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

FreedomCAR and Vehicle Technologies Program

Plug-In Hybrid Electric Vehicle R&D Plan

Working Draft
June 2007

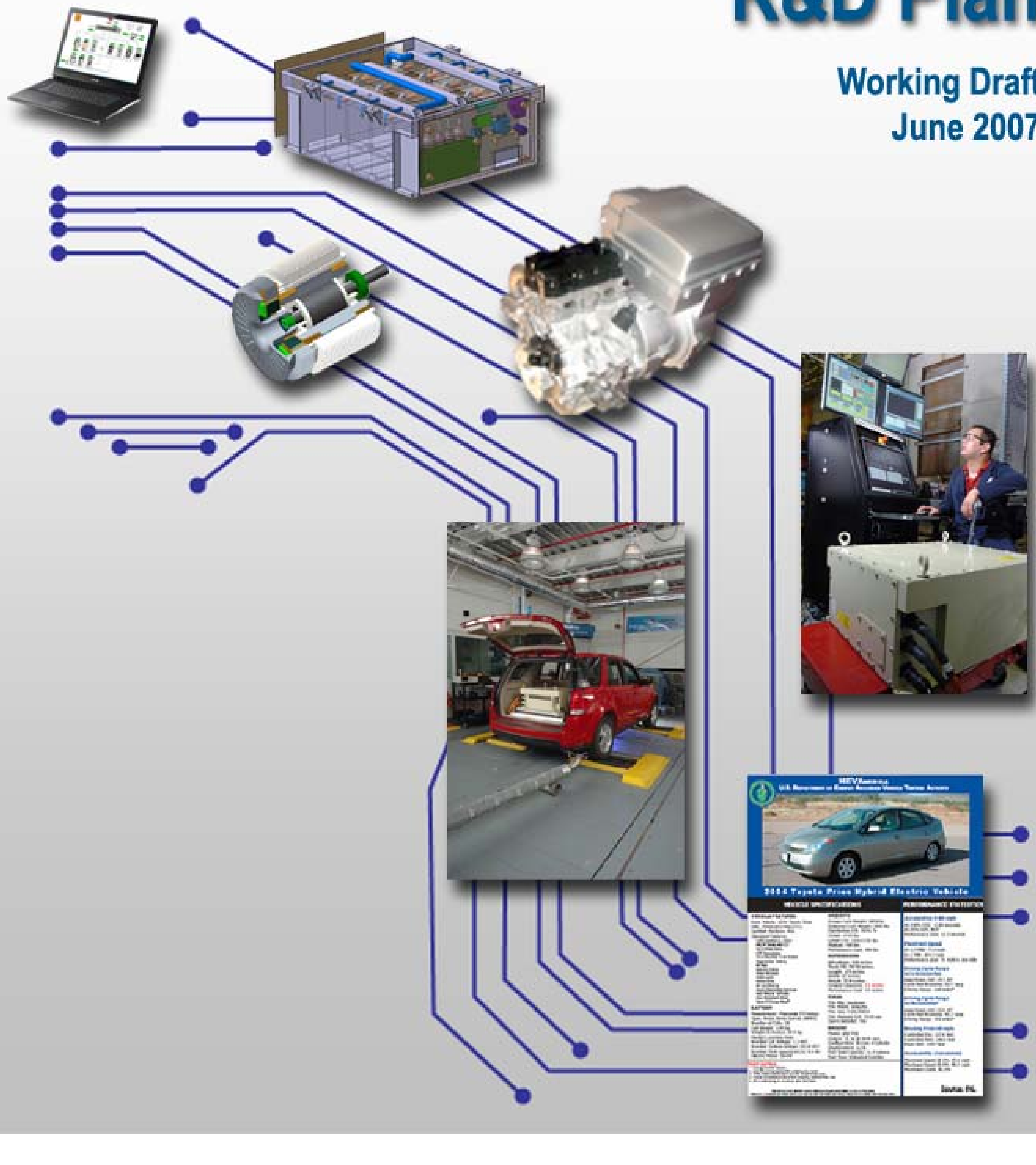


Table of Contents

EXECUTIVE SUMMARY

The Office of FreedomCAR and Vehicle Technologies (FCVT) in the Department of Energy (DOE) conducts research and development that targets energy-efficient and environmentally-friendly highway transportation technologies that enable America to use less petroleum. Plug-in hybrid electric vehicles (PHEVs), i.e., *hybrid vehicles that can be driven in electric-only or hybrid modes and recharged from a standard electric outlet*, have been added to the FCVT R&D portfolio because of the potential national benefits of increased energy efficiency and decreased petroleum consumption by using electricity as the primary fuel for urban driving. **This plan describes FCVT efforts to develop PHEV components and systems for light duty vehicles[1] that could be commercialized for volume production in 2016 to 2020.**

BACKGROUND

The Administration's Advanced Energy Initiative (AEI) announced in the 2006 State of the Union address called for technology development to support PHEVs. DOE and industry were challenged to develop technology that would provide 40 miles electric range, enough to satisfy approximately 70 percent of the daily travel needs in the US.

To better understand the specific technical and/or economic challenges associated with PHEVs and assess the potential impact on their activities, DOE invited representatives of the automotive and electric utility industries, government, national laboratories and academia to a 2-day discussion meeting in May 2006. In addition to vehicle issues, the attendees debated the impact on the electric power grid, consumer expectations and the role of the Federal government. There was substantial agreement that cost is the primary impediment, battery technology is the potential showstopper, the electric power grid is not a limiting factor (in the foreseeable future) and the potential benefits of PHEVs warrant support for the critical technologies.

Recognition of the benefits of PHEVs has led to growing support within Federal and State governments as well as the public. The President and members of Congress were exposed to displays and demonstrations of concept cars and hybrid vehicle conversions. FCVT launched analysis and benchmark testing at the national laboratories to assess PHEVs and confirm the potential benefits. Opportunities to incorporate PHEV requirements in existing FCVT technology development activities were assessed and formal planning was initiated. And the President reiterated the Administration's support in the 2007 State of the Union address by explicitly citing PHEVs, "*We need to press on with battery research for plug-in and hybrid vehicles*".

TECHNICAL CHALLENGE

There is a high degree of uncertainty that cost-competitive batteries with adequate performance and life can be commercialized by 2016. The extent of the challenge is illustrated by current hybrid vehicles with batteries capable of only 1-2 miles electric range at significantly reduced performance. High energy lithium batteries (as used in the

[1] Medium- and heavy-duty vehicles are not excluded from consideration and the potential benefit of PHEV technology will be addressed in the analyses, but the initial focus is on light duty vehicles (passenger cars and SUVs) consistent with the Administration's expectations to target mass market vehicles.

PHEV concept cars and hybrid conversions) can increase the electric range up to ~25 miles, but add $15,000-30,000 to current hybrid vehicle prices, which are only marginally cost competitive. Acceptable battery life with the demanding (deep discharge) duty cycle of PHEVs has not been demonstrated – increasing the risk of substantial replacement costs. Cost reduction, increased energy and life are the challenges – all while meeting safety standards and customer expectations.

The electric propulsion system requires further development as well to reduce cost and improve efficiency. Though not considered a showstopper, PHEVs could require power electronics and electric motors with twice the power of today's hybrids (to provide full performance in electric mode) while attempting to reduce cost. And the need for an onboard battery charger (likely 'smart' to ensure efficient and cost-effective recharging) adds more pressure for cost reduction.

Engines, fuels and vehicle efficiency technologies are included in addition to PHEV propulsion components to support system optimization studies – to identify possible trade-offs that could result in lower cost or higher system efficiency. For example, can a lower cost, 'simplified' engine be used in a PHEV with significant all-electric range (because the engine is not used very often)? Or would lightweight body/chassis materials be a cost-effective approach to reduce the vehicle power and energy requirements (i.e., to reduce battery and electric propulsion system costs)?

APPROACH

Ongoing FCVT Technology R&D programs are directly applicable to PHEVs, including batteries, power electronics, electric motors, engines, non-petroleum fuels and vehicle efficiency technologies – but they have been focused on hybrid propulsion system targets established under the FreedomCAR program. FCVT and the national laboratories are conducting analyses, testing advanced batteries and plug-in hybrid conversion vehicles as well as assessing global technology development – all in an effort to quantify the state-of-the art, refine development targets and identify PHEV-specific needs.

The activity will pull from the technology R&D programs to support 3 major milestones:

- **FY 2008 – Refine Goals and Development Targets**
  Developing technology to support 40 miles electric range is the primary goal of this activity. But since the necessary components may not be commercialized until 2016 to 2020, FCVT will establish mid-term goals (FY 2012) to promote earlier technology demonstration and deployment. Focusing on PHEV designs that 'maximize societal benefit' (as one reviewer of the draft plan put it), the objective is to identify electric range targets, vehicle configurations and control strategies that would allow larger numbers of PHEVs to be sold sooner and displace more petroleum overall – the ultimate objective.
- **FY 2012 – Demonstrate Technology and Assess Manufacturing Viability**
- **FY 2016 – Focus on Manufacturing and Commercialization**

The procurement process for power electronics and electric motors was initiated in FY 2006 and contractors have been selected. Requests for Proposals for battery development were issued earlier this year.

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 and reducing oil use through the efficiency improvements that PHEVs have compared to conventional vehicles. Some universities, companies and entrepreneurs in the private sector also have promoted plug-in hybrids as a way to realize the benefits of electric vehicles without the range limitation. 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 not committed to manufacturing PHEVs due to the technical hurdles and high cost of batteries.

PHEV Discussion Meeting - 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, with the following major points of consensus[2]:

- PHEVs could substantially reduce petroleum consumption, but cost is the primary impediment and battery technology is a potential showstopper 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., the availability of power from the electric grid is generally 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. A specified AER requirement could drive cost up and decrease the likelihood of production.
- The Federal government is expected to set policy, support pre-competitive research, act as a trusted source of information and minimize market barriers.

Decision to proceed – Based on the results of the May 2006 meeting and initial data, FCVT is 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.

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 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 particularly as that potential is affected by technology performance and cost.

---

[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).

1.2 Relevant DOE Activities and Technology

FCVT's ongoing development of batteries, power electronics and electric motors are directly applicable to plug-in hybrids. Efforts were initiated in FY 2006 to quantify PHEV technology development requirements for passenger car and sport utility vehicle applications. Vehicle modeling and simulation as well as benchmark testing of components and PHEV conversion vehicles have been used to develop preliminary requirements in support of the FreedomCAR technical teams' re-assessment of goals. Current R&D activities to address the technical challenges of PHEVs include:

- **Energy storage –** Lithium-ion (Li-ion) batteries with developments targeting cost reduction (e.g., materials and processing, cell and module packaging), improved specific energy (reducing size and weight), longer life and abuse tolerance. The Office of Science is a contributor to this effort with advanced materials development.
- **Electric drive system –** Power electronics and electric motors with developments targeting cost reduction, efficiency and packaging.
- **Advanced combustion engines and fuels –** Combustion optimization, after-treatment, alternative fuels (e.g., ethanol blends and other bio-fuels) and integrated system control to improve efficiency while reducing emissions.
- **Vehicle efficiency technologies –** Low-cost lightweight materials and efficient auxiliary systems (e.g., climate control) to reduce power and energy requirements.

