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An Overview of the Hybrid and Electric Systems R&D at the U.S.–DOE (FY 2015–2016)

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Summary

The U.S. Department of Energy (DOE) through its Vehicle Technologies Office (VTO), often in close partnership with industry, has supported the development/deployment of cleaner, more efficient automotive technologies with electric drive systems. This paper provides an overview of efforts to promote market adoption of hybrid electric vehicles (HEVs) and electric vehicles (EVs) in the U.S. and the associated VTO R&D and Deployment initiatives for accelerating this adoption. It also highlights the many significant research breakthroughs resulting from R&D in the hybrid vehicle systems areas of research (with particular emphasis on advanced electric drive technologies) funded directly by or in collaboration with VTO.

Keywords: EV, Electric Drive, Energy Storage, HEV, Battery

1 Introduction

This paper provides an overview of the Fiscal Years (FYs) 2015–2016 Hybrid and Electric Systems (HES) research and development (R&D) activities – with emphasis on its advanced electric drive research – funded by the Vehicles Technologies Office (VTO) of the U.S. Department of Energy (DOE). VTO spearheads the R&D needed for a new generation of electric-drive vehicles, following a comprehensive multi-year research program plan [1]. Its subprograms cover electric drive technologies (EDT), advanced batteries, and vehicle systems (VS). Status updates on the hybrid electric systems (HES) program R&D have been regularly provided at prior EVS meetings [e.g., 2-4]. VTO leverages significant resources to address the technical barriers that prevent the commercialization of electric drive vehicles (EDVs). VTO works with automakers and other industry stakeholders through partnerships such as the U.S. DRIVE (United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability) to fund high-reward/high-risk research and enable improvements in critical components to enable more fuel efficient and cleaner vehicles. As shown in Table 1, there is significant U.S. commitment to HES – and its FY 2016 budget of $166 million is nearly three times the size of its FY 2005 budget.

Table 1: Recent HES R&D budgets.

	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
HES Budget ($, Million)	$57.1	$55.6	$72.3	$92.1	$122.7	$142.3
	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016
HES Budget ($, Million)	$145.8	$164.9	$156.4	$148.3	$140.1	$166.4

2 Goals, Barriers, and Strategies

2.1 Goals and Technical Barriers

The commercialization of plug-in electric vehicles (PEVs) by making them cost-competitive with conventional internal combustion engine-powered vehicles requires reducing the production cost of market-ready, high-energy, high-power batteries by about 70% in the near-term and that of associated market-ready EDT systems by about 60% in the mid-term (compared with Year 2009 costs). Current technical targets for batteries, developed in collaboration with the United States Advanced Battery Consortium (USABC), are listed in the VTO multi-year program plan [1]. Additional performance targets, e.g., those for hybrid electric vehicles (HEVs), electric vehicles (EVs) and ultracapacitors are available at the website of the USABC [5] and are also listed in the VTO Energy Storage R&D annual progress report [6]. For the EDT and VS subprograms, the technical targets for peak power, costs, etc. can be found in the corresponding sections of the VTO multi-year program plan [1].

2.2 Strategies

DOE works with industry, academia, and national laboratories to support research on next-generation transportation technologies, including batteries and EDTs. In May 2011, it announced a cooperative research effort comprising of, in addition to DOE itself, the US Council for Automotive Research (which included automakers Ford Motor Company, General Motors Company, and Chrysler Group), Tesla Motors, and some representatives of the electric utilities and the petroleum industry. This cooperative effort is titled U.S. DRIVE and is aimed at developing public–private partnerships to fund high-risk–high-reward research into advanced automotive technologies. VTO utilizes a multi-pronged approach involving both near-term and long-term measures to meet its PEV goals. An example of its near-term measures includes its emphasis on clean energy initiatives like the 10-Year Vision Plan entitled *"EV Everywhere"* Grand Challenge which focuses on the domestic production of cost-competitive PEVs. In the long-term, VTO funds topic-specific R&D at national laboratories and cost-shares technology development by industry via development programs.

2.3 The *EV Everywhere* Grand Challenge

The "*EV Everywhere* Grand Challenge" is a DOE Energy Efficiency and Renewable Energy (EERE) office initiative for facilitating the market feasibility of PEVs, which envisions enabling U.S. innovators to rapidly develop and commercialize the next generation of technologies to achieve levels of cost, range, and charging infrastructure necessary for widespread PEV deployment. VTO collaborates with outside stakeholders and the DOE offices of Science, Electricity, and the Advanced Research Projects Agency–Energy (ARPA-E). The EERE-produced *EV Everywhere* Blueprint [7] describes the steps needed to meet its overall goals as well as additional technology-specific aggressive "stretch goals" developed in consultation with stakeholders across the industry. Figures 1 and 2 summarize the advancements necessary for the commercial feasibility of electric drive technology and batteries, respectively, in EDV applications.

