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Hybrid and Electric Systems R&D at DOE: Fiscal Year 2011-2012 Status

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Abstract

This paper presents an overview of the recent highlights and accomplishments, for fiscal years (FYs) 2011-2012, by the hybrid and electric systems (HES) R&D Team at the Vehicle Technologies Program (VTP) Office of the United States Department of Energy (DOE) Energy Efficiency and Renewable Energy (EERE) Office. There is significant U.S. commitment to HES R&D and additional responsibilities were assigned under the American Recovery and Reinvestment Act (ARRA) of 2009, an economic stimulus package from the 111th United States Congress. DOE has supported the development of HES technologies, including advanced automotive energy storage technologies, power electronics and electric machines, and simulation and testing tools, over the long term. This support has involved leveraging resources and expertise from automobile manufacturers, battery, motor, and electronics developers, small businesses, national laboratories, and universities to address the technical barriers which prevent the market introduction of vehicles which would use those advanced technologies. The HES R&D Team has had many significant accomplishments and continues to advance the state of the art for many technologies. This paper provides a discussion of the most recent highlights and a description of R&D coordination efforts with other government agencies in associated areas.

Keywords: Battery, Energy Storage, Simulation, PHEV, EV

1 Introduction

The Hybrid Electric Systems (HES) subprogram of the Vehicle Technologies Program (VTP) in the U.S. Department of Energy (DOE) Energy Efficiency and Renewable Energy (EERE) Office spearheads R&D needed for the new generation of electric-drive vehicles. HES R&D is an important component of the VTP multi-year program plan [1] and includes R&D on energy storage, vehicle and system simulation and testing (VSST), and advanced power electronics and electric machines (APEEM). Status updates on these were regularly provided at prior EVS meetings (e.g., [2-4]). VTP leverages significant resources to address technical barriers preventing the commercialization of advanced transportation technologies like plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles. Table 1 shows the FY 2003–2013 VTP budgets for HES R&D. The fiscal year (FY) 2013 budget (President's Request) is approximately $259.8 million – nearly five times the FY 2003 budget.

Table 1: Recent HES R&D budgets

Fiscal Year (FY)	HES Budget ($, Million)
2003	$55.48
2004	$57.26
2005	$57.07
2006	$55.56
2007	$72.24
2008	$92.07
2009	$122.73
2010	$142.29
2011	$145.81
2012	$164.92
2013	$259.8*

* President's Request

1.1 Goals and Strategies

A current VTP goal is the commercialization of PHEVs and making them cost-competitive with conventional internal combustion engine vehicles. Intermediate goals include reducing the production cost of market-ready, high-energy, high-power batteries by 70% by 2014 (compared with 2009 costs) and reducing the cost of a market-ready advanced APEEM system at least 60% by 2015 (again, compared with 2009 costs). Technology development in collaboration with industry partners can enable rapid integration of new technologies into production vehicles. VTP works with industry, universities, and national laboratories to support research on the next-generation energy storage and electric-drive technologies to facilitate their commercialization.

1.1.1 Energy Storage R&D

Energy storage technologies, especially batteries, represent a critical enabling technology towards electrified transportation. Multiple DOE offices support R&D on energy storage. The Office of Basic Energy Sciences (BES) supports fundamental research to understand, predict, and control matter and energy at electronic, atomic, and molecular levels. The Advanced Research Projects Agency-Energy (ARPA-E) supports high-risk, translational research driven by the potential for significant commercial impact in the near-term. The Office of Electricity Delivery and Energy Reliability (OE) supports R&D on modernizing the electric grid, enhancing security/reliability of the energy infrastructure, and mitigating impacts of supply disruptions. Finally, the EERE Office supports work on advanced clean, reliable, sustainable, and affordable technologies which would reduce energy consumption. Figure 1 shows how these offices are positioned with respect to the current technology readiness levels (TRLs) of those technologies. Technologies at a lower TRL generally fall within the domain of BES and ARPA-E, whereas those at higher TRLs would generally be covered by EERE.

To meet the DOE EV/PHEV goals and speed up the commercialization of those technologies, applied R&D is needed. Further, as seen in Figure 1, certain "beyond-Li-ion" chemistries (e.g., Li/S and Li/air) may actually exceed these goals. For example, lithium-sulfur batteries can have theoretical capacities substantially above those of lithium-ion batteries (because of how the ions are assimilated at the electrodes – at the sulfur electrode, each sulfur atom can host two lithium ions instead of the 0.5 to 0.7 for many typical lithium-ion chemistries) with possible specific energy values of up to 3,000 Wh/kg.