Tools and facilities at the national laboratories are being adapted for analysis and development of PHEV technology; progress to date is summarized in italics:

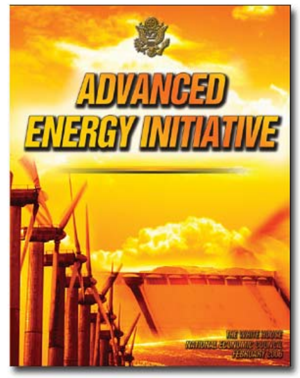
- Vehicle modeling & simulation: *Passenger cars and SUVs have been modeled and simulated to support the FreedomCAR technical teams' evaluation of battery, power electronics and motor development requirements for PHEVs*
- Battery Hardware-In-the-Loop (HIL) testing: *The Saft Li-ion VL41M battery has been installed and tested using an emulated vehicle duty cycle*
- Plug-in Hybrid Test Bed: *A fully instrumented vehicle with a 4-wheel drive 'through the road' (TTR) configuration has been constructed with full-performance in electric mode, flexible battery bay and variable control strategy*
- Vehicle dynamometer testing: *Preliminary PHEV-specific dynamometer test procedures have been developed and are being evaluated in the laboratory.*

1.3 Program Justification and Federal Role

There was substantial agreement at the PHEV meeting in May 2006 that the Federal government should be involved where societal/national benefits are concerned, i.e., energy security, reducing emissions and maintaining public 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 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,

"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****."*

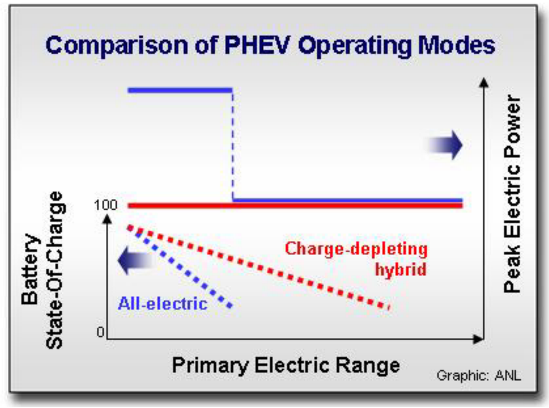
Goals – FCVT has established preliminary technical goals that allow for flexibility in vehicle design and do not unduly constrain automotive manufacturers. The goals encompass vehicle designs with exclusive electric operation before the engine turns on as well as configurations that utilize the power sharing strategies of today's hybrids, but allow the battery to discharge over the day to reduce fuel consumption. Because the performance capabilities are strongly dependent on battery capabilities, the goals were timed to take advantage of the battery development schedule:

- Mid-term (2012-2016) demonstration of component technologies with the potential for early commercialization – targeting PHEVs with all-electric range of 20+ miles and/or charge-depleting hybrid range of 40 miles
- Long-term (2016-2020) commercialization of components for PHEVs targeting all-electric range of 40+ miles and/or charge depleting hybrid range of 60 miles

Approach – Several PHEV designs are being considered that include variations in propulsion system configuration, electric range and control strategy. Designs range from basically electric vehicles with engines used only for long trips (e.g., the Chevrolet Volt concept) to evolutionary designs that supplement or replace the battery in current production hybrids (e.g., conversions of the Toyota Prius by Hymotion or EnergyCS). The following explanation illustrates the consequences of basic vehicle design choices.

The most significant factor in PHEV design is all-electric range. Compared to today's hybrids with only 1-2 miles electric range, the useable battery energy in PHEVs will have to increase well beyond an order of magnitude to approach 40 miles all-electric range. The operating strategy in electric mode is very important as well. If the electric drive must handle all the power demands in electric mode, the peak electric power can be twice that of today's hybrids or a PHEV with a "charge-depleting hybrid" strategy (where peak power is shared by the electric motor and engine, as shown in the graphic). FCVT will analyze several vehicle configurations, electric ranges and control strategies to assess the impact on component requirements and identify promising system combinations for integration and testing.

Since the technical terms associated with PHEVs can be confusing and ambiguous, DOE has developed preliminary definitions of operating modes, control strategies, range and fuel consumption/economy. The *non-regulatory* definitions will be refined during this activity in collaboration with SAE, EPA and the automotive industry.



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

- **Hybrid mode control strategies**
  Charge-depleting – Operation with a net decrease in battery state-of-charge; this includes all forms of 'blended', 'power-sharing', or 'smart' strategies.
  Charge-sustaining – Operation 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 from the grid
  Liquid or Gaseous consumption – Liquid (e.g., gasoline or diesel) or gaseous (e.g., CNG) fuel 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: The fuel economy of PHEVs can vary substantially as a function of distance traveled and the results can be misleading without precise procedures and reporting protocols. An activity is underway to identify the needed changes to standard test procedures to measure and fairly report PHEV fuel economy.]

Technology Development – The activity draws from the ongoing battery, power electronics and electric motor development activities in FCVT that are coordinated with the joint DOE/FreedomCAR technical teams. The general approach within the programs has been to launch new efforts with a rigorous analytical and design phase followed by hardware fabrication and development. Successful demonstration of technical goals leads to further efforts to reduce cost and commercialize the components.

The PHEV activity will influence component requirements within the technology development programs. Components from the programs will be integrated and tested in a vehicle systems context prior to the major PHEV milestones. Since the activity is heavily dependent on battery achievements, the major milestones are aligned with the battery development schedule:

- The **near-term milestone in FY 2008** focuses on analytical and assessment activities (systems analysis and benchmarking), as well as the status of components in the battery, power electronics and electric motor technology development programs. The results of this review will be refined mid- and long-term program goals and component development targets as well as concurrence with the program direction to achieve the mid-term milestone. Mid-term goals will target systems that could be cost-competitive in 2012-2016 and deliver significant petroleum savings. Long-term goals will target commercialization in 2016 to 2020.

  Note that the first battery solicitation (Request For Proposals issued April 2007) will result in designs targeting plug-in hybrid SUV applications by FY 2008, upon which fabrication contracts will be awarded and systems will be delivered and evaluated prior to the mid-term milestone. PHEV-specific designs targeting passenger cars are expected to be solicited in FY 2009 or FY 2010.

  The initial contracts for power electronics and electric motors were selected in May and are to be awarded this year. Additional solicitations are planned targeting delivery of several key components and integrated systems prior to the mid-term milestone.

- The **mid-term milestone in FY 2012** focuses on hardware, i.e., demonstrated accomplishment of mid-term system goals and component development targets in PHEV systems. In addition, "technology readiness" will be assessed, including progress toward technical targets and manufacturing viability (i.e., the level of understanding of critical materials, equipment, processes and economics), and the technical approach for FY 2013 to FY 2016 will be adjusted accordingly.

- The objective of the **long-term milestone in FY 2016** is to facilitate technology transfer for commercialization in 2016-2020. Accomplishment of the long-term goals and component development targets will be demonstrated and the "readiness" of the components will be assessed as in the mid-term review. Program direction and resources will be focused on the factors that hinder manufacturing viability of the key PHEV components.

System Integration, Validation and Demonstration – The national laboratories, with extensive hybrid vehicle technology development experience, will perform analysis, aid development, integrate, test and validate components/systems in this activity. Technical achievements will be evaluated in a system context using hardware-in-the-loop (HIL) or plug-in hybrid technology test beds (PHTBs); both are described in Section 2.2.3. Potential contributions of the national laboratories are listed in the summary of capabilities and facilities in Appendix A.

To confirm operational requirements, a solicitation for strategically located test fleets (e.g., up to 20 vehicles in as many as 5 cities) is being considered for 2008-2012.

1.5 Collaboration

DOE/FCVT has long cooperated with the private sector and other government agencies to accomplish national objectives with mutual benefits; the relationships will continue on this program (summarized below). FCVT may consider other alliances or joint activities with the potential to aid PHEV development or demonstration that are consistent with DOE authority and operating constraints.

Government – FCVT is coordinating with relevant offices in DOE, including the Electricity Delivery and Energy Reliability Office (OE) regarding electric power generation/distribution and the Office of Science regarding materials R&D focused on batteries. The Biomass Program will be consulted regarding domestic fuels utilization (e.g., ethanol). DOE is exploring with the Environmental Protection Agency (EPA) the development of PHEV-specific test procedures/protocols and will explore with the National Institute of Science and Technology (NIST) manufacturing technology to accelerate the introduction of PHEVs. Other DOE offices and government agencies will be approached as needed.

Automotive Industry – FCVT will continue its relationship with the automotive industry to ensure that PHEV technology is applicable and appropriate, including the FreedomCAR Partnership and the United States 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), manufacturers and suppliers to develop PHEV-specific test procedures.

Because of the crucial role of Tier 1 suppliers in developing and introducing new technology in the auto industry, DOE plans periodic interactions to identify opportunities to support critical technology development and manufacturing process needs.

Utilities – DOE and utility representatives (e.g., EPRI, the Electric Power Research Institute) are cooperating on grid impact studies and additional activities to understand potential consumer use patterns are warranted to determine the impact on technical requirements. FCVT will collaborate with OE and the utility industry to identify opportunities to efficiently address the requirements for and ramifications of implementing PHEVs.

National laboratories – The laboratories support the development of technology requirements and often function as the technical managers and evaluators of components and subsystems procured by DOE. Due to their inherent technical capabilities and facilities, the laboratories are directly involved in fundamental and applied research as well as component and propulsion system development. The resources available to DOE are summarized in Appendix A, including analysis and testing of batteries, power electronics, electric motors, engines, integrated propulsion systems and vehicles.

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

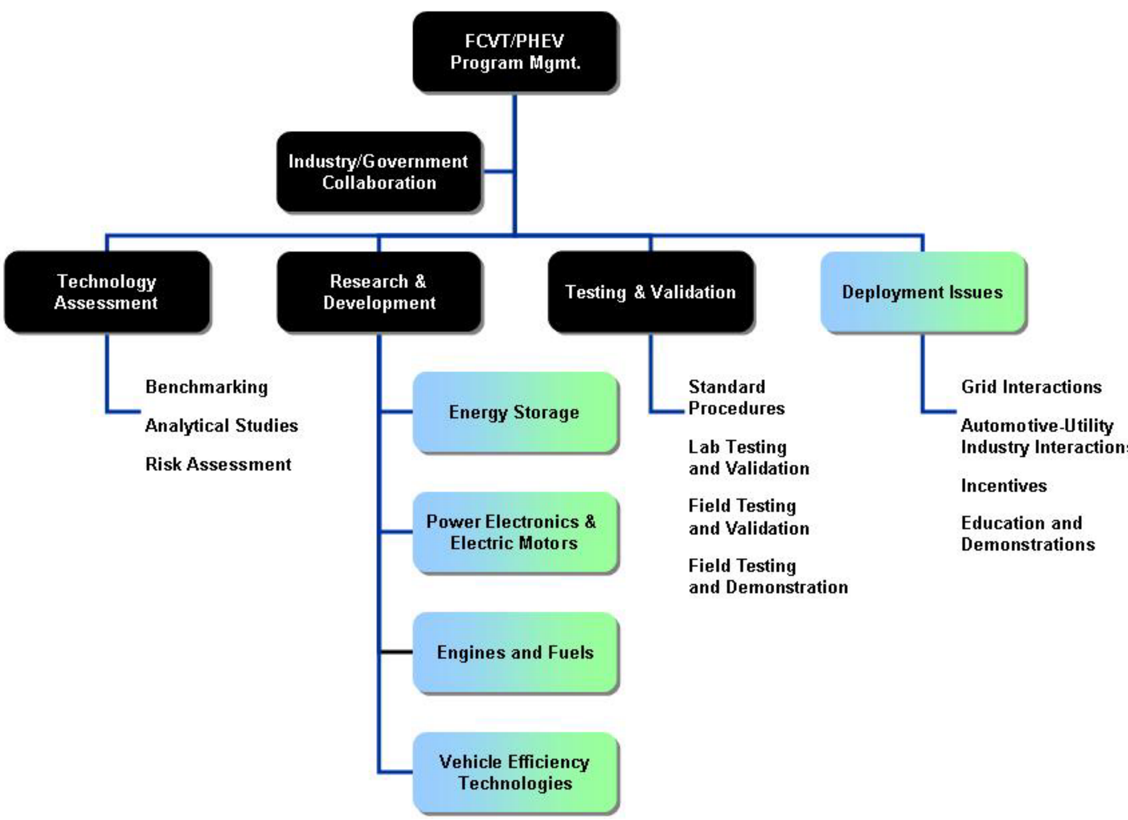
Section 2: Management Functions

The PHEV Discussion Meeting reinforced the need to quantify the widely assumed benefits of plug-in hybrids. FCVT initiated benchmarking, analysis and technology development solicitations in FY 2006 in addition to beginning this plan. It is intended to provide a structure for technology development that, in some cases, has already been launched toward a somewhat undefined target. The President and the Administration provided the goal, but PHEV technology must be commercialized and sold to the mass market for the nation to realize the benefits. Therefore the near-term focus is on analysis and benchmarking to set mid- and long-term targets that balance the national objectives with the prerequisites for commercialization – manufacturing viability and affordability.