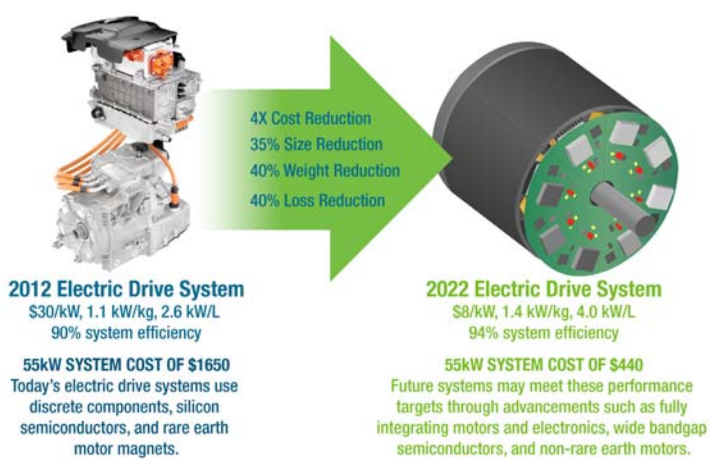

Figure 1: Electric drive advancements needed to enable a large market penetration of PEVs.

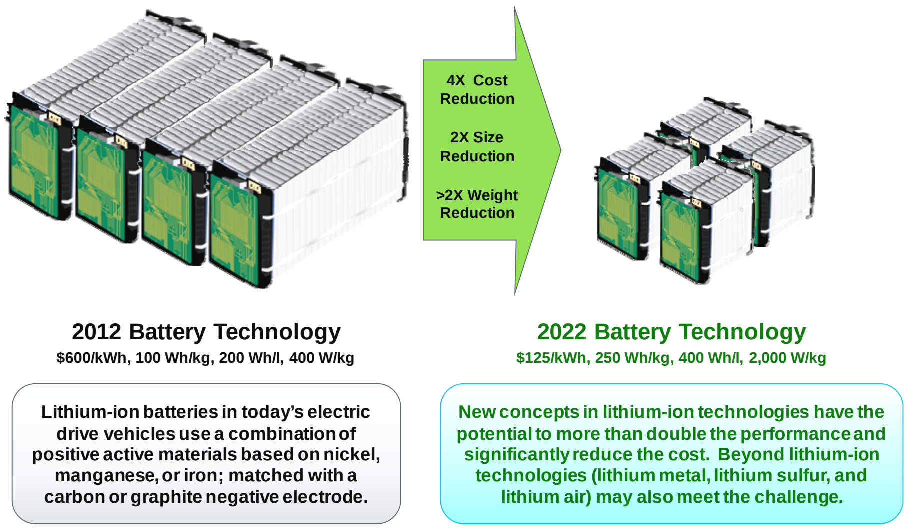

Figure 2: Battery advancements needed to enable a large market penetration of PEVs.

3 Electric Drive Technologies (EDT)

The EDT subprogram within VTO fosters the development of technologies that will significantly improve efficiency, costs, and fuel economy in support of the efforts of the U.S. DRIVE partnership. EDT provides support and guidance for many cutting-edge automotive technologies. A key requirement for making advanced vehicles practical is providing an affordable electric traction drive system (ETDS), by attaining weight, volume, efficiency, and cost targets for its power electronics (PE) and electric motor (EM) components. EDT R&D is focused on developing revolutionary new PE, EM, as well as other ETDS technologies that will leapfrog current technologies, leading to a lower cost and better efficiency in transforming battery energy to useful work. It is aimed at achieving a greater understanding of (and improvements in) the way the various new components of tomorrow's automobiles will function as a unified system to improve fuel efficiency. Its areas of development include: novel traction motor designs that result in increased power density and lower cost; inverter technologies that incorporate advanced wide bandgap (WBG) semiconductor devices to achieve a higher efficiency while accommodating higher-temperature environments and delivering higher reliability; converter concepts that leverage higher-switching-frequency semiconductors, nanocomposite magnetics, higher-temperature capacitors, and novel packaging techniques that integrate more functionality into applications offering reduced size, weight, and cost; new onboard battery charging electronics that build from advances in converter architectures for decreased cost and size; more compact and higher-performing thermal controls achieved through novel thermal materials and innovative packaging technologies; and integrated motor-inverter TDS architectures that optimize the technical strengths of the underlying PE and EM subsystems. Table 2 contains an overview of the current projects in each of the EDT task areas. More detailed information on individual EDT projects is found in the EDT Annual Progress Report [8].