However, taking advantage of the higher theoretical capacity is a challenge. In particular, sulfur is an insulating material and only atoms near the surface actually accept lithium ions. Another challenge is that the sulfur binds to lithium ions forming intermediate polysulfides which dissolve in the liquid electrolyte and settle in other areas of the battery, blocking the process of charging/discharging and drastically limiting the cycle life. Lithium/air batteries also have a theoretical specific energy of over 3,000 Wh/kg. However, the cycle life of Li/air cells has typically been much less than 100 cycles. The cell efficiency thus far has been less than 70 percent, due in part to the relatively low cell operating voltage and the polarization at the electrodes. Achieving a good power density is also a challenge. Such fundamental technical issues result in placing those technologies at a TRL level of 2. For lithium metal polymer batteries (theoretical specific energy: 990 Wh/kg), the lithium-salt electrolyte is held in a solid polymer composite (e.g., polyethylene oxide or polyacrylonitrile) instead of an organic solvent. This design can potentially lower the cost of manufacture, provide reliability and ruggedness, and be adaptable to a wide variety of packaging shapes. Although further along than lithium-sulfur, they face issues of a high internal resistance as well as comparatively long charge times and slow discharge rates– and therefore are also assigned a TRL of 2.

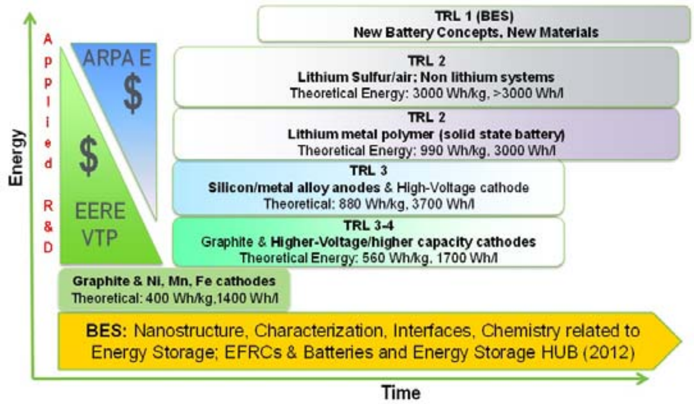

Figure 1: Current energy storage R&D Focus and Technology Readiness Levels

Battery technologies employing silicon/metal alloy anodes and those employing high voltage cathodes (theoretical specific energy: 880 Wh/kg) are assigned a higher TRL of 3. Elements alloying with lithium have significantly higher volumetric and gravimetric capacities than graphite. Challenges to the implementation of alloy materials in commercial cells include maintaining the integrity of the alloy particles and the composite coating during cycling, forming a stable SEI layer on the alloy surface to avoid degradation of the electrolyte, ensuring good rate capability, thermal stability and accommodation of the alloy volume expansion to avoid cell swelling and electrode distortion or tearing. Furthermore, to be commercially viable an alloy anode needs to be made from low-cost raw materials and utilize practical manufacturing methods.

Graphite and higher-voltage/higher-capacity cathodes (theoretical specific energy: 560 Wh/kg) are assigned TRLs of 3 and 4. Still further along are technologies based on graphite and nickel, manganese, iron cathodes (theoretical specific energy: 400 Wh/kg) which could be more readily commercialized if the costs could be further reduced.

Both fundamental and applied research (more of the latter for higher TRL technologies) are needed to resolve associated issues to facilitate vehicular applications of these battery technologies and both are being conducted by VTP.

1.1.2 VSST R&D

Key VSST goals include demonstrating the market readiness of grid-connected vehicle technologies by 2015, supporting laboratory and field evaluations of large-scale demonstration fleets of advanced commercial and passenger PHEVs and EVs, collecting data on the interaction of electric-drive vehicles with charging infrastructure and the electric utility grid to understand electric-drive vehicle usage and charging patterns and their impacts, addressing associated codes and standards issues, developing and integrating technologies to greatly improve commercial vehicle efficiency, and validating in a systems context, performance targets for deliverables from the APEEM and Energy Storage R&D. The main barriers facing VSST's strategic goals include the risk aversion of manufacturers (who may be reluctant to invest in and introduce new technologies), costs, infrastructure issues and a lack of standardized test protocols. The VSST approach for overcoming them consists of activities in five main focus areas, including modeling and simulation, component and system evaluation, laboratory and field vehicle evaluations, codes and standards development, and heavy vehicle systems optimization.

1.1.3 APEEM R&D

The important elements of the APEEM R&D strategic approach include the development of a set of technologies that original equipment manufacturers (OEMs) and their suppliers can adopt (and modify, if necessary), dealing with a wide variety of technologies to make improvements to both the motor and the power electronics, pursuing high-risk concepts and reducing the overall risk of technical failure by pursuing more than one path toward each objective, and carrying out both short-term and long-term R&D to advance the technologies to a suitable point for industry to adopt.

1.2 Technical Barriers and Targets

It has been recognized for some time that the technical barriers to successful commercialization of advanced energy storage technologies (for transportation applications) are associated with cost, performance, life, and abuse tolerance – of which cost is the overriding factor. Also, it is critical for any new vehicle technology (including advanced energy storage systems) to operate safely under both routine and extreme conditions (including abuse conditions of high temperature, overcharge, or short circuit). Technical targets for individual battery applications have been developed in collaboration with the United States Advanced Battery Consortium (USABC) based on input from purchasers and end-users of these technologies. More recently, a significant focus of energy storage R&D has been the development of batteries for PHEV and EV applications. Current targets for PHEV batteries are tabulated in the VTP program plan [1]. Additional performance targets (e.g., those for HEVs, EVs, and ultracapacitors) are available at the USABC partnership website [5] and reported in the VTP Energy Storage R&D annual progress report [6]. The APEEM technical targets for peak power, costs, etc. can also be found in the corresponding section of the VTP multi-year program plan [1].