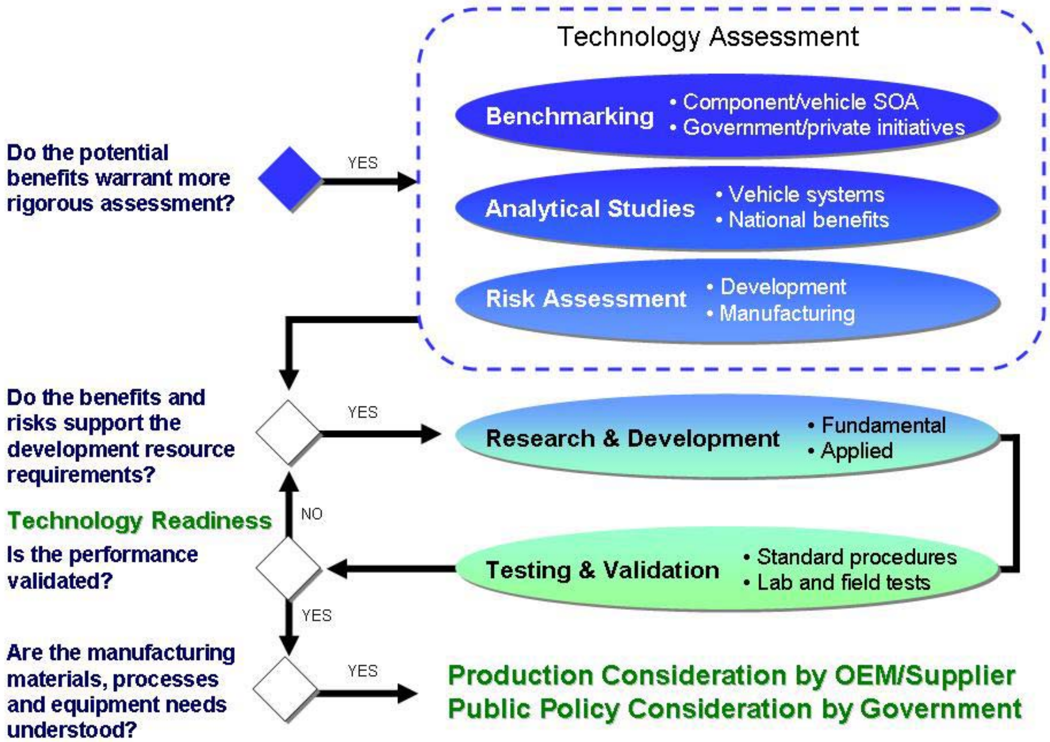
2.1 Structure and Decision Process

Though R&D accomplishments cannot be predicted with certainty, the proposed task structure (below) and decision process (next page) will measure progress with certainty and facilitate informed decision making. This section describes the tasks that support technical management and the decision process (i.e., the black boxes in the graphic) as well as the overall schedule. The specific R&D activities are described in Sections 3 through 6, while deployment issues (that do not immediately impact technology development) are described in Section 7.

PHEV Activity Task Structure



Technology Development Decision Process



2.2 Technology Assessment

Technology assessment provides the data and analysis to support informed decision-making by DOE/FCVT management, i.e., the status of relevant technology and programs, analytical studies (technical requirements, national benefits, etc.) and risk assessment. Argonne National Laboratory is the lead DOE laboratory for modeling, simulation, benchmarking, and testing for PHEVs. Other DOE laboratories are working cooperatively with ANL in support of these activities.

Benchmarking – Benchmarking characterizes the state-of-the-art of components and systems. For example, the latest Saft Li-ion battery is undergoing performance testing now. Performance and efficiency testing of the EnergyCS and Hymotion conversions of the Toyota Prius are underway in laboratory and field testing.

In addition to technical data, relevant programmatic activities are assessed as a form of due diligence, i.e., what should DOE/FCVT be aware of as they carry out this activity? This includes relevant government programs and technology development initiatives being pursued globally. The information influences goals and identifies opportunities for cooperation on pre-competitive technology development in addition to non-competitive tasks such as codes and standards.

Analytical Studies – PHEV systems analyses to date have focused on determining battery and electric drive requirements; to provide information to the FCVT technology R&D programs so they can assess the impact of PHEVs on their development targets. For example, a pre-transmission parallel configuration similar to the Prius has been analyzed with various electric ranges (10-60 miles). Pursuing the more general goal of maximizing petroleum displacement will require evaluating series configurations and new system concepts with the potential to reduce cost, i.e., the best combinations of components and control strategies to get 'the most bang for the buck'. The vehicle simulation results, when combined with market models and regional infrastructure characteristics, support forecasts of petroleum displacement and impacts of PHEVs on the electric utilities. In addition, the potential for PHEVs to facilitate increased renewable energy use (e.g., wind or solar power) will be investigated for regions of the country that could take advantage of the vehicle-to-grid capability.

Vehicle systems – ANL's Powertrain Systems Analysis Toolkit (PSAT) will be used to design and evaluate PHEVs with various mechanical configurations as well as different all-electric and charge-depleting hybrid ranges. The objectives are to quantify the impact of all-electric range on component performance requirements and conversely evaluate the consequences of component capabilities on vehicle performance. The primary outcomes of the vehicle analysis are:

- Component/propulsion system performance requirements,
- Estimated potential to reduce fuel consumption by optimizing the propulsion system configuration, electric range and control strategy.
- Comparison of PHEVs to other alternatives to reduce oil use (vehicle types and fuels); in cooperation with the DOE Multi-Path Study

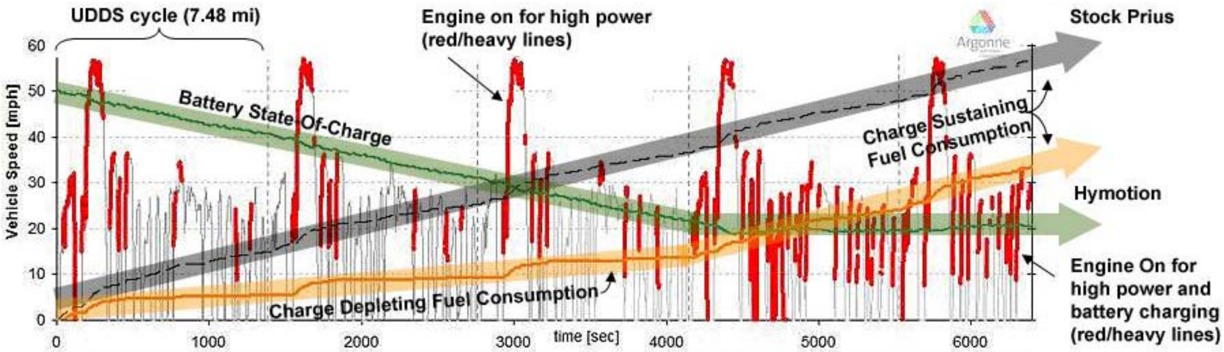
National benefits/impacts – The benefits and impacts of PHEVs depend on the fuel sources (supply side) as well as the vehicle characteristics and customer use patterns (demand side). One objective is to combine energy use characteristics (predicted with the vehicle simulation model PSAT) with energy 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 grid and utilities will be evaluated as a function of consumer use patterns, regional infrastructure and regulatory issues. PHEVs have been proposed as a 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 – Risk assessment will be primarily focused on batteries, i.e., quantifying the factors that could limit availability, assessing the feasibility of domestic manufacturing, identifying critical manufacturing processes, materials and equipment, etc. In addition, the possibility of accelerated (parallel) development of advanced technologies will be explored.

2.3 Integration, Testing and Validation

Testing and validation is the focal point for measuring progress, with laboratory testing focused on component integration, testing and validation in a system context while field testing evaluates in-use performance, efficiency and operational characteristics. And since the benefits of PHEVs depend on the vehicle strategy (i.e., electric and/or hybrid) as well as component capabilities, this activity includes system-level integration and control studies.

PHEV-specific test procedures – Test procedures to measure fuel economy and emissions in today's production vehicles are not adequate for PHEVs. Since electrical energy from the grid is used in addition to liquid fuel onboard, this must be accounted for to accurately characterize the total energy consumption and emissions.



UDDS	#1	#2	#3	#4	#5
Fuel Economy [mpg]	148	200	187	74.3	66.4
Electric Energy [DC Wh/mi]	123	128	125	30.6	-15.9

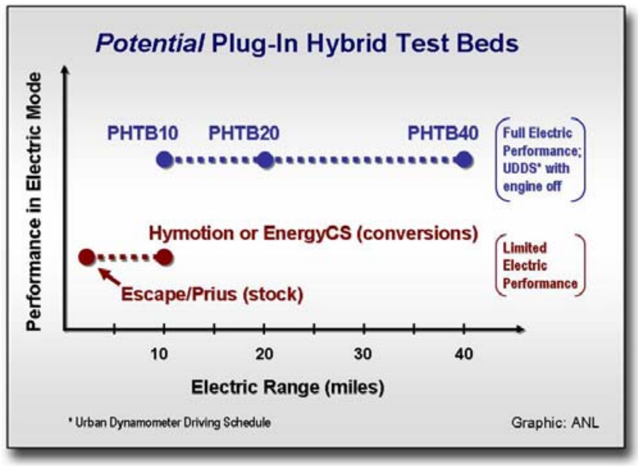
And unlike today's hybrids, the fuel economy of PHEVs can vary substantially as a function of the distance traveled. Sample test data from the Hymotion Prius conversion operating on the Urban Dynamometer Driving Schedule (UDDS) is shown above – with battery state-of-charge and cumulative fuel consumption of the Hymotion highlighted and compared to the fuel consumption of the stock Prius. Fuel economy ranges from 148-200 mpg on short trips (mostly electric) to essentially the same as the stock Prius after the transition to charge-sustaining mode (note the similar slopes of the fuel consumption lines after the third UDDS cycle). The calculated fuel economy does not account for the electric energy for traction consumed during the test or energy to recharge the battery after the test. The test procedure must be robust enough to reflect this shift of energy use from liquid fuel to electricity, in the interest of the consumer as well as the grid/utility.

This characteristic of PHEVs necessitates more complex test procedures and post-test analytical techniques – for all types of vehicle testing. Draft procedures have been developed for the laboratory, closed track baseline testing, on-road fleet and accelerated reliability testing. Testing is underway to validate the procedures. An activity has been initiated with the SAE test procedure committee to address PHEVs, with the participation of the national laboratories, the Environmental Protection agency (EPA), California Air Resources Board (CARB) and automotive industry representatives.

Lab testing and validation – Initial testing has focused on benchmarking batteries and PHEV conversion vehicles. SAFT Li-ion batteries are being evaluated in an emulated vehicle environment using hardware-in-the-loop (HIL) bench testing. MATT (shown in the figure) will be used to accommodate propulsion components or systems for testing on the vehicle dynamometer.

The 4-wheel drive vehicle dynamometer at the Advanced Powertrain Research Facility (APRF) will be used to quantify performance, fuel economy and emissions of propulsion systems integrated in MATT or the plug-in hybrid test beds (described in the next paragraph). In addition, the PHEV conversions slated for field testing will undergo baseline testing as well as periodic and/or end-of-life characterization.

Plug-in hybrid test beds (PHTBs) – Benchmark testing has shown that PHEV conversions are capable of limited electric range at reduced performance – not adequate to cover the design space of PHEVs expected in the market (for either performance or range – as shown in the graphic). To address this limitation, an instrumented test bed with a 4-wheel drive 'through-the-road' (TTR) hybrid configuration has been fabricated to integrate and test development batteries without imposing packaging constraints. The TTR PHTB (photo below) will help develop standard test procedures, refine performance requirements, quantify the impact of electric range and control strategy on fuel consumption and emissions as well as provide the validation link between lab and on-road testing.

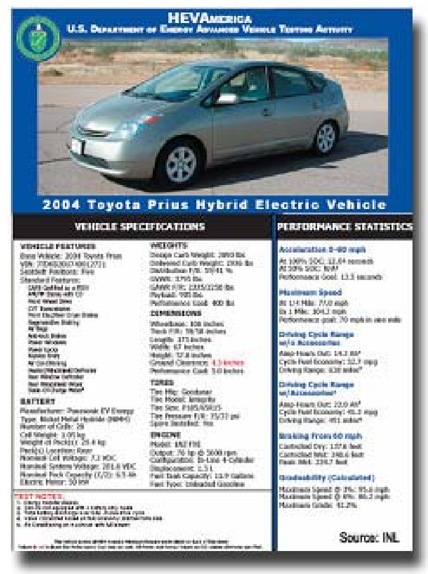


The procedures developed for vehicle testing will be translated for standard component bench testing and vehicle simulation – the basis for load emulation in HIL testing (i.e., a simulated vehicle environment using a power profile and duty cycle generated from vehicle simulation and/or testing).

PHEV data acquisition and interface – ANL has designed a low cost, portable data acquisition and interface system that connects to the vehicle bus and allows monitoring, storage and viewing of key vehicle information as well as communication with the driver. The system, currently in prototype form, will operate with conventional ICE or hybrid vehicles. In addition to low cost data acquisition, the possibility of using the system as a 'pseudo-PHEV' interface is being considered – to monitor and analyze data as well as communicate with the driver as if the vehicle was a PHEV – to better understand consumer use patterns (driving and charging) and estimate the potential fuel savings despite the limited availability of PHEVs. Depending on the objective of the experiment, the system could provide a variety of functions ranging from transparent data collection to real-time driver interaction. Though estimating market potential is primarily an industry responsibility, the low cost of the system could permit a relatively large statistical sample of drivers to participate in a study to gather market data at a fraction of the cost of a comparable fleet of instrumented production hybrids or PHEVs.