4 Advanced Batteries R&D

The objective of the VTO battery R&D subprogram is to develop batteries which enable a large market penetration of electric vehicles. It focuses on overcoming technical barriers so as to obtain: (1) a significantly reduced battery cost, (2) increased battery performance (power, energy, and durability), (3) reduced battery weight & volume, and (4) increased battery tolerance to abusive conditions such as short circuit, overcharge, and crush. Current battery technology performs far below its theoretical limits. For example, in the near-term, with existing lithium-ion technology, there is an opportunity to more than double the battery pack energy density (from 100 Wh/kg to 250 Wh/kg) by using new high-capacity cathode materials, higher voltage electrolytes, and high capacity silicon or tin-based intermetallic alloys to replace the graphite anodes. Much more R&D is needed to achieve the performance and lifetime requirements for their use in PEVs. The VTO battery R&D subprogram includes five inter-related and complementary program elements: advanced battery development, battery testing, analysis, and design, applied battery research (ABR), manufacturing and process development, and advanced battery materials research (BMR).

Table 2: An overview of EDT research projects, FY 2015 (from [8])

Project Area	Project (Participant)	
Electric motor R&D	Non-rare earth motor	ORNL, GE, UQM Technologies, Ames Lab
	Motor design	ORNL, University of Wisconsin, Madison
	Electric motor thermal management	NREL
Power electronics R&D	Inverters	ORNL, GM
	Wide band gap technologies	ORNL (2 projects), APEI
	MOSFET technology	Cree, Inc.
	Innovative traction design	ORNL, University of Colorado, Boulder
	Power electronics thermal management	NREL
	Cost analysis	Sigma Technologies
	On-board charging	Delta Products
	Capacitors	ANL, GE
Benchmarking, testing, and analysis	Benchmarking	ORNL, NREL
	Supply chain analysis	Synthesis Partners
Advanced packaging R&D	ORNL, NREL	
EDT materials R&D	ORNL	

The *Advanced Battery Development* program element's goal is to support the development of a domestic advanced battery industry whose products can meet EDV performance targets. Such R&D focuses on, for example, the development of robust battery cells and modules to significantly reduce battery cost, increase life, and improve performance. Such R&D takes place in close partnership with the automotive industry, through a cooperative agreement with the USABC. The collaboration with USABC has resulted in developing battery and ultracapacitor requirements [5, 10] and test procedures [11, 12, and 13] for various vehicle types. In FY 2015, the USABC supported 9 cost-shared contracts with developers to further the development of batteries for PEVs and HEVs. In addition to co-funding USABC projects, DOE also often directly supports battery and material suppliers via contracts administered by the National Energy Technology Laboratory (NETL). In FY 2015, NETL managed 20 battery R&D contracts.

In the *Battery Testing, Analysis, and Design* program element, which complements the battery development program element, high level projects are pursued in such areas as performance, life and abuse testing of contract deliverables, and other activities. Battery technologies are evaluated according to USABC Battery Test Procedures. The manuals for the relevant PEV and HEV applications are available online [11, 12, and 13]. Benchmark testing of an emerging technology is performed to remain abreast of the latest technologies.

The *Applied Battery Research* (ABR) program element is focused on the optimization of next generation, high-energy lithium-ion electrochemistries that incorporate new battery materials. It identifies, diagnoses, and mitigates issues that impact the performance and lifetime of cells made from these advanced materials. It investigates the interaction between cell components (cathodes, anodes, electrolytes, binders, conductive additives, and separators) as they impact performance and life.

The *Battery Manufacturing and Process Development* program element complements ABR and involves R&D at the national labs on systematic material engineering and customized scaled processes to accomplish kilogram-level high quality material production, in-line analysis methods of quality control to detect electrode flaws and contaminants, and new techniques more amenable to high-throughput manufacturing. It also includes manufacturing process activities in partnership with industry.

