on fundamental battery research is important to achieve the long-term objectives of this activity. Currently DOE is working with 12 universities in cooperation with the national laboratories.

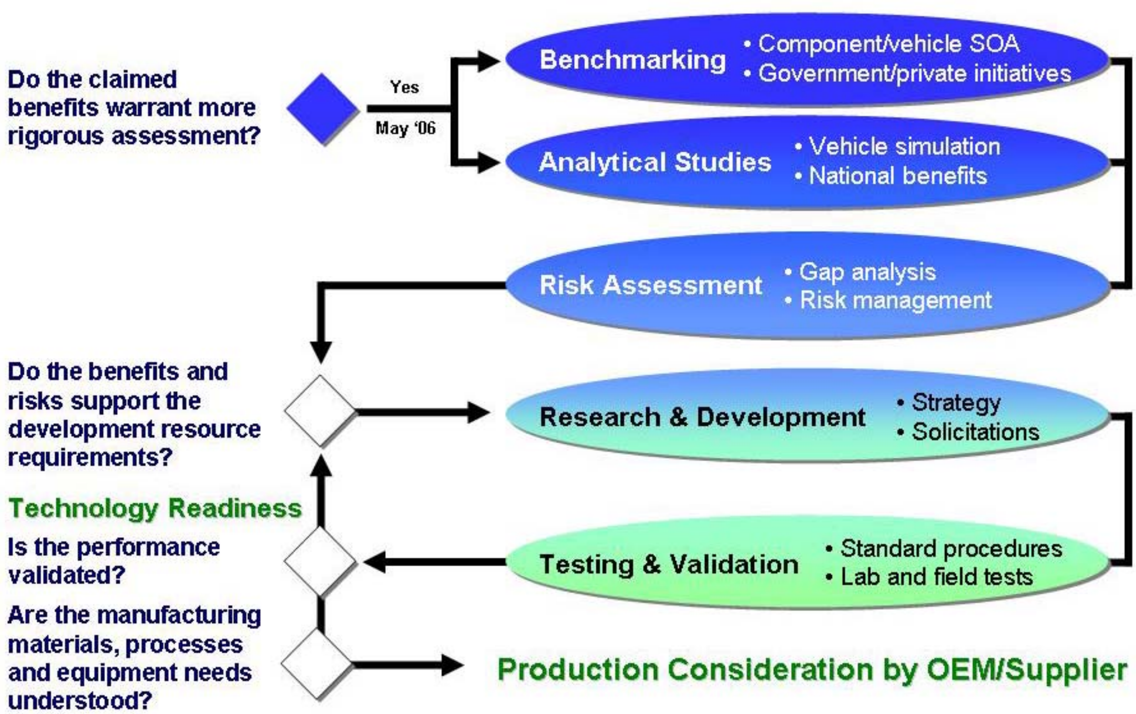
Section 2: Functions

2.1 Management

The FCVT Program utilizes a management decision process based on systems engineering and risk assessment to ensure a cost-effective development activity. This section presents the details related to PHEVs, i.e., the task structure, descriptions and schedule.

Developing PHEV technology suitable for production (i.e., low cost, long life batteries and high power electric drive components) is high risk and success is certainly not guaranteed. The automotive industry has made several attempts to develop electric vehicles with little success due to prohibitive component costs. Therefore, this activity must include decision points with defined metrics that must be met or the resources will be redirected to more promising development paths. Following the PHEV Discussion Meeting with the technical community in May 2006, FCVT decided that the potential benefits of PHEVs warrant further assessment and initiated benchmarking, analysis and technology development solicitations. The figure below illustrates the decision process. Risk assessment identifies and quantifies the most promising development paths to guide resource allocation. DOE supports technology development as far as demonstrating that the components meet their performance targets and that the manufacturing approach is well understood.

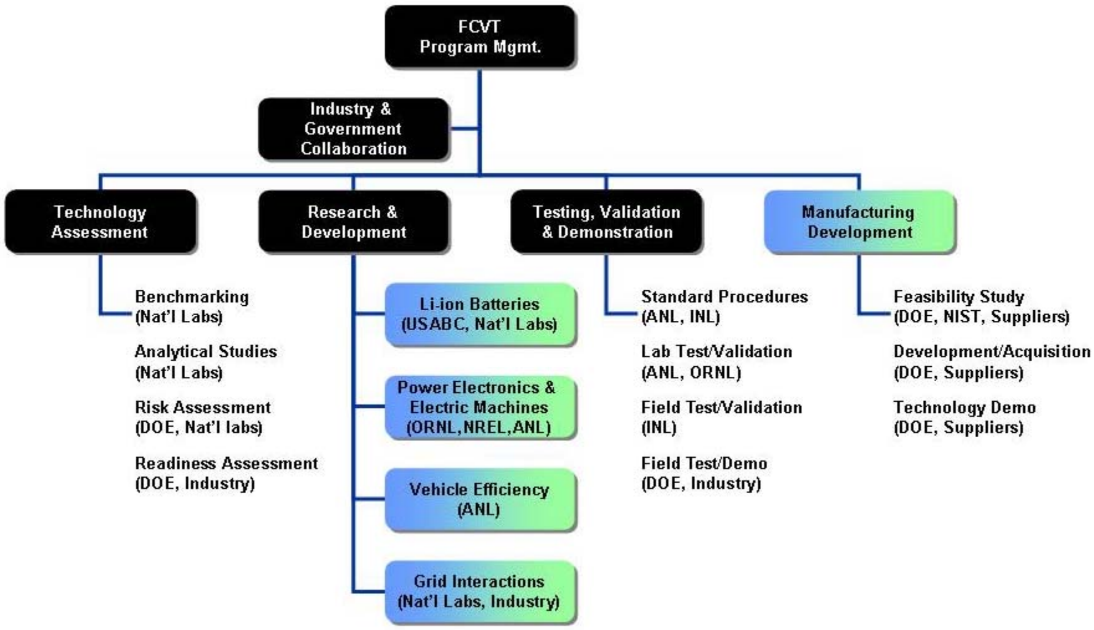
PHEV Technology Decision Process



2.2 Structure of Tasks

The task structure is shown below. The highlighted tasks are detailed in remaining sections of the plan. The other tasks support management activities or technology validation and they are described in this section. Note that the tasks do not necessarily correspond to the FCVT Multi-Year Program Plan due to ongoing projects and prior commitments/contracts.

PHEV Activity Task Structure



2.2.1 Technology Assessment

Technology assessment provides the data and analysis required for informed decision-making by FCVT management, i.e., the status of relevant technology and programs, analytical studies (technical requirements, national benefits, etc.) and risk assessment.

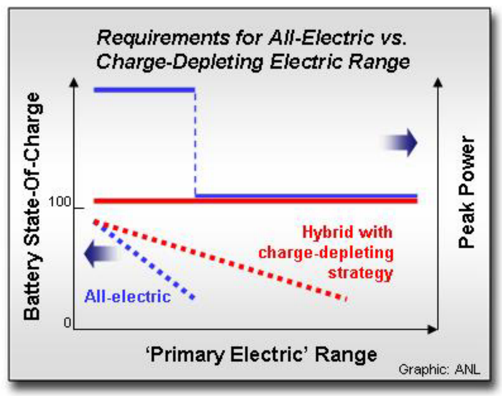
Benchmarking – Benchmarking quantifies the baselines to measure progress against, including characterizing the state-of-the-art of the critical components for PHEVs and the currently available PHEV conversion vehicles. In particular, the baseline technologies at this time have been identified as the following:

- Lithium-ion battery packs (SAFT-JCI)
- Power electronics and electric machines (Toyota)
- PHEV conversions
  - EnergyCS/Toyota Prius (9 kWh Valence Li-ion pack replaces NiMH)
  - Hymotion/Toyota Prius (5 kWh A123 Li-polymer pack plus NiMH)

In addition to the technical data, benchmarking includes assessing programmatic activities as a form of due diligence, i.e., what should DOE/FCVT be aware of as they initiate and carry out this activity? This includes relevant government programs and technology development initiatives being pursued globally. The information will be used to refine goals and identify opportunities for cooperation.

Analytical Studies – Analysis guides technology development by identifying the most promising vehicle configurations, specifying goals for R&D and projecting national benefits. Vehicle modeling and simulation is the basis for this activity and, when combined with market models and regional infrastructure characteristics, supports forecasts of benefits and impacts of PHEVs on petroleum displacement and the electric utilities. In addition, PHEVs have been discussed as a possible enabler for renewable energy sources and the potential benefits will be quantified.

Vehicle modeling and simulation – ANL's Powertrain Systems Analysis Toolkit (PSAT) will be used to design and evaluate a series of PHEVs with various 'primary electric' ranges, considering all-electric and charge-depleting strategies. The objective is to quantify the impact of all-electric range on component performance requirements. The concern is that the peak power requirements for the battery and electric drive are much higher to achieve the same performance in electric and hybrid modes (illustrated at right). This impacts the vehicle economics; higher energy and power requirements drive up costs of the battery and electric drive components, which reduces the likelihood or production. The primary outcomes of the vehicle analysis are:



- Potential for fuel consumption reduction of PHEVs as a function of propulsion system configuration, component sizing and control algorithms.
- Component performance goals and requirements (for R&D/solicitations)

National benefits/impacts – The benefits and impacts of PHEVs depend on the fuel sources (supply side) as well as the vehicle characteristics and consumer use patterns (demand side). One objective of this analysis is to combine energy use characteristics (predicted with the vehicle simulation model PSAT) with energy production characteristics using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (GREET) to perform well-to-wheels analyses. For regional outcomes, GREET requires supply side power generation and distribution data, which falls within the scope of OE. PHEVs will be compared to other hybrids and conventional vehicles in terms of fuel displacement and impact on the environment as well as the electric power grid. The potential impact on the electric power grid and utilities will be evaluated as a function of consumer use patterns, regional infrastructure and regulatory issues. PHEVs have been described as a potential catalyst for the development and proliferation of renewable energy sources (e.g., PHEVs plus wind power); NREL will be clarifying and quantifying this synergistic relationship.

Risk Assessment –The technical reality is that today's hybrid vehicles do not have meaningful electric range because the batteries would be too large, too heavy, too costly and too short-lived for manufacturers to offer an acceptable warranty. In addition, the higher power electric drive would add cost to an already marginally competitive product. Overcoming these barriers will require risk-taking development and new approaches that consider synergistic re-design of the battery, motor and power electronics.

FCVT will attempt to understand and manage the risk by employing technology planning and risk analysis to ensure that developments progress on prescribed paths in a timely fashion or resources are redirected to more potentially successful paths.