Interim hardware demonstrations – Systems analyses and technology assessment (internal and external to DOE) will identify potentially cost-effective propulsion system configurations that fall short of the long-term goal of 40 miles all-electric range. Within the limitations of the development programs, components will be extracted, integrated and tested in system-level technology demonstrations. It is anticipated that components will be integrated in MATT or the plug-in hybrid test vehicles to demonstrate performance in complete systems every 18-24 months.

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 has reprogrammed the onboard data acquisition system to monitor 10 vehicles in fleet applications. The data will be provided to INL to study PHEV charging practices, energy/power requirements, energy storage issues and operating costs.

Field Testing and Demonstration – For additional validation, a solicitation for several small, strategically located demonstration fleets (e.g., up to 20 vehicles in up to 5 cities) is being considered for the 2008-2012 timeframe.

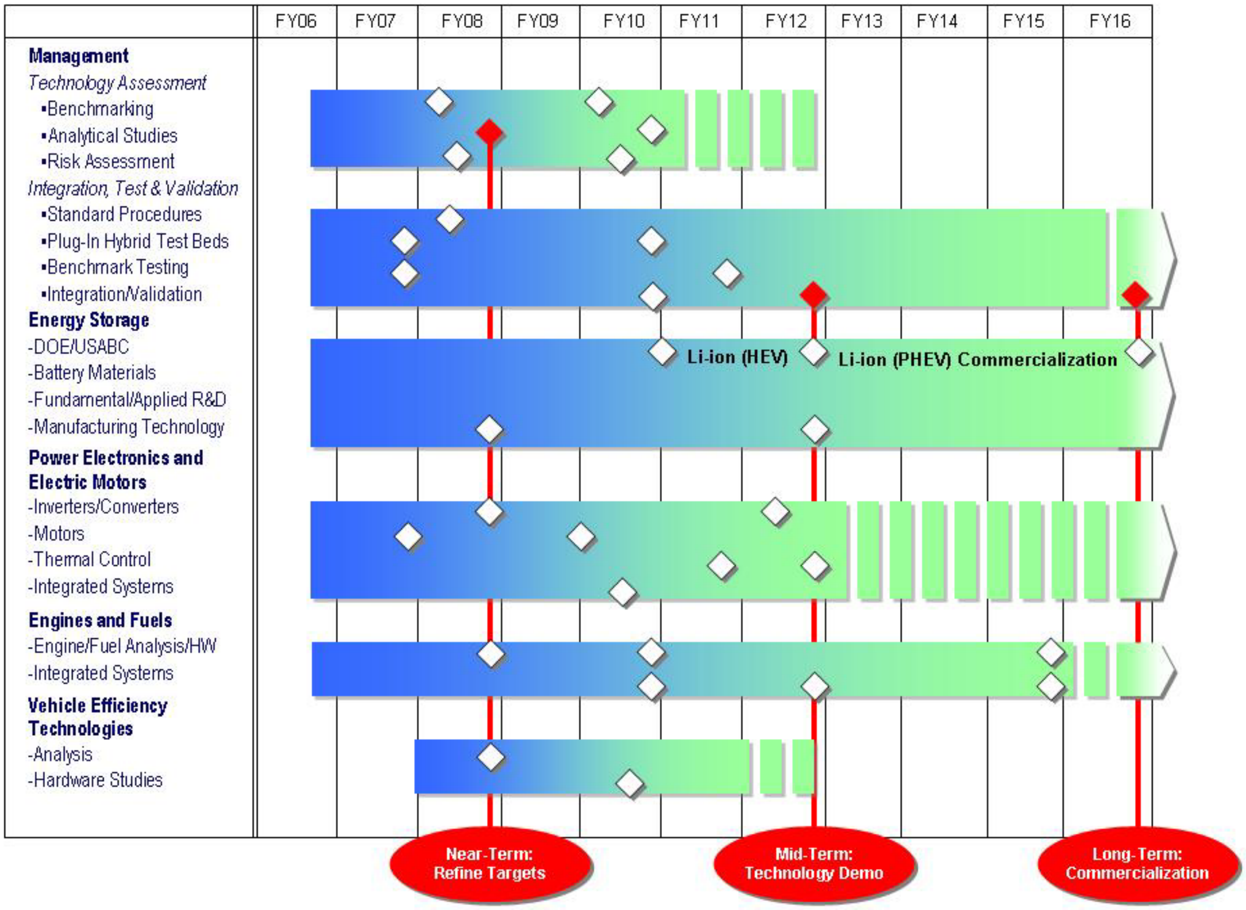
2.4 Schedule and Milestones

The schedule on the next page is based on technical and programmatic reviews at three key milestones in the program summarized below (previously detailed on page 7):

- **Near-term (FY 2008):** benchmarking, analysis and progress within the FCVT technology R&D programs; refine the mid- and long-term program goals and component technical targets.
- **Mid-term (FY 2012):** results of technology demonstrations in a systems context and assessment of manufacturing viability
- **Long-term (FY 2016):** focus resources on critical manufacturing limitations and target technology transfer in FY 2016 to FY 2020

The process is intended to be highly interactive, with refinement of programmatic goals based on external (global) developments and national priorities as well as modifications of technical specifications based on analysis and testing.

Preliminary PHEV R&D Schedule



Though it is not evident in this high-level schedule, the procurement process for batteries, power electronics and electric motors has been initiated:

- The Request for Proposals targeting battery designs for plug-in hybrid electric SUVs was issued in April, 2007.
- Contractors for electric drive components, including inverters, motors, traction drives and dc-dc converters were recently selected (May, 2007) and contracts should be awarded before the end of the fiscal year.

This page intentionally left blank

Section 3: Energy Storage

3.1 External Assessment and Market Overview

NiMH Battery Pack
Photo: Toyota

Onboard electrical energy storage is critical for PHEVs and the primary challenges are higher energy per volume and weight, abuse tolerance and lower cost relative to today's battery technology. 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 maintains the battery depth of discharge to assure long life. In fact, today's hybrids typically maintain the state-of-charge (SOC) within a narrow range (approximately 60 $\pm$ 5%). The depth of discharge for PHEV batteries would be much greater and likely detrimental to battery life.

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 (Hitachi produces 50 packs per month for the Mitsubishi Eco Canter hybrid truck in Japan).

Other energy storage technologies (capacitors, flywheels, etc.) could emerge as candidates during the course of this activity. FCVT regularly monitors the progress of global technology development and will evaluate candidate technologies with demonstrated potential to meet the energy storage requirements for PHEVs.

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 Li-battery cells, packs, and full systems for hybrids.

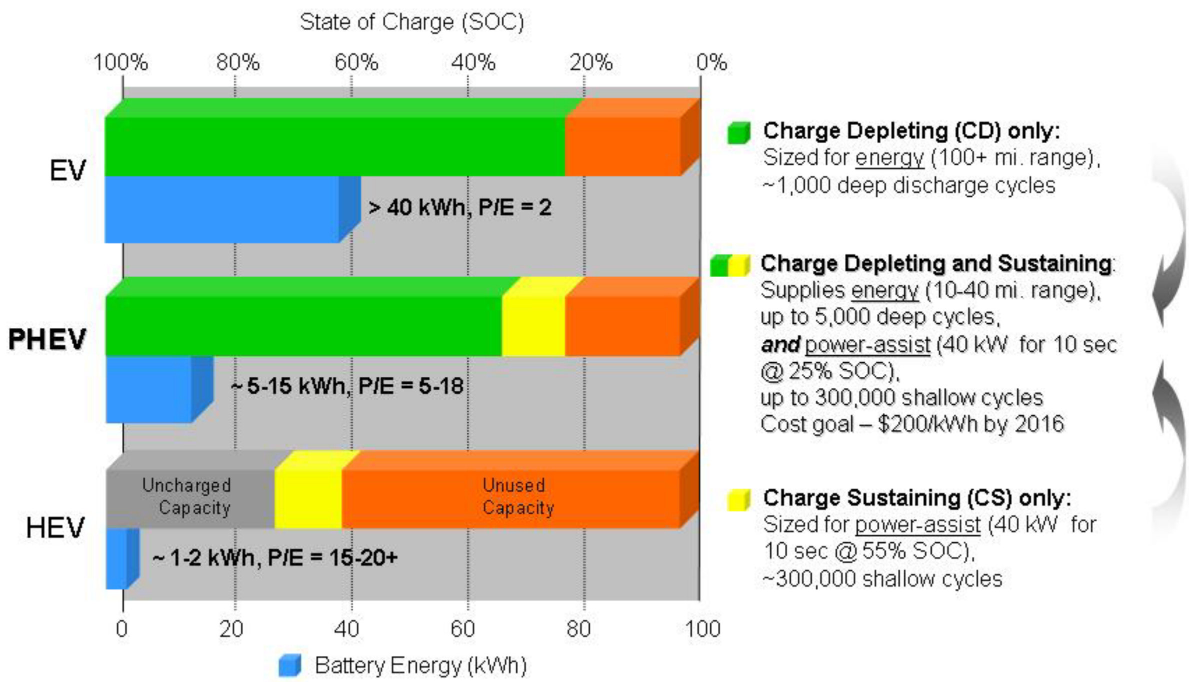
Applied research addresses cross-cutting barriers that face those Li-ion systems closest to meeting the requirements for vehicle applications. Five national laboratories (Argonne, Berkeley, Brookhaven, Idaho and Sandia) participate, each bringing its own areas of expertise to address life, abuse tolerance,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

3.3 Development Goals and Approach

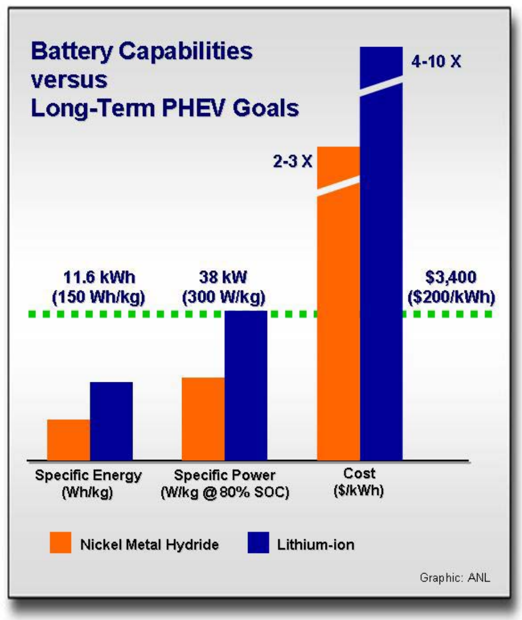
Development goals – The battery duty cycle in PHEVs is more demanding than in conventional hybrid vehicles, as reflected in the graphic below. The deep discharges (in green) that will result from either all-electric or charge-depleting hybrid operation are more detrimental to battery life than the shallow discharge-charge cycles that batteries experience in today's hybrids. Though this is likely the most important factor influencing battery life, differences in discharge profiles also need to be considered when specifying design requirements and development goals. For example, the peak battery power requirements are lower in charge-depleting hybrid mode because the engine and battery combine to meet the power requirements, whereas the battery must supply all the power required in ell-electric operation. Similarly, the average battery power in charge-depleting hybrid mode is lower and it can be controlled (by varying average engine power) to match the desired travel distance before the battery is depleted.

Battery Performance Requirements versus Vehicle Application



Differences in battery requirements as a function of vehicle type are reflected in the various power-to-energy (P/E) ratios shown in the figure. P/E is based on the peak power (for acceleration) and energy (for range) required for a particular vehicle application. P/E ratios for electric vehicles are lower than either HEVs or PHEVs because of the higher energy required for substantial electric range. Similarly, the P/E ratio for an HEV (15-20+) is higher than for a PHEV (5-18); the variation reflects observed differences to date (in vehicles and/or analysis). Different P/E ratios typically mean different battery designs since power is related to surface area of the electrodes and energy is related to active material. One size does not fit all; vehicle assumptions are required to develop requirements. In summary, battery requirements for PHEVs combine the deep discharge characteristics of electric vehicles with shallow discharge cycles of conventional hybrids and PHEV design strongly influences battery requirements.