1.3 HES Grants under ARRA

The American Recovery and Reinvestment Act of 2009 (ARRA) (Public Law 111-5), an economic stimulus package enacted by the 111th United States Congress in February 2009, provided $2.4 billion in one-time grants to accelerate the manufacture and deployment of the next generation of U.S. batteries and electric vehicles. The awards, distributed across the U.S., include $1.5 billion in grants to U.S.-based manufacturers to produce batteries and their components and expand battery recycling capacity, approximately $500M to produce electric drives and their components, plus $400M in grants to purchase, deploy and evaluate PHEVs and all-electric vehicles for test demonstrations, to install electric charging infrastructures, and to support relevant outreach. These created numerous new projects to manufacture advanced batteries and EV components and to conduct deployment and demonstration. The manufacturing areas include those of material supply, cell components, cell fabrication, pack assembly, and recycling. The individual grants are described in the energy storage R&D annual progress report [6]. All ARRA projects for battery and materials manufacturing facilities have been initiated. Production has begun at most facilities, including those listed in Table 2.

2 Energy Storage R&D

The energy storage R&D effort includes multiple activities, from hardware development with industry to mid-term R&D and focused fundamental research. The activities begin by establishing technical requirements for the energy storage technologies in cooperation with industry. Next, commercially available batteries are evaluated against those requirements.

Table 2: List of ARRA-funded battery facilities now in production

Manufacturer	Facility Type	Location
A123Systems	Cell and pack assembly	Livonia, MI
BASF	Nickel-cobalt-metal cathode material	Elyria, OH
Celgard	Separator material production plant	Charlotte, NC
Dow Kokam	Large-format battery manufacturing	Midland, MI
East Penn	Advanced lead acid battery plant	Lyon Station, PA
Enerdel	Cell and pack assembly	Indianapolis, IN
EnerG2	Nano-engineered ultracapacitor carbon	Albany, OR
Exide	Advanced lead-acid batteries	Columbus, GA and Bristol, TN
GM	Battery pack assembly	Brownstown, MI
Honeywell	Electrolyte salt pilot production facility	Buffalo, NY
JCI	Cell and pack assembly	Holland, MI
LG Chem	Li-Ion Battery Manufacturing	Holland, MI
Pyrotek	Anode production plant	Sanborn, NY
Saft	Cell and pack assembly	Jacksonville, FL
Toda	Cathode production plant	Battle Creek, MI

If requirements remain unmet, additional R&D takes place, which involves either short-term directed research (applied research) by commercial developers and national laboratories, or exploratory research generally spearheaded by national laboratories and universities. The three energy storage R&D activities – advanced battery development, system analysis, and testing; applied battery research; and focused fundamental research – are organized to complement each other.

DOE maintains a close partnership with the automotive industry through the USABC to support the development of such technologies, leveraging all available resources, including those of automobile manufacturers, battery developers, small businesses, national laboratories, and universities. The goal is to help develop a U.S. domestic advanced battery industry whose products can meet USABC technical goals.

2.1 Advanced Battery Development, Systems Analysis, and Testing

A significant part of DOE energy storage R&D includes advanced battery development, systems analysis, and testing. It includes systems and materials development projects, systems analysis projects, and battery testing projects (see Table 3). Battery technologies are evaluated according to the USABC Battery Test Procedures Manual (for EV batteries) [7], the Partnership for a New Generation of Vehicles (PNGV) Battery Test Procedures Manual (for HEV batteries) [8], or the PHEV test procedure manual [9]. Over the past few years, the emphasis of development has shifted from high-power batteries (for HEV applications) to high-energy batteries (for PHEV and EV applications). Private battery developers receive cost-shared funding for technology development through the USABC partnership. Several technologies, developed partially under VT-sponsored projects, have moved into commercial applications. Some recent highlights for this activity are listed below.

- HEVs on the market from BMW and Mercedes are using lithium-ion technology developed under JCS.
- Lithium-ion battery technology developed partially with DOE funding of a USABC project at LG Chem is being used in GM's Chevrolet Volt extended-range electric vehicle and has been selected for the upcoming Ford Focus EV battery and Ford Fusion PHEV.
- LG Chem will also supply Li-ion batteries to Eaton for hybrid drive heavy vehicles.
- Johnson Controls-Saft continues to supply Li-ion battery packs to Azure Dynamics for electric delivery vans built on the Ford Transit Connect platform.
- A123Systems is producing lithium-ion battery systems for the Fisker Karma EV and the Navistar Modec Electric trucks.
- A123Systems has been selected to supply lithium-ion batteries for use in the GM Spark EV, the BMW ActiveHybrid 5 and 7 models, and VIA Motors electric trucks.