Technology roadmaps were previously developed for all the components of interest to FCVT. Some modifications and additions are required, but specific requirements depend on the vehicle configuration. The tools and resources are in place to refine the development paths, identify gaps, monitor progress, support decisions and manage resources to maintain the schedule of the activity.

Identify technology performance gaps – 'Gaps' are the differences between the state-of-the-art (quantified in benchmarking activities) and component performance requirements (identified in analysis or testing). The gaps are expressed in measurable terms at a level of detail adequate for component research and development. Development gaps for the critical technologies are summarized in sections 3 and 4.

Quantify technology development paths – FCVT and the national laboratories have internal resources focused on batteries, power electronics and electric machines as well as long-standing relationships with universities and private sector sources for research and development. These resources will be utilized to refine the development paths (i.e., technology roadmaps) and identify options, including stepwise accomplishments, milestones and budget estimates to achieve the component targets.

Estimate costs versus benefits – This activity is subjective, blending expert opinion and probabilities. But, it is a necessary step to demonstrate how well each development approach is understood, the risks involved, the decision points and development options. The basic objective is to maximize the benefits realized from DOE resources considering:

- Probabilities of success as a function of time and budget
- Alternative approaches for each component development task
- Alternative approaches to petroleum displacement (e.g., engines/fuels)
- Options considering both the domestic and international R&D/supply base

Readiness assessment – The 'readiness' of a technology for production is determined, to a large extent, by the potential manufacturers. DOE will provide information to determine if a technology is 'viable', i.e., that the performance is validated and the manufacturing materials, processes and equipment needs are understood. This includes technology validation data, materials specifications and manufacturing process requirements in addition to data from benchmark testing and global product assessments.

2.2.2 Research and Development

FCVT has ongoing R&D activities regarding Li-ion batteries, power electronics and electric machines for conventional and fuel cell hybrid applications, but PHEVs can require a much different combination of onboard energy and power (depending on the design). Vehicle designs and control strategies have not been finalized, but several development steps are appropriate under any scenario:

- Near-term focus on adapted technology.
- Mid-term (3-5 years) development for specific vehicles and improved range.
- Long-term (5-10 years) development to meet the 40+ miles electric range target.

Lithium-ion batteries – R&D will continue at the national laboratories and in cooperation with the USABC, including competitively solicited fundamental and applied research as well as system development, with an initial focus on current electrochemistry.

Power electronics and electric machines – R&D will continue on electric motors, power electronics, thermal control and integrated systems, competitively solicited through the National Energy Technology Laboratory (NETL) and in cooperation with the national laboratories. Multiple first generation awards are planned in Q2-FY07, with second generation procurement tentatively scheduled for FY09-10.

Vehicle efficiency technologies – This category covers a variety of materials, components and subsystems associated with the body, chassis and ancillary systems that reduce mass, aerodynamic drag, rolling resistance or parasitic loads – everything except propulsion. Trade-off studies will assess the cost-effectiveness of implementing various efficiency technologies as a means of lowering the power and energy requirements.

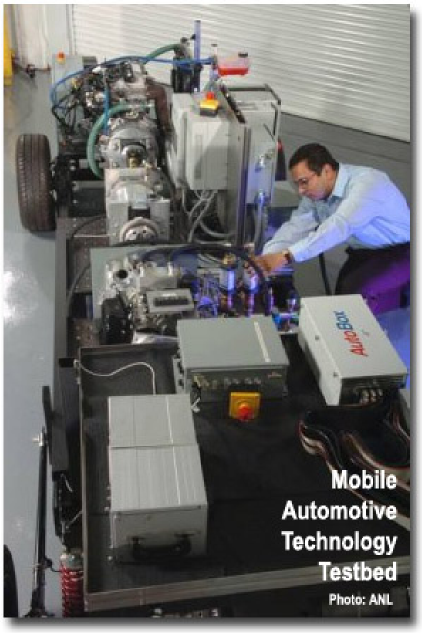
Grid interactions – Two aspects of the vehicle-utility interface will be assessed; the method of connection, power transfer and communication as well as the demand from and impact on the distribution system and power source.

2.2.3 Testing & Validation

PHEV-specific standard test procedures – The various operating modes and control strategies of PHEVs require more flexibility and complexity in test procedures, data acquisition and analysis. Therefore, standard definitions and procedures for both electric range and charge-depleting range hybrids for laboratory and field testing are required.

An activity has been initiated with the appropriate SAE test procedure committee to address PHEVs, with the participation of the Environmental Protection agency (EPA), California Air Resources Board (CARB) and automotive industry representatives.

Lab testing and validation – Initial testing focuses on benchmarking batteries and PHEV conversion vehicles, followed by confirmation of PHEV test procedures using hybrid testbeds (described on the next page). Component validation testing will use standard test benches or the Mobile Automotive Technology Testbed (MATT-shown in the figure) on the vehicle dynamometer. Testing of the SAFT-JCI Li-ion batteries, developed with DOE support, is already underway using the HIL test bench.

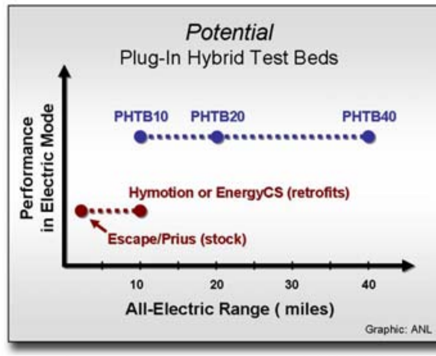


Mobile Automotive Technology Testbed

Photo: ANL

The 4-wheel drive vehicle dynamometer at the Advanced Powertrain Research Facility (APRF) will be used to characterize performance, fuel economy and emissions under controlled conditions. The PHEV conversions will be tested when new, field tested, then returned to for periodic and/or "end of life" testing.

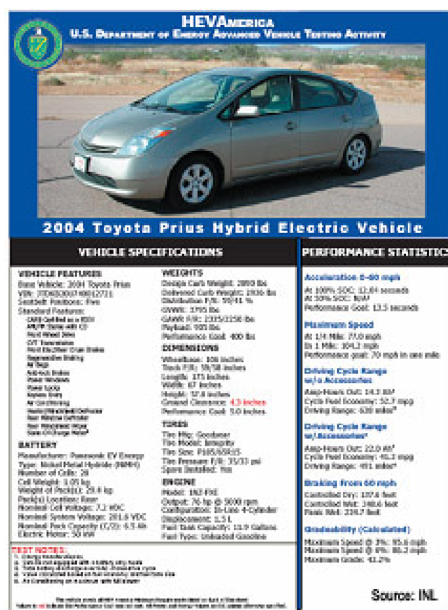
Plug-in hybrid test bed (PHTB) – PHEV conversions are capable of limited electric range at reduced performance – not adequate to cover the design space (i.e., range or performance) of PHEVs intended for the mass market. PHTBs will be full-performance, instrumented vehicles capable of all-electric or charge-depleting range up to 40 miles (figure on the right). The test beds will help develop standard test procedures, refine component performance requirements, quantify the impact of electric range and control strategy on fuel economy and emissions as well as provide the validation link between lab and on-road testing.



The Saturn VUE Greenline is a potential platform because it has a belted-alternator-starter (BAS) that enables on-off operation of the engine and it can be augmented to become a split/RWD hybrid.

The procedures developed for vehicle testing will be translated for standard component bench testing and vehicle simulation – the basis for load emulation in HIL testing (i.e., in an emulated vehicle environment using a power profile and duty cycle generated from vehicle simulation).

Field testing and validation – Field testing will be used to determine on-road performance, fuel consumption and operational characteristics in limited fleet applications. Testing will be performed in Phoenix by Electric Transportation Applications (ETA) for eight months of the year, with summer testing at Idaho National Laboratory (INL) due to battery operating temperature limits. A third location is being considered as well.



EnergyCS is reprogramming their onboard data acquisition system to monitor 10 vehicles in fleet applications (7 vehicles currently operating in California). The data will be provided to INL to study PHEV charging practices, energy/power requirements, energy storage issues and operating costs.

OEM Validation and Demonstration – For additional validation, a solicitation for several small, strategically located demonstration fleets (e.g., 10 to 20 vehicles in 3 to 5 cities) is being considered for the 2008-2010 timeframe. This action would support the development and in-use validation of production-intent PHEVs, not conversion vehicles.

2.2.4 Manufacturing Technology

The critical component of PHEVs is the Li-ion battery, but there is no domestic production despite DOE support of R&D for many years.[1] Asia is the primary source of Li-ion batteries (due to the demand for consumer electronics). DOE proposes to support the development of manufacturing technology to enable U.S. production of domestically developed Li-ion technology. The linkage between Johnson Controls and SAFT is a step in the right direction. In addition, DOE experience supporting Cobasys as they developed capacity to manufacture NiMH batteries for GM is directly applicable to this activity.

Cobasys NiMH in the Saturn Aura
Photo and graphic: Saturn Corporation

Feasibility study – An assessment of manufacturing materials, processes and equipment needed for Li-ion battery production will be initiated in Q2-FY07 to determine the technical feasibility of domestic manufacturing. This includes identifying critical material content and equipment requirements, identifying sources and supply options and determining availability.

Technology development and/or acquisition – Depending on the results of the technology assessment, develop or acquire the key materials, processes and equipment to demonstrate production of the critical components of Li-ion batteries.

Technology demonstration – Develop and demonstrate a low-volume battery production line as a basis for implementing a manufacturing technology activity for batteries similar to the DOD ManTech program for strategic technologies.

2.3 Schedule

The preliminary schedule is shown on the next page, including two generations of development and long-term research. The process is interactive (denoted by the red arrows), with opportunities for refinement of goals based on external developments and the national priorities as well as modifications of technical specifications based on internal analysis and testing.