Despite the uncertainty in vehicle design, near- and long-term commercialization goals have been drafted for PHEV energy storage systems in collaboration with the USABC. A mid-size SUV with 10 miles electric range is the assumed application for the near-term (2012), resulting in requirements of 5.6 kWh and 45 kW peak power. The long-term battery goal (2016) targets 40 miles electric range in a mid-size passenger car. The respective system cost targets are $1,700 ($300/kWh) and $3,400 ($200/kWh).



The chart compares the capabilities of Li-ion and NiMH batteries to the long-term PHEV battery goals and illustrates the substantial improvements in energy and cost required. Specific energy of Li-ion is roughly twice that of Ni-MH, but it must double to provide energy to meet the PHEV 40-mile electric range goal. Specific power is not a limitation. Cost is the greatest concern for Li-ion; it is estimated to be 4 to 10 times that required to be competitive.

Cycle life using a PHEV duty cycle has not been evaluated for either battery, but NiMH performs adequately in hybrid (power assist) applications for Toyota to offer an 8-year, 100,000 mile warranty. Tests of Li-ion using a hybrid power assist cycle have demonstrated up to 300,000 shallow cycles; PHEVs could require up to 3,000 deep discharge cycles as well.

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 for Li-ion since a PHEV duty cycle includes high power assist at low state-of-charge (SOC) in addition to the high energy demand for electric range over the 15-year life of the vehicle. Li-ion batteries have demonstrated acceptable life for shallow cycle hybrid applications, but battery life typically falls off dramatically with deep discharge cycling.

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

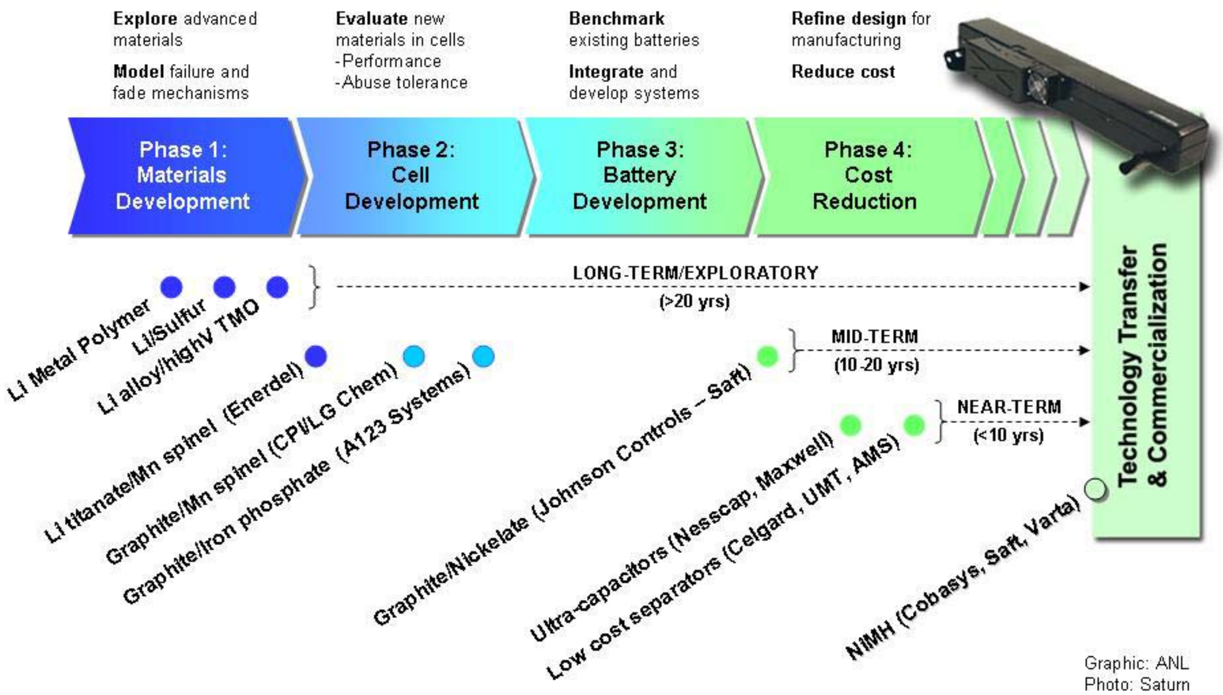
Tolerance of Abuse and Safety **–** Li-ion batteries used in consumer electronics are not intrinsically tolerant of abusive conditions such as short circuits, overcharge, over-discharge, crush, or exposure to fire and/or other high temperature environments.

Availability of Li – The primary sources of lithium are located outside of the US and the question has been posed whether or not this is a limiting factor for Li battery production. This does not appear to be a matter of immediate concern, but it will be addressed in the manufacturing risk assessment.

Approach – The battery development process illustrated below has been employed by the FCVT Energy Storage Technology R&D subprogram 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.

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 and refinement of the design, materials and processes to reduce cost. Note that the timing of the battery R&D process is inherent to the battery technology development program and somewhat independent of the PHEV activity.

Advanced Battery R&D Process



3.4 Tasks

Current activities in each of the four phases of the R&D process are summarized below, followed by a description of the manufacturing technology assessment.

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: for high energy and rate, low cost, with improved life

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

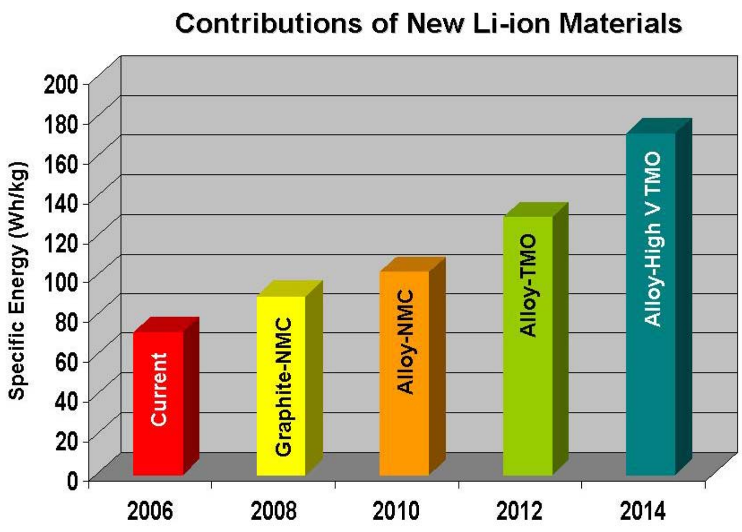
Develop Associated Electrolytes

- 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

- New membranes/glasses: for stable metallic lithium anode surface
- New stabilized surface coatings: for more stability and longer life
- Lower interfacial resistance: for improved performance at low temperatures

The figure shows the contributions of improved materials to Li-ion specific energy and the importance of materials development. But it also implies that new materials are needed to progress from the present capability (~70Wh/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. Accelerated aging and end-of-life testing will be performed. 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 ultra-capacitors (by Nesscap and Maxwell) and low-cost separators (by Celgard, UMT and AMS).

Manufacturing Technology R&D

Background – Assured availability of competitively priced high-energy Li batteries is critical to the success of PHEVs and domestic manufacturing is necessary to support high volume vehicle production. And from a broader perspective, the potential for a substantially more efficient domestic automobile fleet in the future (including fuel cell hybrid vehicles) is jeopardized without cost-effective energy storage.

As described in the 2005 ATP study[3], high volume manufacturing of Li batteries developed to support the consumer electronics industry in Asia despite substantial private investment in Li battery R&D in this country. Domestic Li battery production has begun since the ATP study, but it is focused on industrial, telecommunications and defense applications (e.g., Saft). The Johnson Controls-Saft Advanced Power Solutions partnership (JCS), Lithium Technology Corporation and A123 Systems build batteries for automotive applications using products manufactured in Europe and Asia. JCS recently announced a new French plant for electric and hybrid vehicle batteries. Cobasys and A123 Systems have partnered to develop and manufacture batteries for hybrid electric vehicles, without committing to domestic US manufacturing.

Since battery manufacturers are knowledgeable of the potential as well as the risks of the hybrid vehicle market, what is the appropriate Federal role in promoting domestic battery manufacturing? DOE will attempt to answer this question, estimate what is necessary to have a measurable impact and determine if the role lies within their congressionally mandated fiscal and operational constraints.

Feasibility study – An assessment of manufacturing materials, processes and equipment needed for Li-ion battery production will be initiated this fiscal year, including identification of critical material content and equipment requirements, sources and supply options.

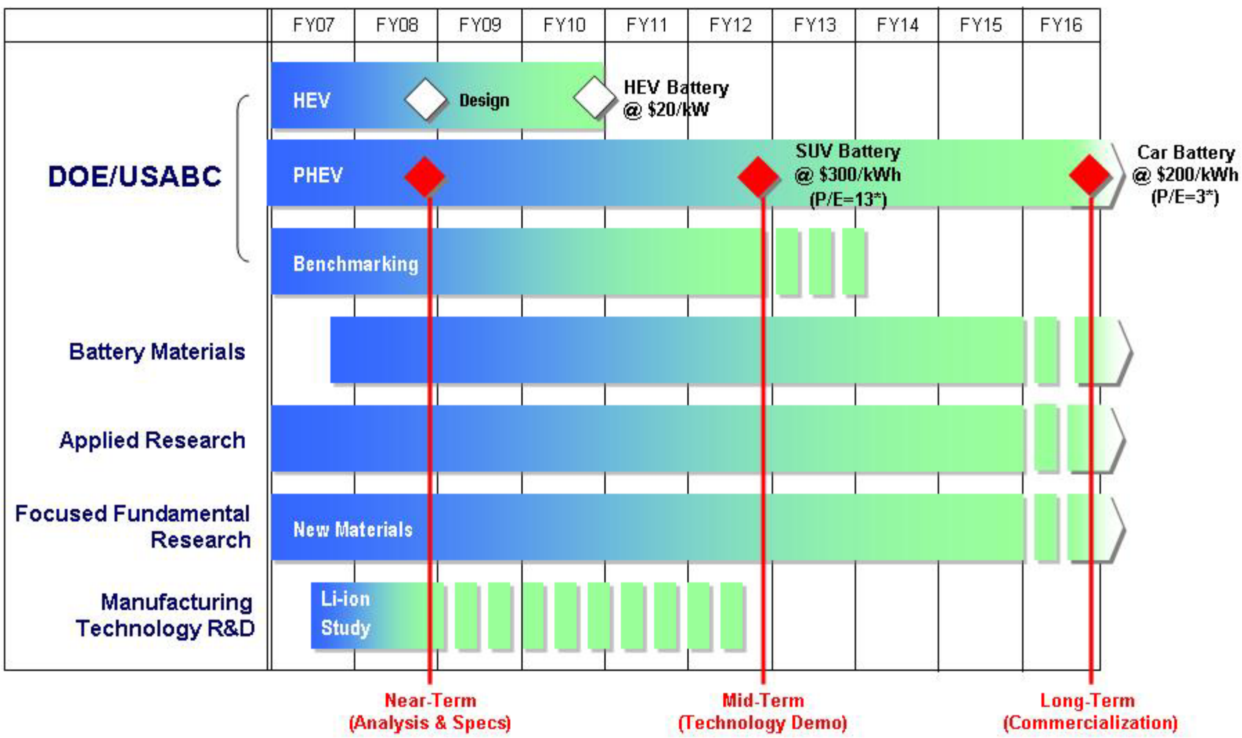
[3] Brodd, Ralph J., "*Factors Affecting U.S. Production Decisions: Why are There No Volume Lithium-Ion Battery Manufacturers in the United States?*", ATP Working Paper Series, Working Paper 05-01, Prepared for the Economic Assessment Office, Advanced Technology Program, National Institute of Standards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

Technology development – Depending on the results of the feasibility study, manufacturing technology development tasks will be initiated to support critical processes and/or equipment. This could include an activity similar to the successful DOD ManTech program to assure the availability of critical technologies.

3.5 Schedule and Milestones

A summary schedule of the FCVT Energy Storage Technology R&D program is shown below with the major PHEV activity milestones highlighted. DOE/USABC recently issued a Request for Proposals and proof of concept contracts should begin this year.

Battery R&D Schedule



* P/E ratio = Peak pulse discharge power (10 seconds) / Available energy for charge depleting mode (10 kW rate)

This page intentionally left blank

Section 4: Power Electronics & Electric Motors

4.1 External Assessment and Market Overview

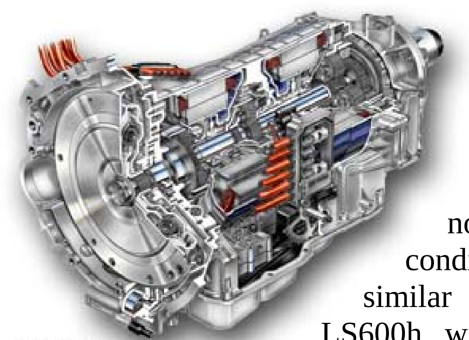
Several automotive and truck manufacturers currently produce hybrid vehicles, with electric drive components sized for the power requirements, duty cycle and thermal loads to assist the engine during peak demands, recover braking energy, charge the battery and, in some cases, provide low speed driving. PHEVs are only available as aftermarket modifications of production hybrid vehicles (i.e., with larger battery packs and modified controls) and their basic electric drive components have not been changed.