Table 3: An overview of battery development, system analysis, and testing projects in FY 2012 (from [6])

Project Area	Participants
EV Batteries (High Energy)	Envia Systems, Cobasys, Quallion
PHEV Batteries (High Energy)	Johnson Controls, LG Chem - Michigan, A123Systems
HEV and LEESS Batteries (High Power)	A123Systems, Maxwell
Technology Assessment (EV, or LEESS)	SK Energy, K2 Energy, Leyden Energy, Actacell
Advanced lithium-ion Battery (Cell Materials)	Amprius, Dow Kokam, Nanosys, 3M, Applied materials, Seeo Inc., Pennsylvania State University
Low-cost Manufacturing Processes	JCI, Miltec UV, A123Systems
Inactive materials/components Reduction	Optodot, Denso
Advanced Materials and Processing	ENTEK Membranes, 3M, FMC, Sion Power, BASF, Angstron, North Carolina State University, EnerDel, TIAX, A123Systems, SBIR (several projects)
Systems Analysis	TIAX, ANL, NREL
Battery Testing	ANL, INL, SNL, NREL
Computer-aided Engineering of Batteries	NREL, ORNL, GM/Ansys, CD-Adapco, Ford/EC Power

2.2 Applied Battery Research

The applied R&D program entitled Applied Battery Research (ABR) for transportation assists industrial developers of high-energy/high-power lithium-ion batteries meet the US-DRIVE long-term battery-level PHEV energy density (~200 Wh/kg) goal, while satisfying cost, life, abuse tolerance, and low-temperature performance goals. ABR projects cover materials development, calendar and cycle life studies, and abuse tolerance studies. ABR utilizes the expertise of six national laboratories, industry, and several universities. An overview of those projects appears in Table 4. More information on each project is available in the VTP Energy Storage R&D annual progress report [6]. Some recent highlights for this activity are listed below.

- SNL and Binrad Industries obtained dramatic improvements in the thermal stability of cathodes and improvements in cell runaway response using electrolytes with LiF/anion binding agent salts. The specific heat measured for a NMC433 cathode was much less in LiF/ABA (611 J/g) than in $LiPF_6$ (1,132 J/g).
- ARL found a new electrolyte additive to significantly improve high-voltage stability. The additive, a highly fluorinated phosphate ester with a fluorine/hydrogen ratio of 6, enhances the high-voltage stability of carbonate electrolytes. ARL also developed a 4.8-V cathode material, Fe-$LiCoPO_4$, in which a portion of the Co is substituted by Fe^{2+} and Fe^{3+}, which showed improved stability and cycle life compared with $LiCoPO_4$.

2.3 Focused Fundamental Research

The Focused Fundamental Research activity, also called the Batteries for Advanced Transportation Technologies (BATT) activity, addresses fundamental issues of chemistries and materials associated with lithium batteries. It attempts to gain insight into system failures, develops models to predict failure and to optimize systems, and researches new and promising materials. It emphasizes the identification and mitigation of failure modes, coupled with materials synthesis and evaluation, advanced diagnostics, and improved electrochemical models. Battery chemistries are monitored continuously with periodic substitution of more promising components based on advice from within this activity, from outside experts and assessments of world-wide battery R&D. The work is carried out by a team headed by the Lawrence Berkeley National Laboratory (LBNL) and involves several other national labs, universities, and commercial entities. A list of the key projects for the BATT activity appears in Table 5. More information on BATT appears at its website [10] and in the VTP energy storage R&D Annual Progress Report [6]. Some recent highlights for this activity are listed below:

- MIT developed a new construction technique for thicker electrodes (almost 10 times more thickness), which uses sintered electrode architecture with aligned, low-tortuosity porosity (see Figure 2).

Table 4: An overview of projects for Applied Battery Research, FY 2011-2012 (from [6])

Project Area	Participants
Materials Research	
Cell Components and Composition	ANL (2 projects), LBNL
Applied Battery Research on Anodes	ANL (4 projects)
Applied Battery Research on Cathodes	ANL (6 projects)
Applied Battery Research on Electrolytes	ANL (3 projects), ARL, JPL, INL
Calendar and Cycle Life Studies	
Diagnostics and Modeling	ANL (4 projects), LBNL, INL, ORNL
Cell Fabrication and Testing	ANL (2 projects)
Abuse Tolerance Studies	
Abuse Diagnostics	BNL
Abuse Mitigation	ANL, SNL, LBNL
Applied Research Facilities	
Battery Materials Pilot Production Facility	ANL (2 projects)
Post-Test Diagnostics Facility	ANL
Battery Electrode and Cell Production Facility	ANL

Table 5: An overview of Focused Fundamental Research projects, FY 2011-2012 (from [6])