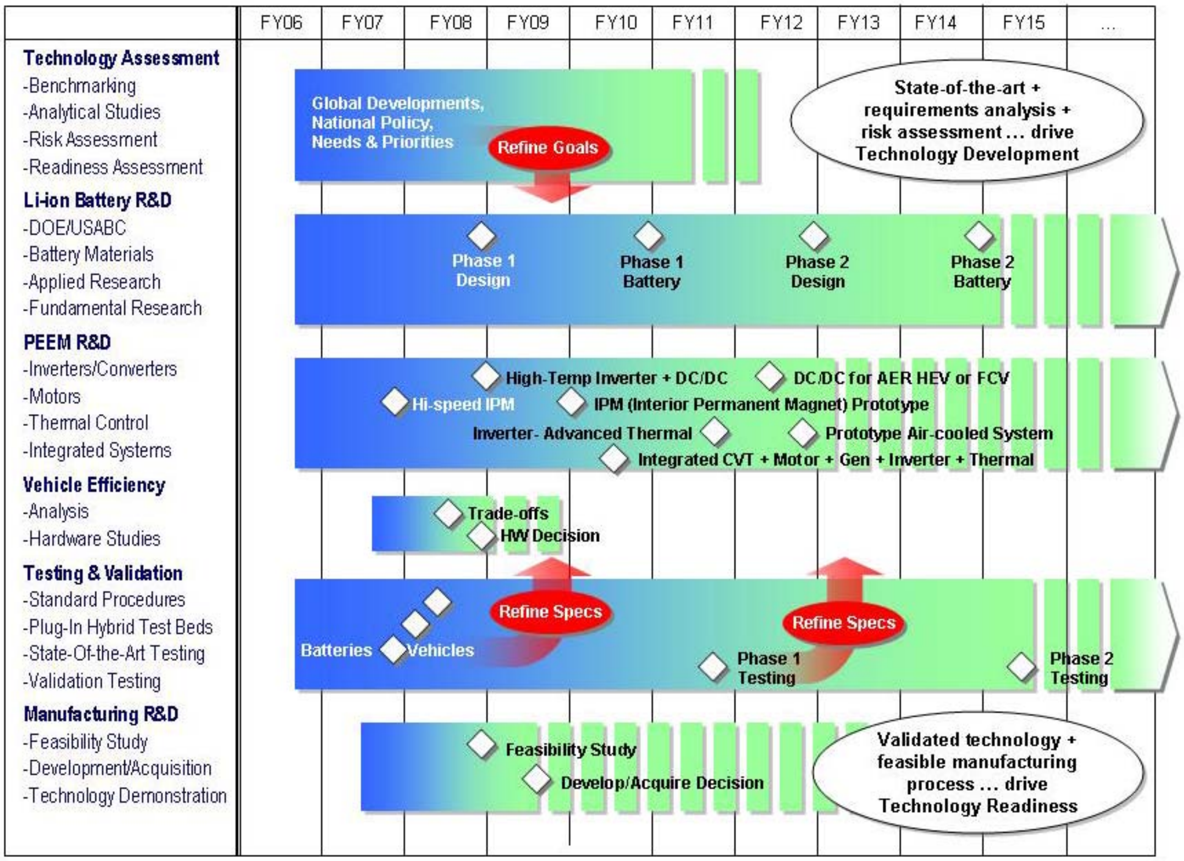
Phase 1 technology development is evolved from related activities in FCVT's portfolio. Although some contract awards are as early as Q2-FY07, there is ample opportunity to refine the specifications based on what is learned from benchmark tests of the PHEV

[1] Brodd, Ralph J., *"Factors Affecting U.S. Production Decisions: Why are There No Volume Lithium-Ion Battery Manufacturers in the United States?"*, ATP Working Paper Series, Working Paper 05-01, Prepared for the Economic Assessment Office, Advanced Technology Program, National Institute of Standards and Technology, June 2005.

conversion vehicles and the latest Li-ion batteries developed by DOE. Testing should be complete prior to finalizing the Phase 1 technology development plans.

Phase 2 development activities will focus on specific PHEV configurations based on additional information from the technology assessment activities, including global developments, refined vehicle analyses and completion of the risk assessment.

Preliminary PHEV R&D Schedule



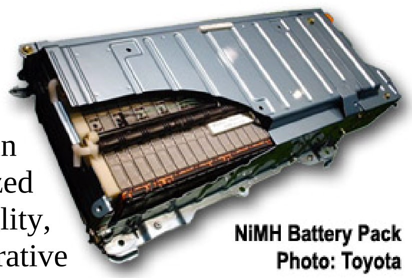
The process drivers are shown in the notations (bubbles) in the chart. Technology development is driven by understanding what the technology is capable of now (the state-of-the-art) versus how the technology must perform to be successful (requirements analysis) and the most promising approaches to close the gaps (risk assessment).

The objective of DOE development is demonstrating technology that has the potential to be produced, i.e., with validated performance and defined manufacturing processes and parameters. Taking the next steps to production is up to OEMs/suppliers and depends on numerous market and economic factors outside the scope of DOE's R&D.

More detail regarding the schedule and deliverables can be found within the respective sections of this plan.

Section 3: Lithium-ion Batteries

3.1 External Assessment and Market Overview



NiMH Battery Pack
Photo: Toyota

Battery technology is critical for plug-in hybrid vehicles and the primary challenges are higher energy and lower cost relative to today's technology.[2] The typical battery in a production hybrid is a nickel metal hydride (NiMH) sized for the vehicle power demands, i.e., start/stop functionality, power assist during acceleration and recovery of regenerative braking energy (e.g., Prius or Escape). The energy provides only a few miles of all-electric range at reduced performance and increasing the capacity to meet the 40 mile PHEV goal is not realistic due to its specific energy limitations.

The life of NiMH batteries is adequate for a substantial warranty (e.g., 8 years/80,000 miles) because the control strategy ensures that the battery is not deep-discharged as would be the case for a PHEV with all-electric range. In fact, today's hybrids typically maintain the state-of-charge within a narrow range (approximately 60% SOC, $\pm$ 5%).

Li-ion batteries are considered the front-runner for PHEVs because of the higher specific energy and power compared to NiMH. Though produced in high volume for consumer electronics, limited quantities are manufactured for vehicle applications in Japan (Hitachi produces 50 packs per month for the Mitsubishi Eco Canter hybrid truck).

3.2 Relevant DOE Activities and Technology

Li-ion Cells
Photo: Saft

DOE has been developing Li-ion battery technology for years in partnership with the auto industry, represented by the USABC. Ongoing projects in technology development, applied research, and focused fundamental research are directly applicable to the PHEV R&D activity.

Technology development in partnership with the USABC includes benchmark testing, technology assessment, and full system development currently focused on developing and evaluating Li-battery cells, packs, and full systems for hybrids.

Applied research addresses cross-cutting barriers that face those Li-ion systems closest to meeting the requirements for vehicle applications. Five national laboratories (Argonne, Berkeley, Brookhaven, Idaho and Sandia) participate, each bringing its own areas of expertise to address life, abuse tolerance, low temperature performance, and cost.

Focused fundamental research addresses chemical instabilities, promoting a better understanding of why systems fail, modeling failure and system optimization, and investigating new materials. The work includes nickelates, phosphates, and new higher energy materials such as composite cathodes and non-graphitic anodes. Three national laboratories (Argonne, Berkeley and Brookhaven) and twelve universities currently participate in this activity.

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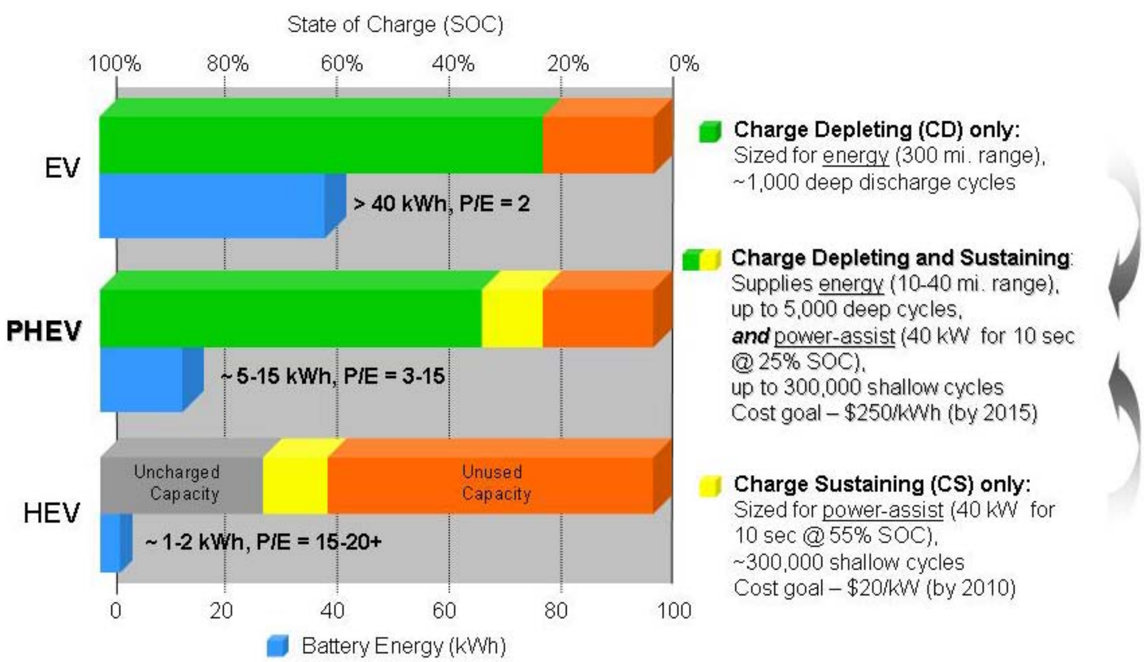
[2] *Summary Report: Discussion Meeting on Plug-In Hybrid Electric Vehicles*, May 4-5, 2006, Office of FreedomCAR and Vehicle Technologies, Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC, August 2006 (DOE/EERE website).

3.3 Development Goals and Approach

Development goals – Battery requirements are extremely sensitive to vehicle design (i.e., all-electric or charge-depleting range) and a single PHEV design has not been (and likely will never be) agreed upon. This means that battery development must cover a range of requirements from providing essentially the same functionality as in today's hybrids (sharing power demands with the engine) to providing all the vehicle propulsion power as well as accessory loads (that could double the demand). The requirements for a PHEV battery combine those of an electric vehicle (EV) which only depletes the battery during operation (i.e., "charge depleting only") and a typical HEV in production today that maintains the battery state of charge within bounds (i.e., "charge sustaining"), as illustrated in the figure below. A PHEV battery will experience both deep discharges like an EV (i.e., the large swings in SOC shown in green) and shallow cycling necessary to maintain the battery for power-assist in charge sustaining HEV mode (in yellow). In addition to the stringent duty cycle, the power-to-energy (P/E) ratio (an influential design parameter) is specific to each vehicle application.