Currently PHEVs are not produced for sale by automotive and truck manufacturers, but only for demonstration/development such as the one by Daimler. Daimler has built and is evaluating four prototype Dodge Sprinter Plug-In-Hybrid electric vans in the US in the first phase of the demonstration program. 19 additional vans will be manufactured in Phase 2 of the program (through the 2nd quarter of 2008) and evaluated in the States. The prototypes are imported under a federal waiver that permits testing and evaluation by customers for three years.

The PHEV Sprinter has the ability to operate in all-electric mode up to 20 miles (at GVWR 8,553.9 lbs.) due to the 14 kWh (Li-ion or NiMH) battery packs; larger than would be required for hybrid operation alone. The electric motor and power electronics are rated at 70 kW with a peak power and torque of 87 kW and 275 Nm, respectively. The battery charger is rated 3.3 kW (208-240 VAC, single phase) or 1.2 kW (120 VAC).

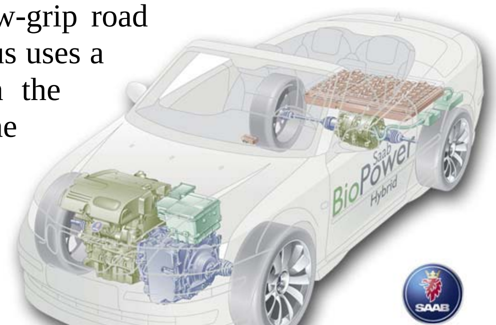
Electric drives in production hybrid passenger cars or SUVs are packaged as fully integrated front-wheel drive (FWD) units such as the original Prius (right), as in-line rear-wheel drive (RWD) units such as the Lexus GS450h or LS600h and axle-mounted RWD units such as in the Lexus RX400h.

Power ranges from $50kW_{max}$ (at 1200-1540 rpm for the approximately $25kW_{cont}$ Prius motor) up to $160kW_{max}$ for the Lexus LS600h. In all cases the electric traction motors provide about half the maximum power of their respective propulsion systems.



Graphic: GM

High power electric rear drive, such as in the 'two-mode' system being developed by the joint venture of GM, BMW and Daimler (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 LS600h with an in-line motor, generator, power split planetary gear mechanism and speed reduction in one transmission casing. Saab uses both the FWD version of the two-mode system and an electric rear axle to boost performance in the BioPower hybrid concept vehicle.

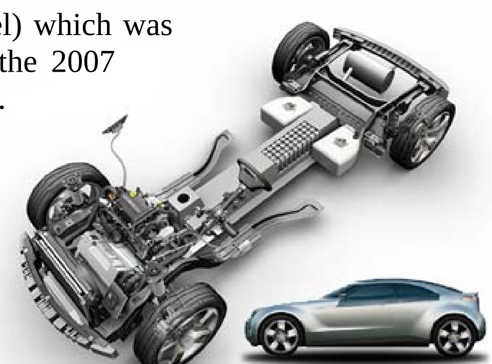


Graphic: Saab

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.

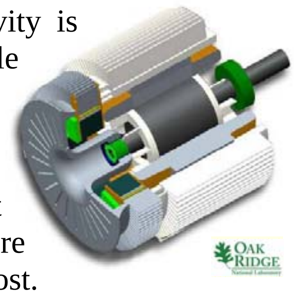
Batteries are nominally 200-288V, with power electronics operating at 500-650V (using a boost converter, e.g., the Camry) to decrease the current and associated losses. Consequently, power semi-conductors are rated about twice the battery voltage. Battery voltage is apparently increasing – up to about 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.



Graphics: GM

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 all-electric drive. This exacerbates electric drive cost, but the smaller engine-generator (used to extend the range) and simpler mechanical drive could bring the cost closer to that of 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 recently unveiled the fuel cell version of the Volt at the Shanghai Motor Show and described it as being capable of 20 miles electric range on the Li-ion battery alone and 300 miles range on hydrogen.

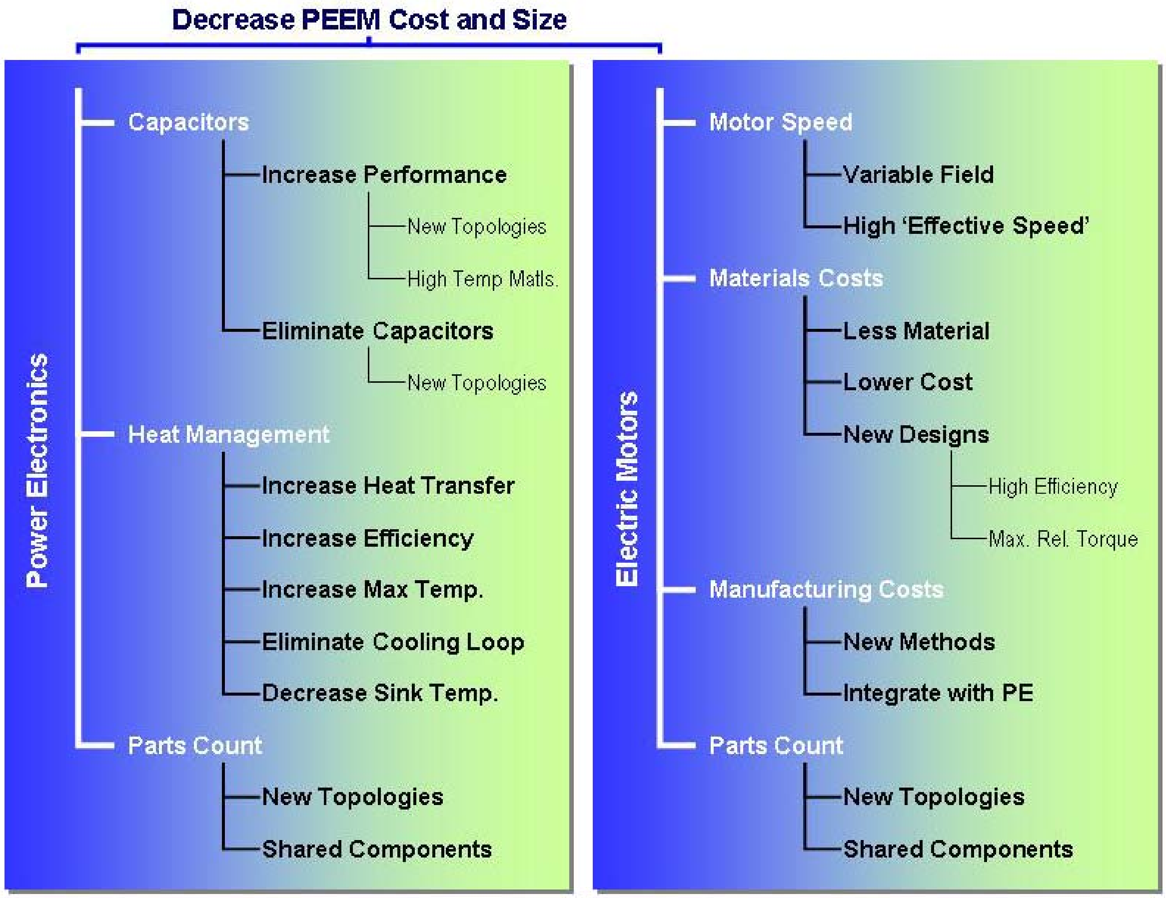
4.2 Relevant DOE Activities and Technology



The Power Electronics and Electric Motors (PEEM) R&D activity is developing technology for a variety of hybrid and electric vehicle applications (including fuel cell vehicles). The resulting range of performance requirements necessitates multiple development paths for components and systems (e.g., the integrated motor-inverter design concept shown on the right). Several development paths are summarized in the following chart and table, but all are focused on improving performance, reducing volume or lowering cost.

PHEVs do not present additional technical barriers for electric drive components. The need to charge using an onboard charger (perhaps with a 'smart' connection to regulate charging in the future) will require determining integration requirements.

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



Power Electronics and Electric Motors 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

PEEM component/system development is described below, followed by a summary table of the system-level development targets.

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

- Ongoing FY 2007 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 (IPM) 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 ensure 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).
- 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.

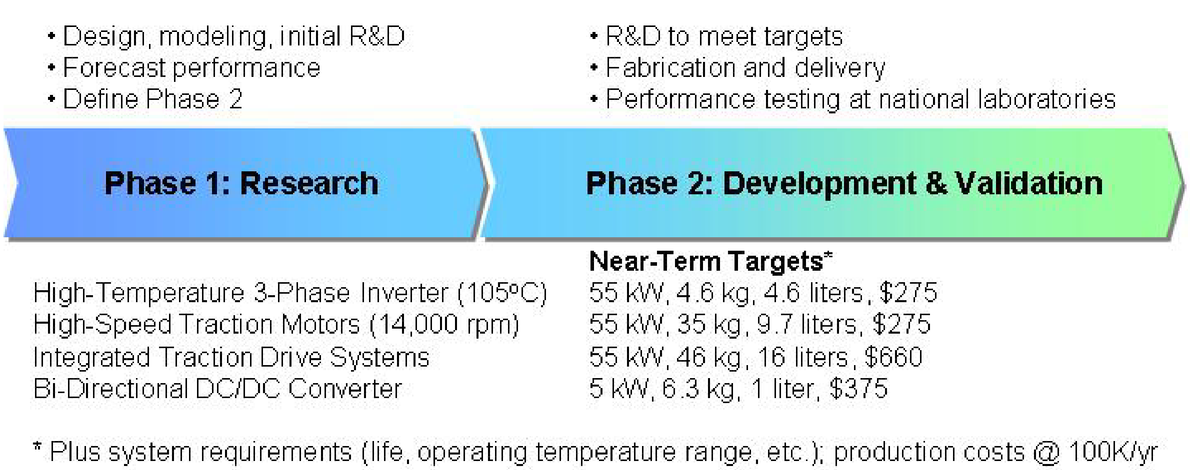
Integrated Systems Development – PHEVs could require up to 200 kW, depending on vehicle type, configuration and control strategy (with charge-depleting hybrid on the low end and full-performance all-electric on the high end). The PEEM Technology R&D subprogram targets 55 kW peak power established in the FreedomCAR program; and since it is more challenging to meet the specific power and volume targets at the low end and the technology is scaleable, the targets have not changed. Vehicle-specific targets will be defined for integration and testing prior to the PHEV mid-term milestone in 2012.

PEEM Development Targets (FreedomCAR program)				
		2010	**2015**	**2020**
Integrated Electric Propulsion System ***(Motor and Power Electronics Inverter/Controller)***				
Requirements	Peak Power (18 seconds), kW	55	55	55
	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
	Vol. Power Density, kW/L	>2.60	>3.5	>4.0
	Cost, $/kW	<19	<12	<8
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

4.4 Tasks

The following graphic summarizes the current solicitations as well as the two-phase procurement and development approach within the PEEM Technology R&D program.