Project Area	Participants
Cathodes	MIT (2 projects), SUNY (2 projects), LBNL (4 projects), University of Texas, HQ, BNL, U. Mass, ANL, PNNL, ORNL (2 projects)
Anodes	University of Pittsburgh, LBNL (2 projects), University of Texas, SUNY (2 projects), PNNL, ANL, Drexel University, NREL, University of Colorado, Penn State University, Southwest Research Institute, Stanford University, ORNL
Electrolytes	UCB, LBNL, University of Utah, CWRU, ANL, NCSU, University of Rhode Island, Arizona State University, ORNL
Cell Analysis, Modeling, and Fabrication	LBNL (5 projects), University of Michigan, ORNL (2 projects), MIT
Energy Frontier Research Centers	ANL, LBNL
Integrated Lab-Industry Research Program	ANL, LBNL

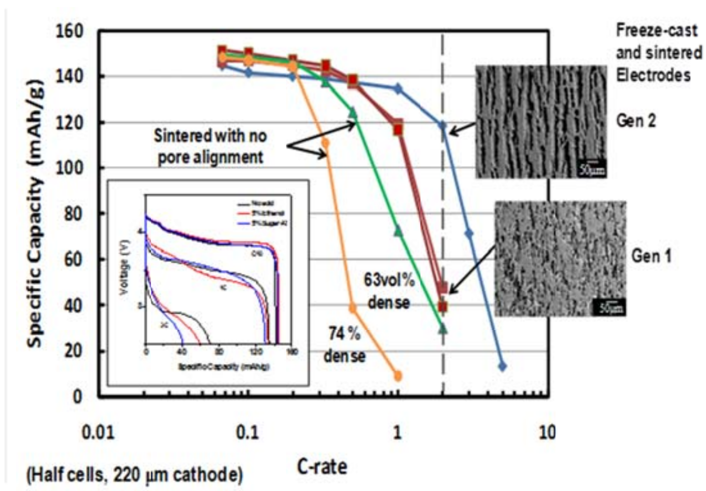

Figure 2: Specific capacity vs. C-rate for sintered $LiCoO_2$ electrodes (with/without aligned low-tortuosity porosity) [6]

- NREL developed a technique for hot wire chemical vapor deposition of amorphous-Si powders to make amorphous-Si electrodes of sufficient thickness for high energy batteries. Electrodes 15-μm thick displayed an initial capacity of ~2500 mAh/g, with a durable capacity of ~1,000 mAh/g (about 3 times that of graphite).
- LBNL developed a new Single-Ion Conductor (SIC) gel (based on a polysulfone/carbonate blend) which can enable thick electrodes (see Figure 3).
- ORNL demonstrated that a nanometers-thick coating of lithium phosphorus oxynitride (Lipon) on high-energy Li-rich or layer/layer cathodes vastly improves rate capability.
- ANL developed a sodium/lithium ion-exchange process to produce a new high-energy cathode material with reduced site disorder and improved rate capability.

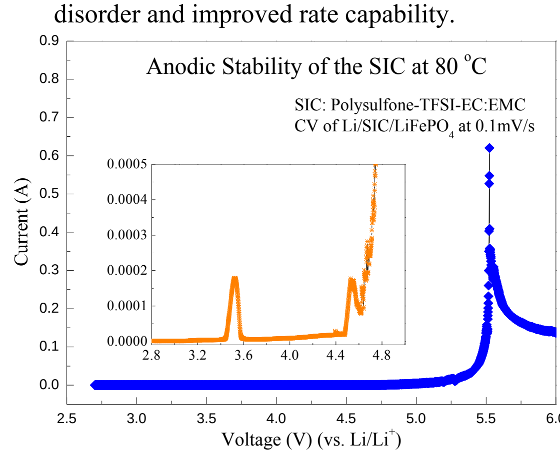

Figure 3: Voltammetry of Polysulfone SIC gel in Li/SIC/$LiFePO_4$ cell [6]

- PNNL developed a chromium-doped high-voltage spinel, $LiNi_{0.45}Cr_{0.05}Mn_{1.5}O_4$ with stable cycling and improved efficiency.
- INL and the University of Hawaii developed tools to better understand cell aging mechanisms.

2.4 Other Energy Storage R&D

In addition to the R&D described above, VTP-funded small business innovation research (SBIR) contracts (focused on new battery materials and components) provide valuable support to EV and HEV battery development efforts. DOE also has extensive ongoing coordination efforts with other government agencies, e.g., the Chemical Working Group of the Interagency Advanced Power Group (IAPG) and technical meetings sponsored by other government agencies. Recent activities have involved the U.S. Army-TACOM, U.S. Army – CERDEC, NRO, CIA, ONR, NSWC, NASA, and JPL. DOE is a member of the Executive Committee of the International Energy Agency (IEA) Implementing Agreement on Hybrid and Electric Vehicles and participates in various Annexes of the Implementing Agreement. It attends the IEA Executive Committee meetings held in various countries and provides status updates on other implementing agreements.