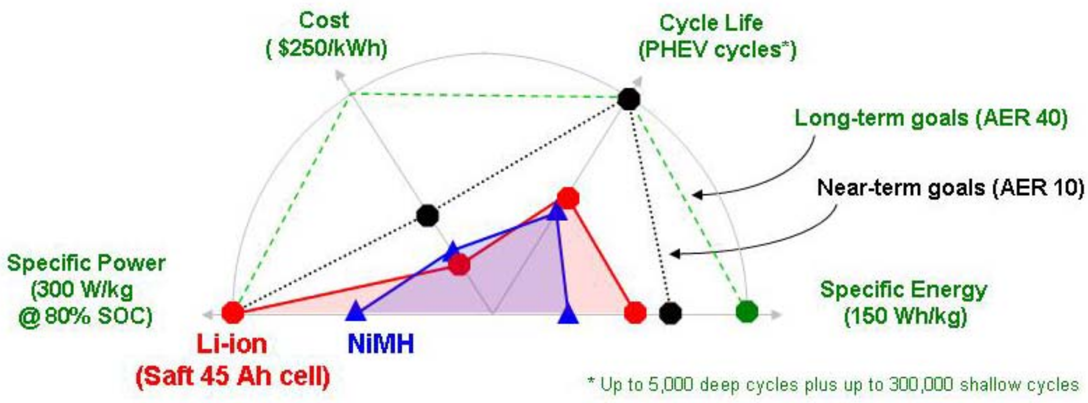
Battery Performance Requirements versus Vehicle Application



With the uncertainty in vehicle requirements, near- and long-term goals are being developed. The near-term goals, drafted in collaboration with the USABC, target a 10 mile all-electric range for a mid-size SUV, which implies a 5-10 kWh battery with approximately 40 kW peak power, costing no more than $4,000. Mid-term goals will be established as PHEV requirements solidify. The long-term goal is 40 mile all-electric range for a mid-size passenger car and the same $4,000 system cost.

Li-ion batteries have made significant progress in recent years and the simplified spider chart below illustrates the advantages over NiMH batteries, however durability with a PHEV duty cycle and the ultimate cost remain key challenges.

Comparison of NiMH and Li-ion Battery Status to PHEV Goals



Li-ion batteries excel in power capability (2 times NiMH) and cycle life up to 300,000 shallow cycles has been demonstrated for conventional hybrid vehicle applications, but the technology has not been rigorously tested with PHEV duty cycles. Cost is the most obvious challenge (est. 4-10 times too high), though specific energy requires doubling.

Cost – The lack of a high volume manufacturing facility for high energy automotive batteries is considered a major factor in the cost gap since Li-ion uses low-cost and abundant materials compared to NiMH. In addition, it should benefit from the material refinements and production maturation in the high-volume consumer electronics market.

Life **–** A combination of energy and power fade are anticipated challenges as the battery will likely have to support high power HEV cycling at low states-of-charge (SOC) and provide electric range over the 15-year life of the vehicle. Li-ion batteries have been tested extensively for hybrid vehicle applications (shallow cycles) but battery life typically falls off dramatically with deep discharge cycling.

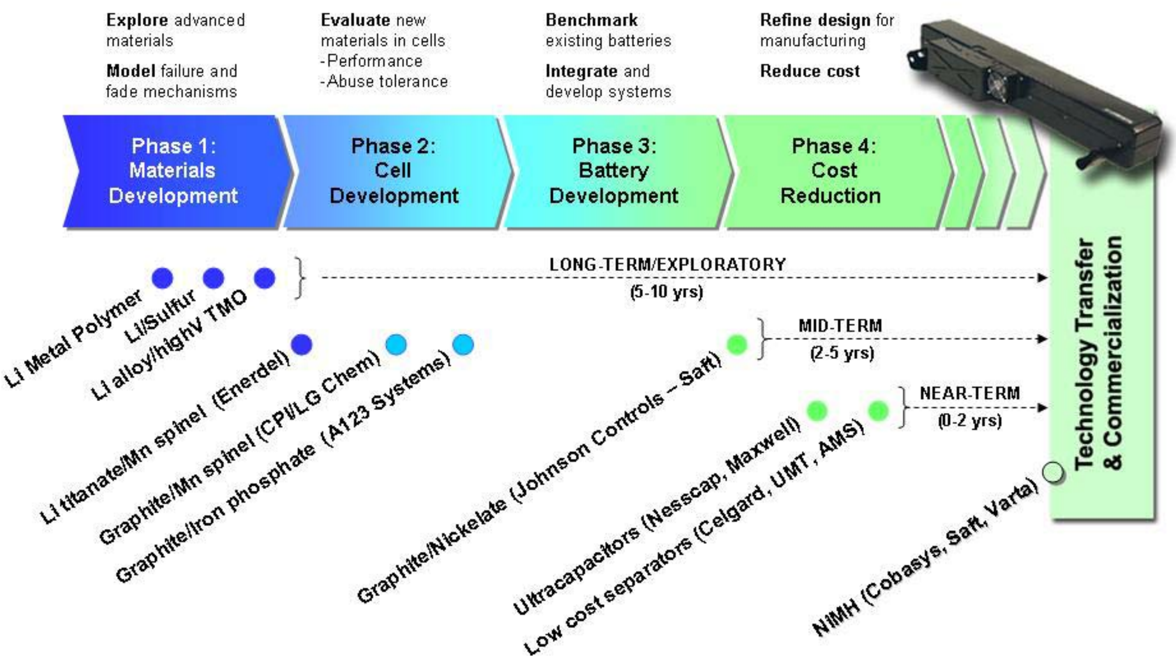
Other factors to consider for Li-ion include the high voltage per cell, 4.0v versus 1.2v for NiMH, (which positively impacts battery pack design and integration) as well as low-temperature performance and abuse tolerance, which require further development.

Low Temperature Performance **–** Li-ion exhibits significant discharge and regenerative power reduction at temperatures less than -20ºC.

Tolerance of Abuse and Safety **–** Li-ion batteries used in consumer electronics are not intrinsically tolerant of abusive conditions such as short circuits, overcharge, over-discharge, crush, or exposure to fire and/or other high temperature environments. High energy PHEV batteries are expected to present further challenges.

Approach – The proven approach, illustrated on the next page, has been employed since 1991 and is based on highly interactive fundamental and applied R&D – leading to the successful development of NiMH batteries now being used in production hybrids. To briefly describe the approach, new materials and basic physical mechanisms are investigated to identify promising electrochemical couples for advancement to cell construction and evaluation. Demonstration of acceptable performance and tolerance of abuse (e.g., thermal) at the cell level is the threshold for battery fabrication, integration and system development. Performance of the battery system in a vehicle duty cycle shifts the focus to manufacturing concerns and refinement of the battery design, materials and processes to reduce cost.

Advanced Battery R&D Process



This activity will enhance commercialization efforts, including supplier support, technology validation in the private sector and implementation of a manufacturing technology activity, further explained in Section 7. Tasks associated with each of the phases are explained in the following paragraphs.

3.4 Tasks

Phase 1: Materials development (national laboratories and universities) – The tasks are exploratory research with long-term potential to improve Li-ion technology:

Develop Improved Positive Electrode Materials

- Transition metal oxide (TMO)-based cathodes: for high capacity (>250 mAh/g) leading to improved energy density and lower system cost
- Organic redox cathodes (and anodes): for high energy and rate, low cost

Develop Improved Negative Electrode Materials

- Novel inter-metallic alloys and new binders: for improved energy density (> 2 times graphite) and lower system cost
- Nanophase metal oxides (*e.g.*, $Li_4Ti_5O_{12}$) with voltage higher than graphite: to avoid Li-deposition on charge and result in lower cost than graphite

Develop Associated Electrolytes

- High voltage electrolytes (4.5 – 5 Volts): to take advantage of cathodes that operate above 4.3 Volts
- Solid polymer electrolytes (with improved conductivity & mechanical strength): to inhibit dendrite growth and to enable Li-metal batteries

- Ionic liquids: for improved stability against high voltage electrode materials, enabling the use of higher energy materials
- Electrolyte additives including redox shuttle overcharge protection additives: for improved safety and interfacial stability for longer life

Conduct Inter-phase Studies

- Continue search for better membranes or glasses: to stabilize the surface of the metallic lithium anode, leading to Li-metal batteries
- New stabilized surface coatings: to inhibit cathode degradation, leading to more stable and longer lived batteries
- Continue search for the cause of high interfacial resistance: for improved performance at low temperatures

The figure shows the potential contributions of material advancements to Li-ion specific energy and the importance of materials development. It also shows that new materials are needed to progress from the current capability (~70 Wh/kg) to meet the near- and long-term goals of 100Wh/kg and 150Wh/kg, the initial requirements drafted by the USABC.

Phase 2: Cell development (national laboratories and industry/USABC) – The focus is new, higher energy materials in appropriately sized cells/modules. This includes the Li-based cell configurations of Enerdel, CPI/LG Chem and A123 systems.

Phase 3: Battery development (industry/USABC) – Design and build systems for evaluation in the laboratory and validation with industry (suppliers and OEMs) within their development environment to accelerate technology transfer. The latest generation of Li-ion batteries by Johnson Controls-SAFT is presently undergoing tests at ANL.

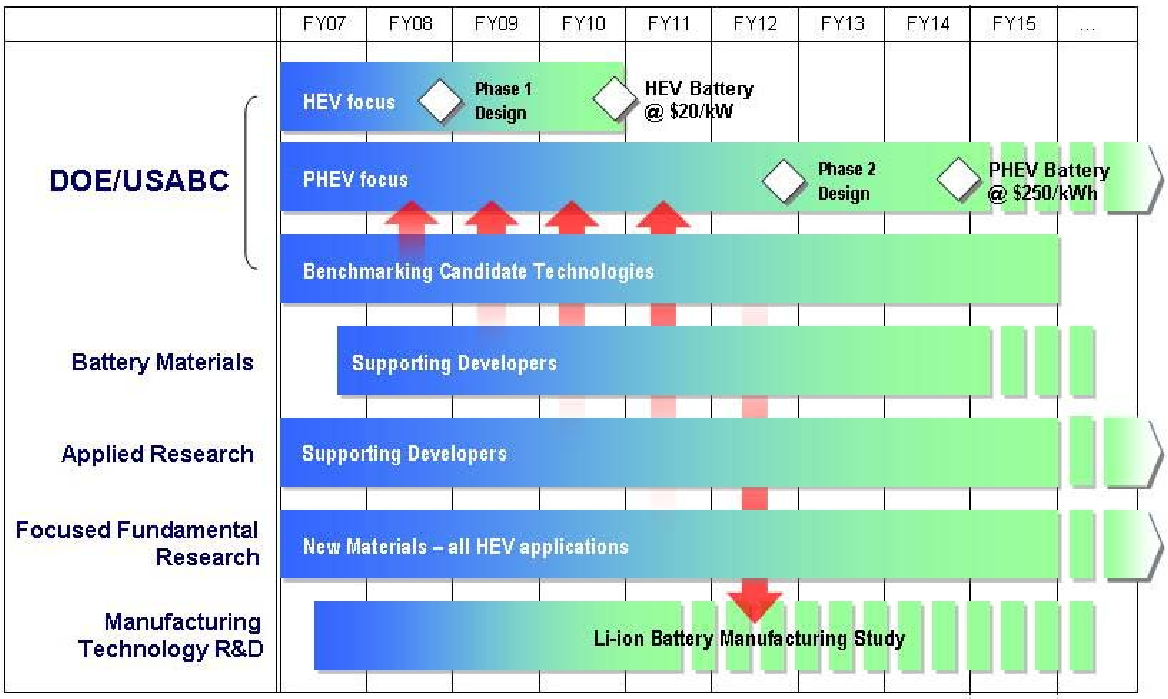
Phase 4: Cost reduction (industry/USABC) – The task focuses on refinement of the battery design and materials in concert with the processes and equipment required for low-cost volume battery manufacturing. Earlier Li battery developments by SAFT have entered this stage of development as well as ultracapacitors (by Nescap and Maxwell) and low-cost separators (by Celgard, UMT and AMS).