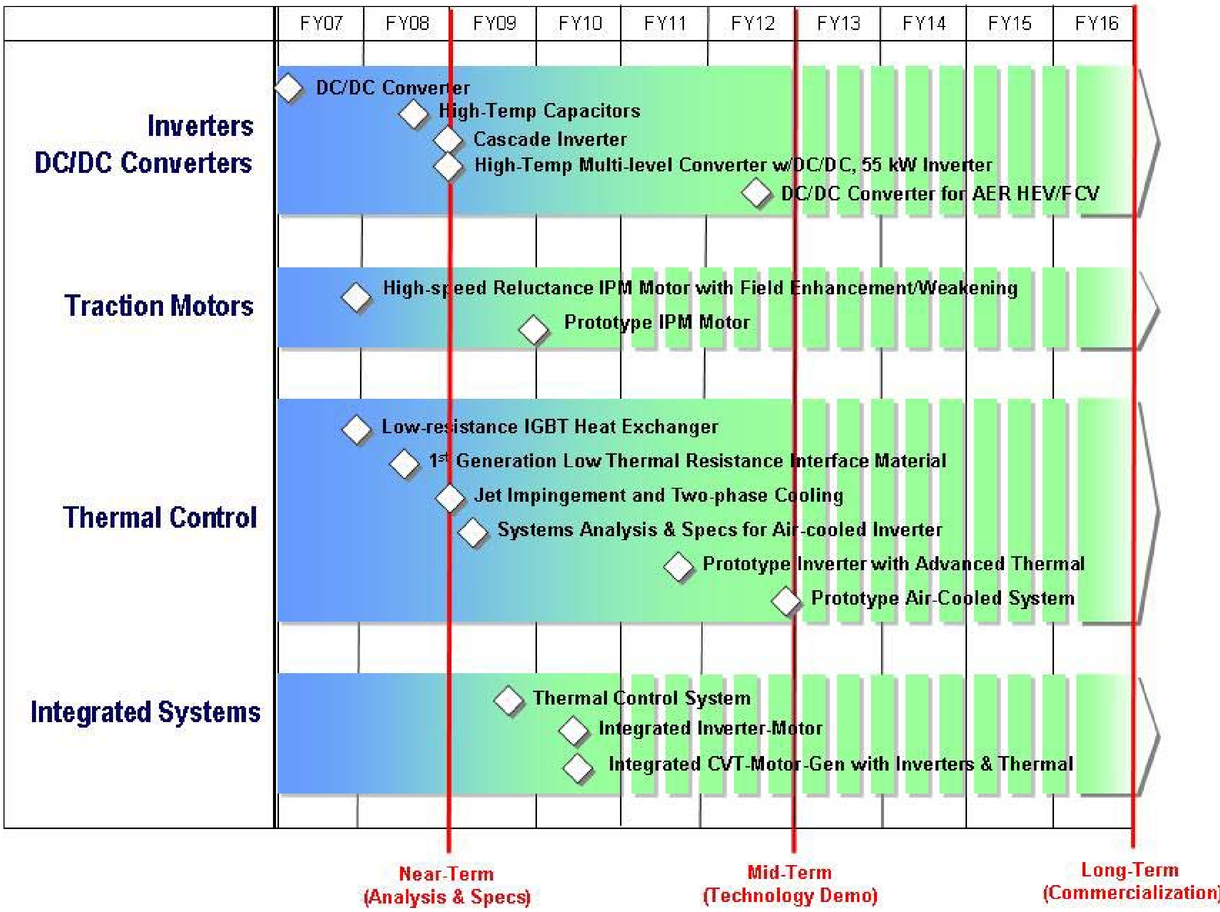
Advanced PEEM R&D Process



4.5 Schedule and Milestones

The schedule below reflects the range of components and applications for advanced power electronics and electric motors within the PEEM Technology R&D program, ranging from conventional hybrids to PHEVs and fuel cell vehicles. The PHEV program milestones are shown for reference.

PEEM R&D Schedule



This page intentionally left blank

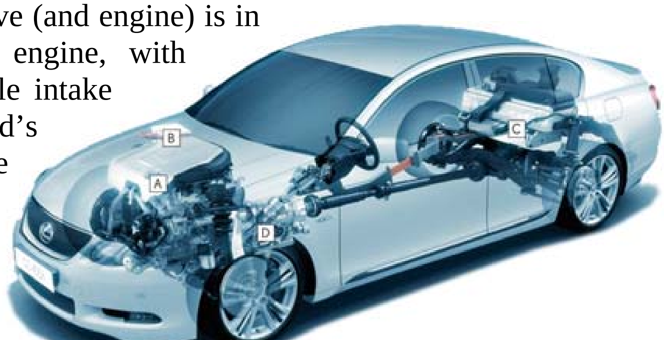
Section 5: Engines and Fuels

The application of engine technology in the PHEV R&D activity will draw from the Advanced Combustion Engine R&D and Fuels Technology R&D programs in FCVT, whose aim is to dramatically improve the efficiency of internal combustion engines (ICEs) and identify fuel properties that improve system efficiency or can displace petroleum based fuels. The R&D focus is on improving engine efficiency while meeting future federal and state emissions regulations through a combination of combustion and fuels technologies that increase efficiency and minimize in-cylinder formation of emissions, and after-treatment technologies that further reduce exhaust emissions. The near-term focus is on analysis and technology assessment to identify PHEV-specific engine and fuels development and to quantify mid- and long-term targets.

5.1 External Assessment and Market Overview

Production hybrid vehicles use a 'parallel' propulsion system with power shared between the engine and electric drive, but the systems also have 'series' functionality in that the battery can be charged when necessary. The most prevalent hybrid, the Toyota Prius, uses an Atkinson cycle engine with variable valve timing, contributing to efficiency and enabling seamless power blending. Most PHEV conversions to date are based on the Toyota powertrain and it is safe to assume that it will be used in production PHEVs since it needs only a higher energy battery and control modifications to implement a 'charge-depleting' hybrid strategy. The system does not provide full performance in all-electric mode, as demonstrated by the PHEV conversions, because the motor and power electronics are designed to supplement the engine, not provide peak power.

The state-of-the-art parallel hybrid drive (and engine) is in the Lexus 600h. The 5-litre V8 engine, with stoichiometric direct injection, variable intake and exhaust valve timing plus the world's first electric motor driven intake camshaft is coupled to an in-line transmission housing that contains the electric motor, generator, power split planetary gear mechanism and motor-speed reduction gearing.



Drawing: Lexus

Photo: ANL

Since Toyota introduced the Prius with a hybrid drive that combines parallel and series functionality, there has been little interest in 'pure' series hybrids because of the relatively higher power (and higher cost) electric drive components required. There is some interest in parts of Europe where EVs are more prevalent (e.g., France) and range extension is desired. In fact, Dassault recently announced the production of the Cleanova hybrid system that combines a 54 hp Weber (German) engine that can run on gasoline/E85 and an ac alternator by TM4.

The push for PHEVs with all-electric capability has renewed stateside interest in series hybrids, as evidenced by the Chevrolet Volt (shown previously in Section 4.1). The Volt has a 1-liter, 71 hp 3-cylinder engine-alternator set that produces 120 kW (electric) packaged with the front-wheel electric drive system and a 16 kWh Li-ion battery in the tunnel. GM's 'E-flex platform' in the Volt aptly demonstrates the flexibility of series configurations in that it can incorporate either an engine or fuel cell as the onboard electric power generator, plus the necessary energy storage.

Gasoline is the primary fuel used in current production hybrid vehicles, though concept vehicles have been displayed that could use diesel or hydrogen. Ethanol blends are an important element of the Administration's petroleum displacement strategy and will be included in the PHEV program.

5.2 Relevant DOE Activities and Technology

Advanced Combustion Engine R&D covers a range of activities that are relevant to most engine applications as well as PHEVs. These include fundamental combustion, emission control, enabling technologies (such fuel systems, engine control and engine technologies) and integrated engine and emission control. Of particular interest are those activities that can be combined to address the particular needs of PHEVs that might not otherwise be considered. For example, adapting the combustion and emission control technologies to small engines (1 to 2 liters) is important for series hybrid configurations. In addition, the impact of the PHEV duty cycles on emission control requirements needs to be addressed and potential system solutions for series and hybrid configurations need to be identified.

Similarly, the Fuels Technology R&D subprogram is evaluating properties and determining the impacts of a range of fuels and lubricants for typical engine systems. This activity is interested in renewable non-petroleum fuels (e.g., ethanol and other bio-fuels) and their applicability to PHEV propulsion system configurations and duty cycles.

5.3 Development Goals and Approach

The technical targets for light duty compression ignition direction injection (CIDI) and hydrogen-fueled internal combustion engines (H2-ICE) are directly applicable to this program. The key technical challenge is to achieve 45% peak brake thermal efficiency, targeting CIDI by 2010 and H2-ICE by 2015, while meeting EPA emission requirements.

Near-Term – Activities will focus on technology assessment and systems analysis to quantify performance or functional characteristics that could impact combustion/fuels development as well as to identify candidate engine systems and fuels for integration and system development. A key output of the assessment activity is to quantify and contrast requirements for series and parallel PHEV configurations as a function of the control strategy (i.e., all-electric or charge-depleting hybrid). Mid- and long-term targets for PHEV engines and fuels will be defined as well.

Mid-term – Development will likely focus on integrating the most promising systems identified by systems analysis and technology assessment. The objective is to demonstrate the potential benefits of candidate systems and to refine engine/fuels development targets for long-term development to address the specific needs of PHEVs.

Long-term – The focus is expected to be fundamental design and control targeting specific PHEV engines and emission control systems. Examples include engines designed specifically for series hybrid applications (smaller 'constant power' systems focused on efficiency and cost reduction) or after-treatment systems that might utilize the connection to the grid to enhance system performance by pre-heating. The implications of V2G on engine operation, efficiency and emissions must be determined as well.

5.4 Tasks

Near-term – Analysis and technology assessment

- Determine engine and emission control requirements as a function of PHEV configuration, control strategy and potential use patterns
- Identify and analyze systems with the potential to meet efficiency and emission targets cost-effectively for the PHEV application
- Set mid- and long-term targets for integrated engines, emission control, fuels and control systems; modify requirements of near-term component development programs accordingly

Mid-term – Hardware studies

- Integration and development of components and control systems to demonstrate achievement of mid-term targets

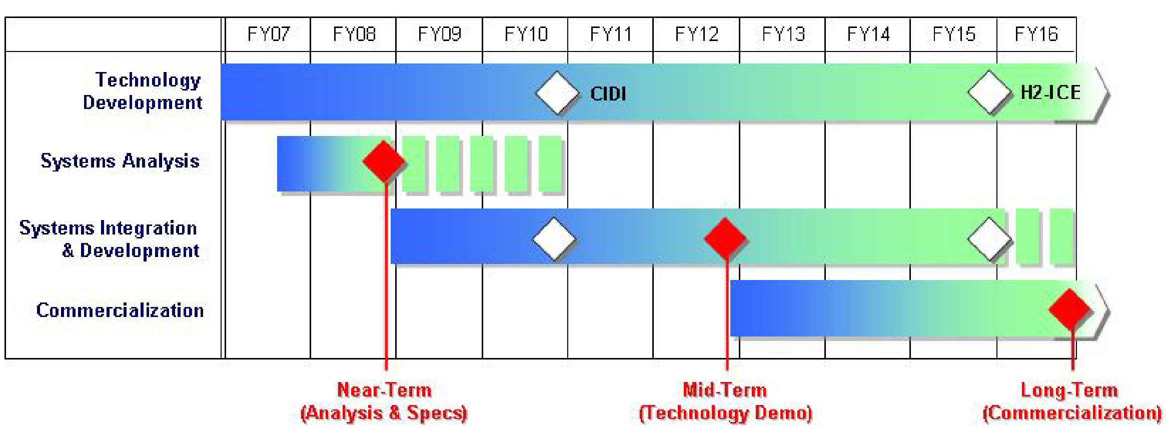
Long-term – Component commercialization

- Focus on manufacturing barriers and cost reduction for commercialization

5.5 Schedule and Milestones

The schedule below summarizes the PHEV-specific activities and milestones in relation to the major Advanced Combustion Engine R&D subprogram goals for CIDI engines and H2-ICEs. PHEV-specific analysis will be initiated this fiscal year to identify candidate technologies, systems and fuels for integration and development prior to the mid-term technology demonstration.

PHEV Engines and Fuels R&D Schedule



This page intentionally left blank

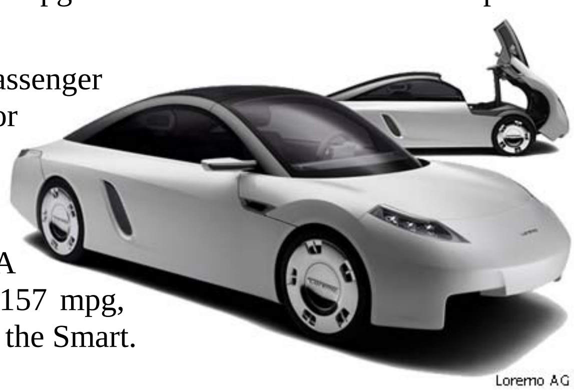
Section 6: Vehicle Efficiency Technologies

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- and mid-term cost goals stated previously, the battery and electric propulsion system could cost $3,400-5,800[4] in a passenger car. This provides an incentive to determine which vehicle efficiency technologies/components might be cost-effectively applied to reduce the propulsion system demands.

6.1 External Assessment and Market Overview

Lightweight body and chassis technologies for transportation applications have been developed for many years, 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 aluminum, magnesium and plastic/composite components 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.