3 Vehicle & Systems Simulation & Testing

Vehicle & Systems Simulation & Testing (VSST) represents a significant component of the HES subprogram. Its mission is to evaluate the technologies and performance characteristics of advanced automotive power-train components and subsystems in vehicle systems. Its systems integration and validation evaluations employ modelling and simulation, laboratory testing, and operational fleet testing. The modelling and simulation tools used by VSST include those for forecasting national-level energy and environmental parameters (e.g., oil use, infrastructure economics, and greenhouse gas analyses) and those for conducting vehicle-level simulations. Hardware-in-the-loop (HIL) simulation allows hardware components to be tested in the laboratory at vehicle level without requiring a prototype vehicle. During benchmarking, both production vehicles and component technologies are extensively tested to verify any significant advances over current technologies. Technology validation involves testing components/subsystems to evaluate them in a systems context. VSST works with industry partners to accurately measure real-world performance of advanced technology vehicles using a testing regime developed in partnership with industry stakeholders. In addition to baseline performance testing, fleet testing and accelerated reliability testing are also carried out.

Table 6 contains a short overview of the project features in each of the six project focus areas for FY 2012. Detailed information on individual VSST projects appears in the current VSST Annual Progress Report [11]. Significant recent accomplishments include the following:

- The Advanced Vehicle Test Activity (AVTA) accumulated data on advanced technology vehicles during 34 million test miles. The data was collected from 6,500 electric-drive vehicles (representing 111 models). The data describes the operational characteristics for 62 models within the EV, PHEV, and Extended Range Electric Vehicle (EREV) categories.
- Initiated data collection on thousands of vehicles and EVSE units placed into service through the largest ever deployment of electric-drive vehicles and charging infrastructure in the U.S. Test settings included grid-connected EDVs in 'on-road' fleets, 'on the test track' and 'in laboratory'. Recent testing includes: The EV Project, Chrysler Ram PHEV Pickups, ChargePoint America Vehicle Charging Infrastructure, and GM Chevrolet Volt Vehicle Demonstration.
- Improved fuel economy estimates for advanced vehicles by adding emissions constraints to vehicle simulations.
- Explored benefits of combining thermal management systems in EDVs. Simulated a full thermal management system in an EV to include air-conditioning, cabin, power electronics cooling loop, and battery cooling loop.
- Developed full analytical, computational and experimental understanding of the physics of wireless power charging of stationary PEVs. This will provide information toward SAE standards development and implementation of designs meeting industry requirements. Performed experimental hardware tests focused on topics of interoperability, coupling coil compatibility, alignment tolerance, positioning control, and wireless communications.

Table 6: An Overview of Vehicle Systems and Simulation Testing Research projects (from [11])

<table>
<tr><th>Project Area</th><th>Project Group</th><th>Participants</th></tr>
<tr><td rowspan="5">Industry Awards for Technology Development and Demonstration</td><td>PHEV Technology Acceleration and Demonstration Activity</td><td>Chrysler, Ford, General Motors</td></tr>
<tr><td>Transportation Electrification</td><td>Cascade Sierra Solutions ,Coulomb Technologies, Chrysler, ECOtality North America, General Motors, Navistar, South Coast Air Quality Management District, Smith Electric Vehicles</td></tr>
<tr><td>SuperTruck</td><td>Cummins, Daimler, Navistar, Volvo</td></tr>
<tr><td>Wireless Charging</td><td rowspan="2">To Be Announced</td></tr>
<tr><td>Electric Cargo Transport</td></tr>
<tr><td rowspan="2">Laboratory and Field Evaluations</td><td>Light Duty</td><td>INL (3 projects), ANL (7 projects), NREL(2 projects)</td></tr>
<tr><td>Medium/Heavy Duty</td><td>ORNL (3 projects), NREL (3 projects)</td></tr>
<tr><td rowspan="2">Vehicle Simulation and Modeling</td><td>Light Duty</td><td>ANL (9 projects), NREL (2 projects), ORNL (3 projects)</td></tr>
<tr><td>Medium/Heavy Duty</td><td>ANL, NREL (3 projects), ORNL (2 projects)</td></tr>
<tr><td colspan="2">Component/Systems Evaluation</td><td>ANL (2 projects), ORNL(4 projects)</td></tr>
<tr><td colspan="2">Codes and Standards</td><td>ANL (7 projects), ORNL (2 projects) PNNL</td></tr>
<tr><td rowspan="4">Vehicle Systems Optimization</td><td>Aerodynamics</td><td>LLNL</td></tr>
<tr><td>Fast & Wireless Charging</td><td>INL, NREL, ORNL</td></tr>
<tr><td>Friction & Wear</td><td>ANL (2 projects)</td></tr>
<tr><td>Thermal Control</td><td>ANL (4 projects)</td></tr>
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4 Advanced Power Electronics and Electric Machines

The Advanced Power Electronics and Electric Motors (APEEM) activity provides support and guidance for many cutting-edge automotive technologies under development. It is focused on the requirement that an affordable electric traction drive system will need to attain weight, volume, and cost targets for the power electronics and electrical motors subsystems of the traction drive system. Its R&D areas include novel traction motor designs for increased power density and lower cost; inverter technologies with more efficient topologies; converter concepts for reduced component counts and integrated functionalities to decrease size, weight, and cost; new on-board battery charging concepts; more effective thermal control and packaging technologies; and integrated motor/inverter concepts.