The goal of this phase is a battery design consistent with a demonstration (low-volume) battery production line to be implemented by the Manufacturing R&D activity (Section 6). The activity will supply the critical material, process and equipment requirements necessary to implement a battery activity similar to the DOD ManTech Program to ensure a U.S. battery manufacturing capability.

3.5 Schedule and Milestones

The DOE/USABC will release a PHEV battery solicitation in Q2 FY07 and is expected to begin benchmarking or proof of concept contracts by early spring 2007. Similarly, the applied and focused fundamental research activities are planning to ramp up work on higher energy battery materials and cells following approval of the 2007 DOE budget.

Battery R&D Schedule



Section 4: Power Electronics & Electric Machines

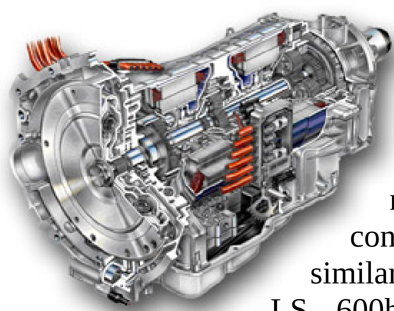
4.1 External Assessment and Market Overview

Several automotive and truck manufacturers currently produce hybrid vehicles, though the plug-in feature is only available on a limited basis (domestically) on converted production hybrid vehicles. The electric drive components (unchanged other than control) are sized for the power requirements, duty cycle and thermal loads to assist the engine during peak demands, recover braking energy, charge the battery and, in some cases, provide low speed driving.

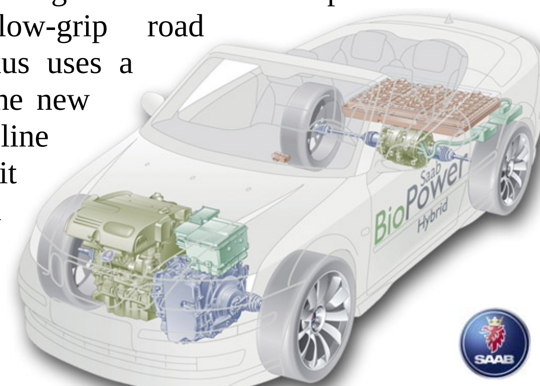

Photo: ANL

Drive motors/generators in today's hybrids are packaged as fully integrated front-wheel drive (FWD) units, e.g., the original Prius (right) as well as in-line rear-wheel drive (RWD) units such as in the 2007 Lexus LS 600h or axle-mounted RWD units such as in the Lexus RX400h.

Power ranges from 50kW$_{max}$ (at 1200-1540 rpm for the approximately 25kW$_{cont}$ Prius motor) up to 160kW$_{max}$ for the Lexus LS 600h. But in all cases the electric traction motors provide about half the maximum power of their respective propulsion systems.


Drawing: General Motors Corp.

High power electric rear drive, such as in the 'two-mode' system being developed by the joint venture of GM, BMW and DCX (left), appears to be the preferred design direction in the premium hybrid market, providing 4WD to boost performance in normal and low-grip road conditions. Lexus uses a similar rear drive in the new LS 600h with an in-line motor, generator, power split planetary gear mechanism and speed reduction in one transmission casing. Saab reaches for maximum performance in the BioPower hybrid concept vehicle, which utilizes both the FWD version of the two-mode system and an electric rear axle.

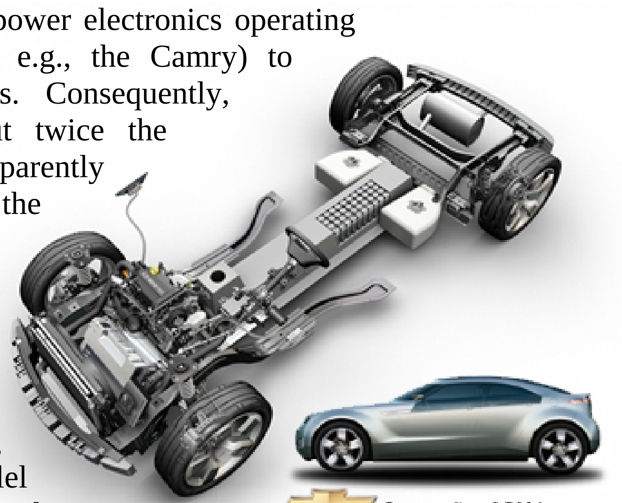


Graphic: Saab

Photo: ANL

Power electronics are designed to match the characteristics of the battery and traction motor. The 2007 Toyota Camry integrated power unit (left) exemplifies the state-of-the-art, a 15.4 kg package that replaces the standard starting battery, containing the traction drive, generator inverter and boost converter.

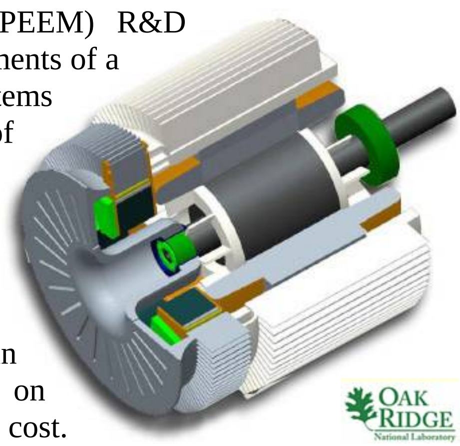
Batteries are nominally 200-288V, with power electronics operating at 500-650V (using a boost converter, e.g., the Camry) to decrease the current and associated losses. Consequently, power semi-conductors are rated about twice the battery voltage. Battery voltage is apparently increasing – up to about 400V in the Chevrolet 'Volt' (right, with Li-ion battery pack in the tunnel) which was presented as a plug-in hybrid concept vehicle at the 2007 North American International Auto Show in Detroit.


Composite of GM images

Of the powertrain architectures being considered for plug-in hybrids, the parallel power-sharing configuration (e.g., today's production hybrids) with a modified control strategy to allow battery charge depletion would likely be the most cost-effective and have the least impact on the motor and power electronics. However, because of cost, mass and packaging considerations, performance may be compromised. In a series hybrid configuration such as the Volt, full-function electric traction components (more than twice the power as in current production hybrids) are required for full-time electric drive. This exacerbates electric propulsion system cost, but the smaller engine-generator system (used to extend the range) and the elimination of the mechanical drive should cost less than the conventional engine and driveline components. And from a longer term perspective, development of higher power electric drive components for PHEVs will benefit fuel cell vehicles where all traction and accessory power will be supplied electrically. In fact, GM has stated that they are building a fuel cell-powered Volt to demonstrate the flexibility of the 'E-Flex' platform.

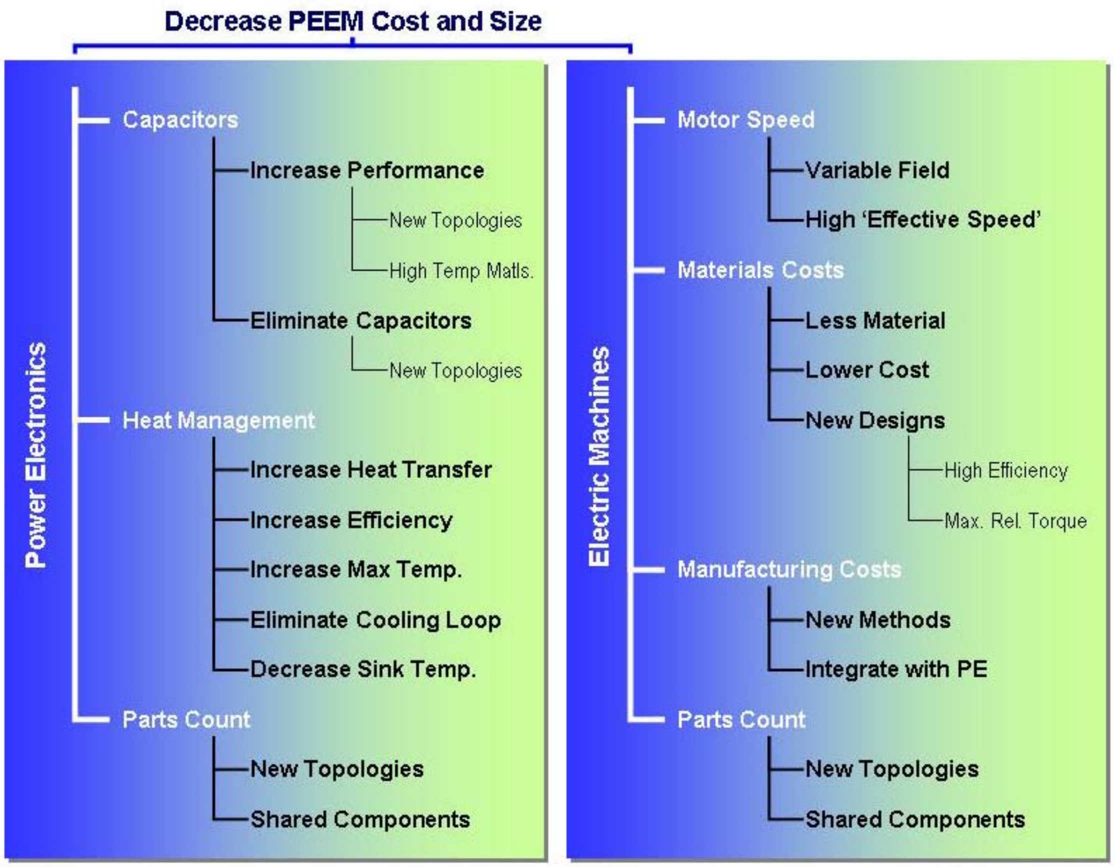
4.2 Relevant DOE Activities and Technology

The Power Electronics and Electric Machines (PEEM) R&D activity is developing technology to meet the requirements of a variety of hybrid and electric propulsion systems (including fuel cell vehicles). The broad spectrum of applications and propulsion system configurations necessitates multiple technology development paths that cover components as well as integrated systems (such as the integrated motor-inverter design concept shown on the right). Various options under development are shown in the chart and summarized in the table on the next page, but all are focused on improving performance, reducing volume or lowering cost.