Though relevance in the US mass market is debatable due to regulatory differences (e.g., safety) and consumer preferences, high-efficiency vehicles compete with hybrids globally and consumer interest in the States is growing with fuel prices. In 2008, Daimler plans to import the Smart 'fortwo', which combines steel and composite panels with a 3-cylinder turbocharged engine to weigh in at about 730 kg. The European diesel version gets over 60 mpg, but Daimler says the gasoline-fueled US model will get around 40 mpg and it will accelerate to 60 mph in about 16 seconds.



Loremo AG is promoting a 470 kg, 4-passenger vehicle concept that they intend to produce for the European market by 2010. Their analysis indicates that the 'GT" model with a 3-cylinder, 36 kW turbo-diesel engine could accelerate to 60 mph in 9s and get 87.5 mpg. A base model with a smaller engine could get 157 mpg, but at 0-60 mph in 20s it would be slower than the Smart.

[4] Based on $8-12/kW for a 55-110 kW electric propulsion system and $200-300/kWh for a 15 kWh battery; this does not include the mechanical drive train components (gear reduction, transmission, etc.)

6.2 Relevant DOE Activities and Technology

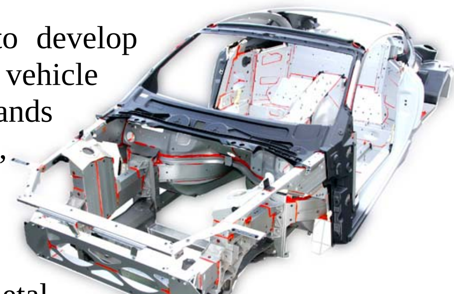


Photo: ANL

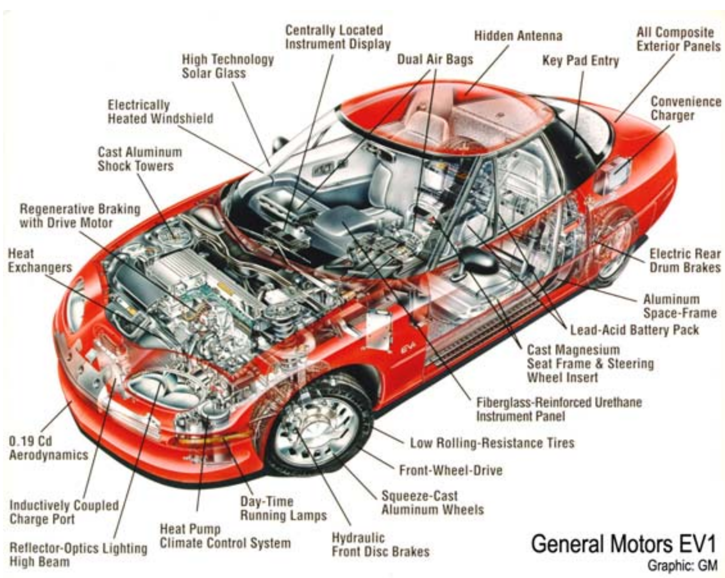
An objective of the Materials R&D activity is to develop lightweight materials as enablers for lightweight vehicle structures to improve fuel economy and reduce demands on the vehicle powertrain and ancillary systems (e.g., braking). The greatest barrier to substituting lightweight, high-strength materials (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 are significant in an electric vehicle or a hybrid in electric mode because they reduce electric range. DOE/NREL has developed tools to address ancillary load reduction that will be applied to the PHEV activity.

6.3 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 an analytical task with the potential for application engineering. 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 could 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 for this study.

6.4 Tasks

Near-term – Analysis and hardware studies

- PHEV propulsion system requirements, identification of potential system components and cost analysis for representative components
- Comparative cost analysis versus hybrid propulsion system cost; prioritized development and application engineering if warranted
- Specific design, packaging studies and cost analysis

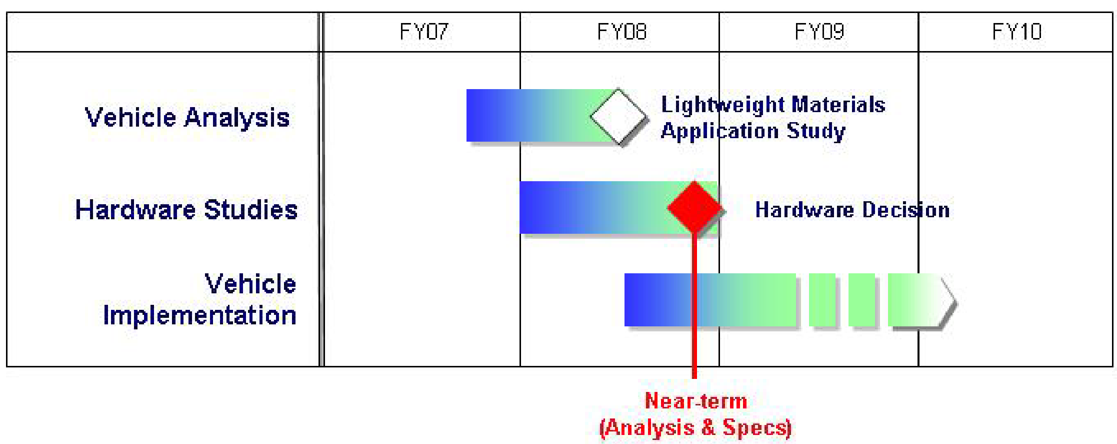
Mid-term – Vehicle integration and development

- TBD; depends on near-term results

6.5 Schedule and Milestones

The vehicle analysis will be initiated this fiscal year and will be completed prior to the near-term review; continuation of the task and the extent of hardware development depend on the results.

Vehicle Efficiency Study Schedule



This page intentionally left blank

Section 7: Deployment Issues

7.1 Grid Interactions

One conclusion of the PHEV Discussion Meeting in May 2006 was that the nation's electric power grid did not present any immediate technical barriers for PHEVs. In fact, studies have shown that a large number of PHEVs could be charged using off-peak power without negatively impacting the grid; this depends on the location and specific regional analyses were recommended by the attendees as well. And both the vehicle and grid efficiency could benefit from communication to provide information or control (e.g., appropriate charge times, costs of charging or charge restrictions).

Several issues were identified for further assessment, but are not limiting factors for R&D or initial deployment of PHEVs, including the vehicle-utility interface (for charging and communication), vehicle-to-home/vehicle-to-grid (V2G) power flow and the long-term impact of PHEVs on the utilities and distribution.

Vehicle-utility interface – No changes to the physical interface (charge plug or voltage) were recommended in the near term by either the vehicle manufacturers or utilities at the PHEV Discussion Meeting. In fact, it was discussed as a possible deterrent for PHEVs. At some point, communication with the utility/grid manager will be required to ensure the most effective recharging (i.e., for cost and efficiency). And the onset of high power or 'smart' grid interfaces will likely require collaboration on standard interfaces.

Residential infrastructure – Though the charging interface is not an immediate concern, the availability of electric outlets for charging is an issue. All potential customers do not have a convenient location for recharging at their home, i.e., either their vehicle is not parked adjacent to their home or apartment (e.g., on-street parking or a public garage) or there is no convenient outlet on the outside of their home. The electric utilities are likely the best source of this information; their billing systems are regularly used to communicate with customers and could provide insight into this issue.

Vehicle-to-grid (V2G) – The batteries in PHEVs have been discussed as a potential flexible energy storage media for the electric power grid (i.e., providing spinning reserves) and as a means to improve the vehicle economics for the customer by selling power to the utility. This unusually complex relationship between manufacturer, residential customer and power provider offers the opportunity for benefits and penalties; rigorous analysis is required to quantify the value proposition for each of the stakeholders. Examples of the issues to consider (from both sides):

- Automotive manufacturers and their battery suppliers bear the production and warranty risk with an uncertain return on their investment.
- Customers risk reduced battery life and high replacement costs due to the additional discharge-charge cycles, but could receive compensation or other less tangible benefits (e.g., home or neighborhood reserve power). Vehicle use patterns and local/regional grid demand profiles must be better understood to determine the potential V2G duty cycle and the impact on battery life.

- Utilities (or grid managers) must rely on power from multiple sources out of their control, but could benefit from reduced investment in spinning reserves.

Neither the utility or automotive manufacturer representatives at the PHEV meeting contended that V2G was an enabler for PHEVs. V2G requires more sophisticated communication and a more complex customer-utility/grid manager relationship, but there are no obvious technical barriers.

Impact on utilities and distribution 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 DOE Electricity Delivery and Energy Reliability Office (OE) has previously sponsored analyses to estimate the impact of PHEVs on the nation's power generating capacity as well as conducting limited 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. Updated studies by ANL, EPRI and PNNL are planned in collaboration with the Office of Electricity to ensure that the latest data and technology assumptions from both the supply and demand sides of the grid are considered.

7.2 Automotive-Utility Industry Interactions

The relationship between the auto and utility industries could be enhanced with the development and introduction of PHEVs. Not since the push for electric vehicle production in the early 90s (and the flurry of battery charger development) has the need arisen for collaboration on their products. PHEVs could lead to a long-lived, beneficial dependency if the V2G scenario matures – this would entail 'sharing' the daily use of batteries. And some in the utility industry have suggested a secondary use for vehicle batteries as spinning reserves when their usefulness as traction batteries has diminished. This is likely a more cost-effective, efficient and environmentally sound approach to battery life cycle management than immediate scrapping and recycling. The potential synergy between the industries can be facilitated by DOE, but implementation lies within the private sector since it is not critical for PHEV technology development.

7.3 Incentives

Incentives for both the supply and demand sides of PHEVs have been discussed, including tax credits, direct subsidies and preferential electric rates for customers as well as regulatory considerations, subsidies or loan guarantees for manufacturers and utilities. Purchase incentives are beyond the scope of FCVT, but the DOE loan guarantee authority could be utilized if it is sufficiently beneficial to achieving national objectives.

7.4 Education and Demonstrations

Some participants in the May 2006 PHEV Discussion Meeting, as well as some comments on the Draft PHEV R&D Plan, supported large scale demonstrations to educate consumers and develop the market. FCVT is exploring possibilities within its scope (and budget authority) and will involve the Clean Cities Program in activities related to public fleet demonstrations and education.

Appendix A: National Laboratory Resources

	 **Analysis**	 **Batteries**	 **PEEM**	 **Engines & Fuels**	 **Vehicle Efficiency**	 **Facilities**
Argonne National Laboratory	• Technology assessment • Risk assessment • Vehicle modeling and simulation • Well-to-wheels energy/emissions • 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	•Combustion, system integration, control	•Trade-off studies •Hardware studies	• Advanced Battery Test Facility (ABTF) • Advanced Lithium Battery R&D Facility • Advanced Powertrain Research Facility (APRF)
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
Brookhaven National Laboratory		• Diagnostic studies: matls., components, and systems • synthesis of new electrolytes				• In situ and time resolved XRD • In situ x-ray absorption • Soft x-ray absorption • Synchrotron based x-ray
National Renewable Energy Laboratory	• Vehicle modeling and simulation • Synergy with renewable energy	•Thermal analysis	• Component & system thermal modeling, analysis & testing	• Fuels R&D	•Efficient climate control	• Thermal Management Test Facility
Oak Ridge National Laboratory	• Regional grid analysis • Policy analysis	•Materials R&D	• Benchmarking, modeling, design, testing and analysis: -Inverters and dc-dc converters -Electric motors -Thermal control	• Engine, after-treatment and fuels integration R&D	•Materials R&D •Heavy-duty vehicles	• Power Electronics & Electric Machines Research Center (PEEMRC) • Fuels, Engines and Emissions Research Center (FEERC) • Hi-Temperature Materials Lab (HTML)
Pacific Northwest National Laboratory	• Regional grid analysis			• Catalyst R&D for emission control		• Exhaust Chemistry and Aerosol Research Center (ECAR)
Sandia National Laboratory		•Cell, module and battery abuse testing		• Combustion R&D		• Battery Abuse Testing Facility • Engine Test Facility

Appendix B: Acronyms

AER	All Electric Range
ANL	Argonne National Laboratory
BAS	Belted-Alternator-Starter
BNL	Brookhaven National Laboratory
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
FTP	Federal Test Procedure
FWD	Front Wheel Drive
Gen	Generator
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation (simulation 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)
NIST	National Institute of Science and Technology
NREL	National Renewable Energy Laboratory
OE	Electricity Delivery and Energy Reliability Office, DOE
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
P/E	Power-to-Energy ratio
PE	Power Electronics
PEEM	Power Electronics and Electric Motors
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-FY 2007	Second quarter of Fiscal Year 2007, i.e., January through March (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
TTR	Through-the-road (hybrid propulsion configuration)
USABC	United States Advanced Battery Consortium

This page intentionally left blank

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