The Advanced Thermal Management for Vehicle Power Electronics and Electric Motors research is focused on developing thermal management technologies that enable advanced power electronics and electric motor technologies that are efficient, small, light, low cost, and reliable. It includes thermal system integration, heat transfer technologies, and thermal stress/reliability studies. In addition, ORNL's Power Electronics and Electric Machinery Research Center conducts fundamental research, evaluates hardware, and provides other technical contributions to the APEEM activity.

Table 7 contains a short overview of the projects in each of the APEEM task areas. More detailed information on individual APEEM R&D projects is found in the APEEM Annual Progress Report [12]. The following are some of the recent significant APEEM accomplishments:

- Researchers at General Motors (GM) developed an integrated Electric Traction System (ETS) capable of 55kW peak power and 30kW of continuous power. GM was able to not only achieve the DOE 2010 targets but also achieve the 2015 targets for weight and volume (see Table 8).

Table 7: An overview of APEEM Research projects, FY 2011-2012 (from [12])

Project Area	Participants
Power Electronics Research and Technology Development	ORNL (8 projects) , ANL, SNL, PSU, NASA-Glenn, General Motors, Azure Dynamics, Delphi Automotive
Electric Motor Research and Technology Development	ORNL (2 projects), Ames Laboratory , General Electric, UQM Technologies
Systems Research and Technology Development	ORNL (2 projects), SBIR
Thermal Management Research and Technology Development	NREL (7 projects)
ARRA Awards (10 Awards)	Allison Transmission, Inc., Delphi Automotive Systems Ford Motor Co., General Motors Corp., KEMET Corp, Magna E-Car Systems of America, Inc., Powerex, Inc. Remy, Inc., SBE, Inc., UQM Technologies

Table 8: Technical Target vs. GM-ETS Results

Parameter	2010	GM
Cost ($/kW)	<19	<16
Specific power (kW/kg)	>1.06	>1.2
Power density (kW/L)	>2.6	>3.5
Efficiency (%)	>90%	>90%

- Using advanced packaging, capacitors, and cooling strategies, Delphi Automotive has developed a high temperature traction drive inverter. The inverter meets DOE 2015 power electronics targets with significant decreases in the cost, volume, and weight. NREL, in collaboration with UQM Technologies Inc., has designed a jet-impingement-based heat exchanger (see Figure 4) for a commercial inverter. The new heat exchanger has been shown by computation fluid dynamics (CFD) modelling to reduce the silicon device junction-to-coolant thermal resistance by at least 34%, and consequently increase power density by at least 52%, over a heat exchanger based on a conventional channel flow configuration.
- Researchers at Ames Laboratory are using computational materials discovery to further the pursuit of superior permanent magnetic (PM) materials that do not contain rare earth (RE) elements, which are quickly rising in global strategic importance. Ames has developed computational algorithms and codes to perform supercomputer assisted phase diagram exploration and materials structure prediction and discovery, especially for iron-based alloys. This breakthrough speeds up the search process by at least 1000 times, making it possible to perform accelerated computational studies to identify candidate chemical compositions and structures that have desirable properties.
- Oak Ridge National Laboratory (ORNL) researchers have utilized new reverse blocking semiconductor devices in a new topology called current-fed Z source inverter (ZCSI) which integrates the boost converter, inverter, and battery charger functionalities, improves fault tolerance, and substantially reduces capacitor requirements. The new design is capable of functioning as a universal charger for PHEVs allowing charging low-voltage and high-voltage batteries from single (120 V/240 V) or three-phase supplies (Figure 5). By incorporating all the three power electronics functions into a single module, significant advancements will be made in achieving the U.S. DRIVE targets in regards to reducing size, weight and costs.

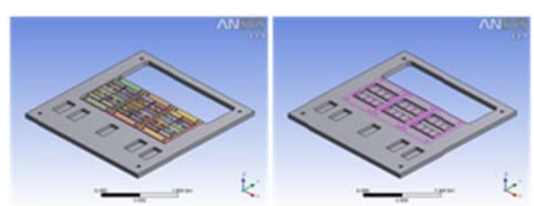

Figure 4: (Left) Delphi Automotives' three power modules in the inverter with the heat exchanger in place, and (Right) the jet-impingement manifold design.