PHEVs do not present any additional technical barriers for electric drive components since the power requirements fall within the spectrum of previously considered hybrid and electric vehicles. However, the need to charge PHEVs from a wall outlet (perhaps with a 'smart' connection to regulate charging in the future) necessitates consideration of further functional integration in the power electronics and control.

PEEM Technology Development Options (*all details not shown*)



Power Electronics and Electric Machines Development Paths
Motor R&D
• Multiple motor design concepts including variable-voltage traction motors • Sintered or bonded magnets for permanent magnet motors
Power Electronics R&D
• Multiple topologies for hybrid propulsion subsystems • Multiple design and material approaches for capacitors • Consideration of alternative materials including current silicon semiconductor materials and higher temperature wide bandgap materials, such as SiC
Thermal Control R&D
• Multiple cooling approaches including HEV combustion engine 105°C coolant, spray and jet cooling, forced air cooling and improved heat transfer materials
Integrated System Development
• Multiple design concepts, such as inverter-motor subsystems with and without DC/DC converters.

4.3 Development Goals and Approach

The development approach for PEEM components/systems is described below, followed by a summary chart of the system-level development targets. Production hybrid propulsion technology has been thoroughly benchmarked and many of the component targets are based on achieving substantial improvements from the Toyota Prius baseline, as summarized in the system-level spider chart that follows the targets.

Motor R&D – Decreasing the cost and size of electric motors requires increasing speed (i.e., higher power from smaller machines) and/or redesigning for increased material utilization or lower cost materials.

- Ongoing FY07 PEEM R&D activities are focused on high speed 16,000 rpm permanent magnet motors that achieve field weakening within the structure of the motor and eliminate the need for a DC/DC boost converter. And motor speeds up to 20,000 rpm are being explored.
- Cost issues associated with interior permanent magnet motors are being addressed by applying concentrated windings to interior permanent magnet designs to reduce motor manufacturing costs.
- Control methods will be analyzed to provide further benefits by extending the motor constant power speed range (CPSR).
- Several motor designs with system-level savings for PHEVs are being explored. A motor concept with controllable winding configurations is being developed that enables high starting torque with considerably less power from the battery, potentially lowering battery cost and weight. A traction motor with a substantially higher CPSR than that required for an HEV or FCV would enable reductions in gearing that will provide vehicle cost and weight reductions.

Power Electronics R&D – Reducing the cost and size of the power electronics requires addressing the (large) capacitors, waste heat (more tolerant components, reducing heat or dissipating it more efficiently) and new designs that reduce parts count by integrating functionality.

- A current source inverter (as opposed to a conventional voltage source inverter) is being designed and developed to eliminate the DC bus capacitor by using inductors.
- A portfolio of projects is being pursued that spans a range of cooling temperatures. A long term focus, possibly in conjunction with higher temperature wide bandgap semiconductor components such as SiC, is the use of high temperature, air cooled systems. Such an approach would insure that technologies are being developed for all potential future vehicle platforms (HEV, PHEV, and FCV).
- Several efforts are being directed specifically at PHEV applications, including determining the potential to use the existing HEV inverter to fulfill the plug-in charging function on the vehicle.
- A bidirectional DC/DC converter is being explored to reduce cost and volume.

Thermal control R&D – The objective is to maintain the electronic devices at operating temperatures that will ensure performance and reliability over the life of the vehicle while reducing system cost, weight, and volume.

- Development is continuing on advanced heat transfer techniques (single and two-phase sprays and jets, direct backside cooling, alternative coolants, materials for heat transfer, enhanced heat transfer thermal greases) to provide cooling for low ΔT applications.
- The effort to develop inverter and motor technologies that take advantage of two-phase cooling using refrigerants will be continued as well.
- The use of energy storage to provide a thermal buffer in heat rejection from the inverter is being explored. This effort would allow the heat rejection system to be sized for the average heat load rather than the peak heat load, thereby reducing the size and cost of the thermal management system.
- R&D also is being conducted on the integration of power electronics thermal control technologies and the impacts of thermal stresses on component life and reliability.
- The effects of PHEV power and duty cycle requirements will be evaluated in terms of thermal stresses on the devices, heat dissipation requirements, and the impacts of PHEV design configurations on life and reliability of the power electronics components.
- Capacitor developments are continuing to emphasize ceramic and glass capacitor efforts. These efforts are directed toward improving high temperature capacitor performance as well as reducing the volume of capacitors required in the inverter.

Integrated Systems Development – Efforts are being initiated to integrate the motor and inverter, focusing on development of a system that will accommodate the spectrum of performance requirements of internal combustion engine hybrid and fuel cell vehicles. The resulting range of requirements encompasses the needs of envisioned PHEVs.

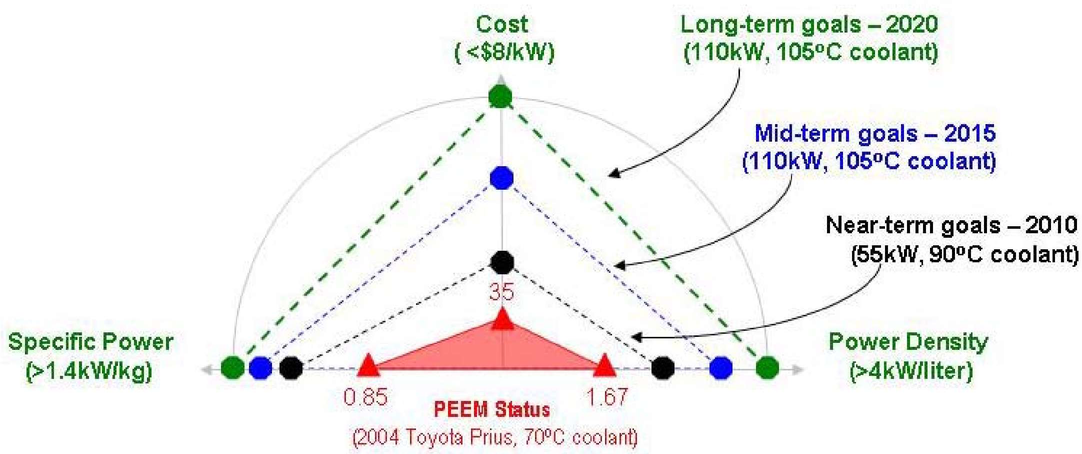
Power Electronics and Electric Machines Development Targets

		Gen 1 (2010)	Gen 2 (2015)	Long-Term (2020)	Status*
Integrated Electric Propulsion System (Motor and Power Electronics Inverter/Controller)					
Requirements	Peak Power (18 seconds), kW	55	110	110	
	Continuous Power, kW	30	30	30	
	Life, years	15	15	15	
Targets	Spec. Power at Peak Load, kW/kg	>1.06	>1.2	>1.4	0.85
	Vol. Power Density, kW/L	>2.60	>3.5	>4.0	1.67
	Cost, $/kW	<19	<12	<8	35 (est.)
Desired	Coolant Temperature, °C	90	105	105	
	Efficiency (10-100% speed, 30% torque)	>90	>93	>94	
Vehicle Power Management (Bidirectional DC/DC Converter)					
Targets	Spec. Power at Peak Load, kW/kg	0.8	>1.0	>1.2	
	Vol. Power Density, kW/l	1.0	>2.0	>3.0	
	Cost, $/kW	<75	<50	<25	
Desired	Coolant Temperature, °C	90	105	105	
	Efficiency (10% to 100% speed, FTP)	92	95	96	

* 2004 Toyota Prius

The component technology developments to date have not been tested as part of an integrated system. The following chart shows the targets established for the PEEM activity versus the baseline system performance.

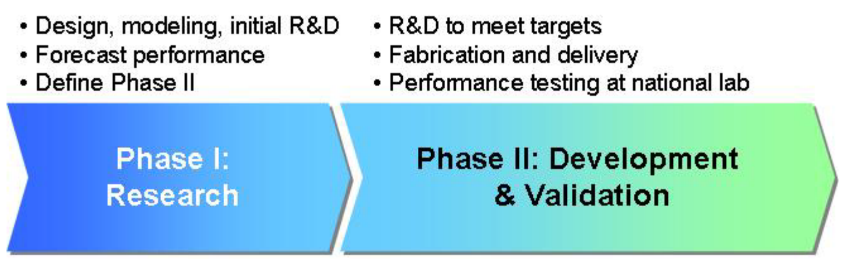
Integrated Electric Propulsion System Status versus Targets



4.4 Tasks

The FY06 actions address high-temperature inverters, high-speed motors, integrated systems and DC/DC converters. Awards are expected in Q2-FY07 and each activity will have two phases. The first focuses on design, modeling and initial R&D to forecast performance and precisely define second phase development activities. The second phase produces the components for validation testing at an appropriate DOE national lab.