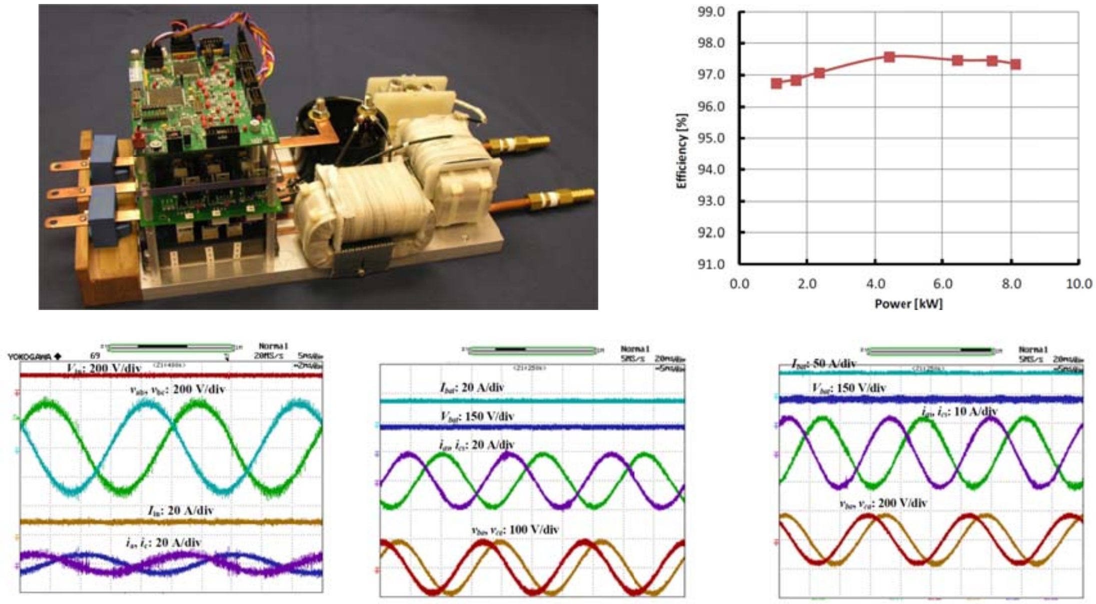

Figure 5: (Top) ORNL 10 kW ZCSI prototype (left) and Efficiency chart at V_{in}: 250 V (right);
(Bottom) Test waveforms for 3x voltage boost (left), charging in boost mode (middle) and in buck mode (right).

5 Conclusions

DOE Vehicle Technologies R&D activities for hybrid electric systems are focused on advanced batteries, power electronics and electric machines, and simulation and testing for transportation applications. They currently emphasize PHEVs. The past successful commercialization of DOE-funded batteries is a testimony to the success already achieved by the DOE-USABC cooperative program. Future advances in HES technologies will be leveraged with the progress in other enabling technologies (e.g., heat engines, lightweight materials, and fuels) to reach the challenging VTP goals. The Program will continue to reassess longer-term candidate technologies for propulsion systems promising performance, life, and cost benefits.

Abbreviations

3M: Minnesota Mining and Manufacturing Co.
ABR: Applied Battery Research
ANL: Argonne National Laboratory
APEEM: Advanced Power Electronics and Electric Machines
APRF: Advanced Powertrain Research Facility
ARPA-E: Advanced Research Projects Agency – energy
ARL: Army Research laboratory
ARRA: American Recovery & Reinvestment Act
BATT: Batteries for Advanced Transportation Technologies
BES: (DOE office of) Basic energy Sciences
BNL: Brookhaven National Laboratory
CFD: Computational fluid dynamics
CIA: Central Intelligence Agency
CWRU: Case Western Reserve University
DOE: (United States) Department of Energy
EDV: Electric drive vehicle
ETS: Electric traction system
EVS: Electric Vehicle Symposium
EVSE: Electric Vehicle Supply Equipment
FY: Fiscal year
GE: General Electric
GM: General Motors
HES: Hybrid and electric systems
HIL: Hardware-in-the-loop
HQ: Hydro-Quebek
IAPG: Interagency Advanced Power Group
IEA: International Energy Agency
IGBT: Insulated-Gate-Bipolar Transistor
INL: Idaho National Laboratory
JCI: Johnson Controls, Inc.
JCS: Johnson Controls-Saft
JPL: Jet Propulsion Laboratory
LBNL: Lawrence Berkeley National Laboratory
LEESS: Low-energy energy storage system
LLNL: Lawrence Livermore National Laboratory
MIT: Massachusetts Institute of Technology
MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor

NASA: National Aeronautics and Space Administration
NCSU: North Carolina State University
NREL: National Renewable Energy Laboratory
NRO: National Reconnaissance Office
NSWC: Naval Surface Warfare Center
OE: (DOE) office of electricity
ONR: Office of Naval Research
ORNL: Oak Ridge National Laboratory
PEV: Plug-in electric vehicle
PHEV: Plug-in hybrid electric vehicle
PM: Permanent magnet
PNNL: Pacific Northwest National Laboratory
PSAT: Powertrain Systems Analysis Toolkit
R&D: Research and development
RE: Rare earth
SAE: Society of Automotive Engineers
SBIR: Small Business Innovation Research
SNL: Sandia National Laboratories
SUNY: State University of New York
TRL: Technology readiness level
UCB: University of California, Berkeley
USABC: United States Advanced Battery Consortium
VSST: Vehicle and system simulation and testing
VT, VTP: Vehicle Technologies Program
ZCSI: Current-fed Z-source inverter

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