Advanced PEEM R&D Process



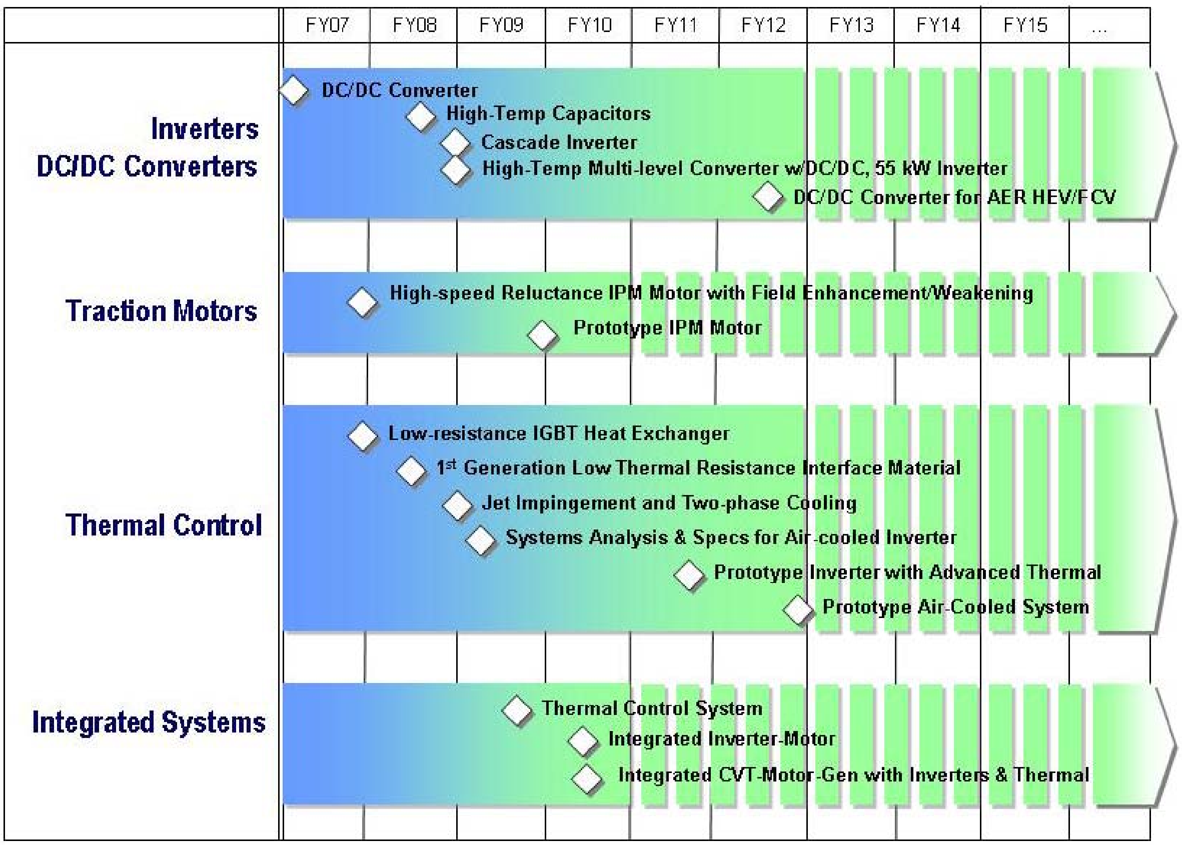
		Gen 1 Targets*
High-Temperature 3-Phase Inverter	High temperature (>105°C), low cost, weight and volume inverters.	55 kW, 4.6 kg, 4.6 liters, $275
High-Speed Motors	Brushless dc traction drive motor with operating speed in excess of 14,000 rpm	55 kW, 35 kg, 9.7 liters, $275
Integrated Traction Drive Systems	Smaller, lighter and lower cost than those in today's hybrid vehicles.	55 kW, 46 kg, 16 liters, $660
Bi-Directional DC/DC Converter	Boost from battery voltage to high voltage bus in a lower cost, smaller configuration	5 kW, 6.3 kg, 1 liter, $375

** In addition to system-level requirements (life, operating temperature range, etc.); costs are for 100K/yr production*

4.5 Schedule and Milestones

Development of advanced power electronics and electric machines covers the spectrum of requirements and timing, ranging from the ongoing FCVT Program components for conventional hybrids to PHEVs and fuel cell vehicles – as shown in the figure below.

PEEM R&D Schedule



Section 5: Vehicle Efficiency Technologies

Increasing vehicle efficiency can reduce the cost of integrating new propulsion technology – due to propagated savings throughout the vehicle and reduced component performance requirements. Since PHEVs are expected to cost more than today's hybrids (which already cost more than conventional vehicles), this approach could be particularly beneficial if the cost of reducing the power and energy required is less than the cost of providing it. Considering the long-term cost goals stated previously, the hybrid components alone could cost $3,000 to $6,000[3] (much more if only near- or mid-term goals are achieved). This provides an incentive to determine which vehicle efficiency technologies/components could payoff versus higher cost propulsion components.

5.1 External Assessment and Market Overview

Lightweight body and chassis technologies for transportation applications have been developed for many years in both the public and private sectors, with varying degrees of success determined by how cost effective they were in mainstream products. The most efficient vehicle designed for production was the EV1 by General Motors. But, the high production costs of the lightweight body and chassis plus the electric propulsion system strongly influenced the decision to limit production to a small number for demonstration purposes. Since that time many of the component technologies (e.g., using aluminum, magnesium and plastics/composites) have been introduced throughout the world in production cars and the costs have dropped dramatically. The Chevrolet Volt, shown previously, uses composites (with up to 50% parts weight reduction) that would not have been considered in years past due to cost. And lightweight vehicles are making progress toward production; Loremo AG, a German manufacturer, has announced plans to produce a 470 kg, 4-passenger vehicle by 2009. Powered by a 3-cylinder, 36 kW turbo-diesel engine, the 'GT' is supposedly capable of accelerating from rest to 100 km/h in 9 s and consuming fuel at a rate of only 2.7 l/100km (87.5 mpg). The list price for the GT is 14,990 € ($19,500 at $1.30/€). A model with even lower fuel consumption (1.5 l/100 km or 157 mpg) also will be offered, but the lower performance (0-100 km/h in 20 s) is not likely adequate for the typical US consumer.

Image: Loremo AG

5.2 Relevant DOE Activities and Technology

One objective of the Materials R&D activity is to develop lightweight materials as enablers for lightweight vehicle structures to improve fuel economy and reduce demands on the vehicle powertrain and ancillary systems (e.g., braking). The greatest barrier to

[3] Based on $8/kW for a 55-110 kW electric propulsion system plus $250/kWh for a 10-20 kWh battery; this does not include the mechanical drive train components (gear reduction, transmission, etc.)

substituting lightweight, high-strength materials (such as aluminum, magnesium, titanium, advanced high-strength steels, fiber-reinforced composites, and metal matrix composites) for mild steel in vehicle applications is cost. FCVT is leading research efforts to develop and validate technologies that reduce the cost of materials, components, and structures and/or improve their manufacturability.

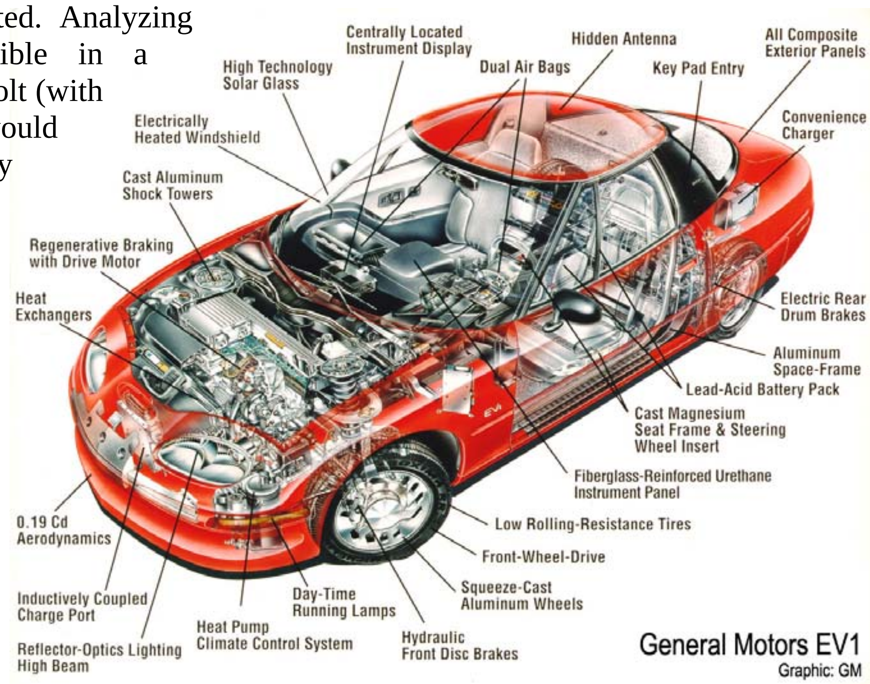
Accessory loads in an electric vehicle have a much more noticeable impact on fuel consumption and range. DOE has developed tools to address ancillary load reduction and they will be utilized as needed in this effort.

5.3 Development Goals and Approach

Development goals - The overall goals of the lightweight materials development activity include 50% reduction in the weight of the vehicle structure and subsystems while maintaining affordability and increasing the use of recyclable/renewable materials. But the objectives for the PHEV activity are relative, i.e., a vehicle level weight/cost savings considering the additional cost of power and energy in the hybrid propulsion system:

- Identify promising efficiency technologies and quantify the costs of implementation,
- Prioritize technologies/components by comparing the cost of implementation to the cost of supplying the power and energy storage in the hybrid propulsion system, and
- Depending on the analytical results, demonstrate efficiency technologies in a vehicle.

Approach – This is primarily an analytical task with the potential for specific application engineering if warranted. Analyzing the trade-offs possible in a vehicle such as the Volt (with the latest materials) would be ideal, but a study considering some of the key components in the EV1 also can provide insight into the benefits of combining lighter body and/or chassis components with hybrid propulsion. In addition, DOE has an EV1 that could be used as the basis for this study.



5.4 Tasks

Phase 1 – Analysis

- PHEV propulsion system requirements, identification of potential system components and cost analysis for an EV1
- Identification and updated cost analysis of key EV1 efficiency components; Comparative cost analysis versus hybrid propulsion system cost; Prioritized development and application if warranted

Phase 2 –Hardware studies

- Specific design, packaging studies and cost analysis

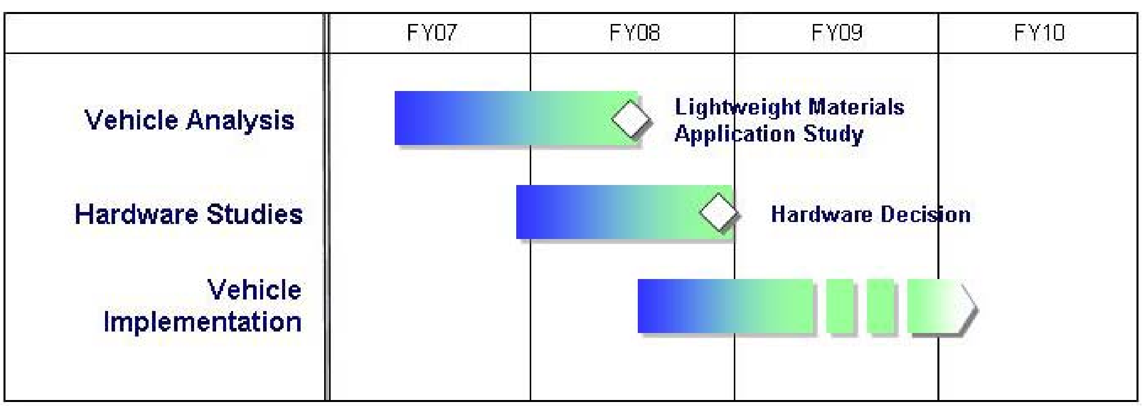
Phase 3 – Vehicle implementation

- Depends on the results of Phases 1 and 2

5.5 Schedule and Milestones

The vehicle analysis will be conducted in FY07 with hardware studies continuing into FY08. A decision at that time will determine the extent of hardware development and vehicle integration.

Vehicle Efficiency Study Schedule



Section 6: Grid Interactions

One outcome of the PHEV Discussion Meeting in May 2006 was the conclusion that the nation's electric power grid did not present any immediate technical barriers for PHEVs. In fact, analyses in the past have shown that a large number of PHEVs could be charged without negatively impacting the grid – as long as charging occurs in off-peak periods. Of course, this depends on the location and specific regional analyses were recommended by the attendees as well.

It also was made clear that the overall system efficiency (vehicle and grid) would be more efficient if there was communication between the vehicle and the utility regarding the appropriate times to charge (or the consequences of charging during peak periods, e.g., increased cost or restricted charging).

Other aspects of PHEV-utility interface, such as vehicle-to-grid power flow, could have system-level benefits as well, but it requires more sophisticated communication and a more complex relationship between the customer and utility. It is not considered an enabler for vehicle technology in the short term. Therefore, the two main issues of interest in this plan are the specific requirements of the interface for vehicle charging and the impact of charging on the grid and utilities.

6.1 Vehicle-Utility Interface

The DOE laboratories currently involved with propulsion system development, testing and demonstration (ANL and INL) will determine additional needs for the hardware interface (if any) in collaboration with utility and automotive industry representatives. Substantial effort was expended by the automotive industry in the early 90s when EVs were being developed for production, including interface design and safety studies, and near-term needs are expected to be consistent with the earlier work.

6.2 Impact on Utilities and Infrastructure

Electric or plug-in hybrid vehicles represent a substantial electric load in comparison to standard household appliances. If PHEVs penetrate the market in volumes necessary to reap the projected benefits, they will have to be considered in the load forecasting and distribution system considerations of utilities. The Office of Electricity has previously sponsored analyses to predict the impact of PHEVs on the nation's power generating capacity as well as conducting some regional studies. Detailed studies were conducted by the Pacific Northwest National Laboratory (PNNL) as well as the Electric Power Research Institute (EPRI) within the past few years. FCVT will collaborate with the Office of Electricity to ensure that updated analyses to be performed by ANL, EPRI and PNNL are consistent and benefit from the latest data and technology assumptions from both the supply and demand sides of the grid.

Section 7: Manufacturing Technology

The ability to competitively manufacture high-energy battery systems is critical to the success of PHEVs. From a broader perspective, the potential for a substantially more efficient domestic automobile fleet in the future (including fuel cell vehicles) is jeopardized without cost-effective energy storage. Li-ion batteries are primarily manufactured for consumer electronics in Asia and there is no domestic volume manufacturing capability. DOE plans include activities to develop and demonstrate Li-ion manufacturing technology, including evaluation of the feasibility of domestic production and – considering the potential impact on petroleum displacement and energy security – implementation of an activity similar to the successful DOD ManTech program (e.g., batteries, lightweight materials, bonding, manufacturing processes, etc.).

7.1 Feasibility Study

Manufacturing requirements (materials, processes and equipment) for critical battery components will be identified and quantified in cooperation with the development activity, DOE/USABC Li-ion battery development partners and others. Potential (global) sources will be identified and availability of the technology and/or equipment will be determined. A demonstration production line will be designed and a feasibility study will be conducted – including economic analyses – to support a decision to proceed with hardware acquisition. The results will be used as the basis for technology development support of a ManTech-type initiative.

7.2 Development and/or Acquisition

Depending on the results of the technology assessment, develop a strategy to acquire the key materials, processes and equipment to fabricate a production line to demonstrate manufacturing and assembly of the critical components of Li-ion batteries. A production demonstration plan will be prepared in cooperation with potential suppliers and the facility operator, including the financial requirements, procurement logistics, facility requirements, operational assumptions, etc. DOE's loan guarantee authority could be utilized for this activity if it is sufficiently beneficial to achieving national objectives.

7.3 Technology Demonstration

Battery components and systems will be fabricated and assembled using the manufacturing demonstration line – with the specifics to be determined at a later date.

Appendix A: National Laboratory Resources

	 Analysis	 Batteries	 PEEM	 Vehicle Efficiency	 Facilities
Argonne National Laboratory	• Technology assessment • Risk assessment • Vehicle modeling and simulation • Well-to-wheels energy/emissions • Agent-based behavior modeling • Macroeconomics modeling	•Standard protocols, benchmarking, validation •Applied R&D; accelerated aging and diagnostics •HIL testing	• Benchmark testing • HIL testing • System integration & control • Capacitor development	•Trade-off studies •Hardware studies	•Advanced Battery Test Facility (ABTF) •Advanced Lithium Battery R&D Facility •Advanced Powertrain Research Facility (APRF)
INL Idaho National Laboratory		•Standard protocols, benchmarking, validation •Applied R&D; accelerated aging and diagnostics	•Vehicle/charger interface and testing		•Advanced Vehicle Testing Activity (AVTA) •Energy Storage Technology Laboratory (ESTL)
Berkeley Lab		•Long-term R&D; materials and electro-chemical couples			•Advanced Battery R&D Facility
NREL	• Synergy with renewable energy sources	•Thermal analysis	• Component & system thermal testing, modeling and analysis		•Thermal Management Test Facility
Oak Ridge National Laboratory	• Regional grid analysis • Policy analysis		• Research, design, modeling, testing, evaluation and analysis: -Inverters and dc-dc converters -Electric motors -Thermal control -Benchmarking		•Power Electronics & Electric Machines Research Center (PEEMRC) •Fuels, Engines and Emissions Research Center (FEERC) •Hi-Temperature Materials Lab (HTML)
PNNL	• Regional grid analysis				•Exhaust Chemistry and Aerosol Research Center (ECAR)
Sandia National Laboratories		•Cell, module and battery abuse testing	• Regional grid analysis		•Battery Abuse Testing Facility

Appendix B: PHEV Definitions

DOE will use standard (non-regulatory) definitions to ensure precise communication and unambiguous results with respect to the vehicle and technology development goals:

- **Operating modes**

  Electric mode – Propulsion and accessories powered by the electric drive and onboard electric energy storage (i.e., engine off)
  Hybrid mode – Propulsion and accessories powered by the electric drive and/or engine, encompassing all power sharing/blending strategies

- **Control strategies**

  Charge-depleting strategy (hybrid) – Operation in hybrid mode with a net decrease in battery state-of-charge
  Charge-sustaining strategy (hybrid) – Operation in hybrid mode with a relatively constant battery state-of-charge

- **Range**

  All-electric range (AER) – Distance traveled in electric mode (engine off) on standard driving cycles
  Charge-depleting range (CDR) – Distance traveled in hybrid mode with a charge-depleting strategy until the vehicle transitions to the charge-sustaining strategy

- **Fuel consumption/economy**

  Electric consumption – Electrical energy consumed in electric or hybrid mode
  Liquid or Gaseous consumption – Liquid (e.g., gasoline or diesel) or gaseous (e.g., CNG) consumed on standard driving cycles
  Fuel economy – Distance traveled per unit of total fuel consumed (electric, liquid and/or gaseous) on standard drive cycles.

  [Note: Unlike conventional or current production hybrid vehicles, the fuel economy of PHEVs can vary substantially as a function of distance traveled (e.g., by a factor of 2 or more) and the results can be misleading without precise standard procedures and reporting protocols. An activity is underway to identify the needed changes to standard test procedures and protocols to measure and fairly report PHEV fuel economy.]

Appendix C: Acronyms

AER	All Electric Range
ANL	Argonne National Laboratory
BAS	Belted-Alternator-Starter
CARB	California Air Resources Board
CD	Charge Depleting
CDR	Charge Depleting Range
CNG	Compressed Natural Gas
CPSR	Constant Power Speed Ratio
CS	Charge Sustaining
CVT	Continuously Variable Transmission
DC	Direct Current
DC/DC	DC-to-DC converter
DOD	Department of Defense
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ETA	Electric Transportation Associates
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
FCVT	FreedomCAR and Vehicle Technologies Program within DOE/EERE
FTP	Federal Test Procedure
FWD	Front Wheel Drive
Gen	Generator
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
HEV	Hybrid Electric Vehicle
HIL	Hardware-In-the-Loop testing
HW	Hardware
IGBT	Integrated Gate Bipolar Transistor
INL	Idaho National Laboratory
Inv	Inverter
IPM	Interior Permanent Magnet motor
Li-ion	Lithium-ion battery
ManTech	Manufacturing Technology program
MATT	Mobile Automotive Technology Testbed
NETL	National Energy Technology Laboratory
NiMH	Nickel Metal Hydride battery
NMC	Ternary compound of three transition metals - Nickel (Ni), Manganese (Mn), Cobalt (Co)
NREL	National Renewable Energy Laboratory
OE	Office of Electricity, DOE
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
P/E	Power-to-Energy ratio
PE	Power Electronics
PEEM	Power Electronics and Electric Machines
PHEV	Plug-in Hybrid Electric Vehicle
PHTB	Plug-in Hybrid TestBed
PNNL	Pacific Northwest National Laboratory
PSAT	Powertrain Systems Analysis Toolkit – vehicle simulation model
Q2-FY07	Second quarter of Fiscal Year 2007, i.e., January through March (sample of format repeated throughout document)
R&D	Research & Development
RWD	Rear Wheel Drive
SAE	Society of Automotive Engineers
SiC	Silicon Carbide
SLI	Starting, Lighting and Ignition battery
SOC	State-Of-Charge
TMO	Transition Metal Oxide
USABC	United States Advanced Battery Consortium

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

For more information contact:

EERE Information Center
1-877-EERE-INF (1-877-337-3463)
www.eere.energy.gov

Plug-In Hybrid Electric Vehicle R&D Plan

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

FreedomCAR & Vehicle Technologies Program