The *Advanced Battery Materials Research* program element addresses fundamental issues of materials and electrochemical interactions associated with lithium batteries. It develops new and promising materials, uses advanced material models to discover additional such materials and to predict failure modes and scientific diagnostic tools and techniques to gain insight into why material and systems fail. It also studies issues critical to the realization of beyond lithium-ion technologies, such as solid state technology. Lithium metal systems, lithium sulfur, and lithium air.

Table 3 contains an overview of the projects in each of the battery project areas. More detailed information on individual battery R&D projects is found in the energy storage R&D annual progress report [6].

Table 3: An overview of EERE energy storage R&D projects in FY 2015 (from [6]).

Project Area	Project Topic	Participants
Advanced battery development	USABC battery develoment projects	Envia Systems, LG Chem Power (2 projects), Amprius, Seeo, Xerion ABC, Maxwell Technologies, Saft, AMTEK Research
	Advanced lithium battery cell technology	XALT Energy, OneD Material, 3M Company, PSU, DENSO
	Low-cost processing research	JCI, Miltec UV International, Applied Materials, Optodot Corporation, Navitas Advanced Solutions Group, LLC
Battery testing, analysis, and design	Cost assessments and requirements analysis	ANL (2 projects), NREL
	Battery testing activities	ANL, INL, SNL, NREL
	Battery analysis and design activities	NREL (5 projects), ORNL, SNL, EC Power
Applied battery research for transportation	Core and enabling support facilities	ANL (3 projects), SNL
	Critical barrier focus — enabling high energy, high voltage lithium-ion batteries	ANL (3 projects)
	Next-generation lithium-ion chemistries: "improvements in cell chemistry, composition, and processing"	ANL, 3M, Farasis Energy, Envia-LBNL-ORNL-GM, PSU, TIAX LLC
Battery manufacturing and process development	Process development and manufacturing R&D at national laboratories	ANL (2 projects), ORNL (2 projects), NREL
	Process development and manufacturing R&D with U.S. industry	24M Technologies, Lambda Technologies, Miltec UV International, Amprius, Parthian Energy, Sila Nanotechnologies
Advanced battery materials research (BMR)	Advanced electrode architectures	LBNL (3 projects), HydroQuebec, MIT
	Silicon anode research	PNNL, Stanford U, NREL
	High energy density cathodes for advanced lithium-ion batteries	ORNL (2 projects), Binghamton U, PNNL, BNL, ANL (2 projects), UTA (2 projects), LBNL
	Electrolytes for high voltage, high energy lithium-ion batteries	ANL
	Diagnostics	LBNL (3 projects), BNL, PNNL, ANL, U Cambridge, UCSD, UC Berkeley
	Modelling advanced electrode materials	LBNL (2 projects), MIT, TAMU, GM, MSU, BYU
	Metallic lithium and solid electrolytes	ORNL (2 projects), University of Michigan, University of Maryland, Stanford University, PNNL, Daikin America, Wildcat Discovery Technologies
	Lithium sulfur batteries	U Pittsburgh, LBNL, ANL, BNL, PNNL, Stanford U, TAMU
	Lithium-air batteries	PNNL, Liox Power, ANL, BNL, UWM
	Sodium-ion batteries	BNL

VTO also funds *Small Business Innovation Research* (SBIR) projects in the battery area, and also maintains coordination in battery R&D across DOE and with other government agencies. It coordinates such efforts with the DOE Office of Science, the DOE Office of Electricity, and the ARPA-E, the Interagency

Advanced Power Group (IAPG), the Department of Transportation/National Highway Traffic Safety Administration (DOT/NHTSA), the Environmental Protection Agency (EPA), and the United Nations Working Group on Battery Shipment Requirements. International collaboration occurs through the International Energy Agency's (IEA's) Implementing Agreement on Hybrid Electric Vehicles (IA-HEV), the eight-nation Electric Vehicle Initiative (EVI), and the Clean Energy Research Center (CERC) bilateral agreement between the U.S. and China.

5 Vehicle Systems (VS)

The VS mission is to accelerate the market introduction and penetration of advanced vehicles and systems that significantly impact petroleum displacement, GHG reduction, and vehicle electrification goals. VS performs systems engineering to develop and evaluate advanced vehicle systems and infrastructure. In support of VTO technology target requirements analysis, VS tools are used to predict vehicle-level and national-level energy and environmental performance metrics (including petroleum use, infrastructure economics, and greenhouse gas emissions). In support of parasitic load reduction technology design and development the tools are used to predict energy savings from novel approaches and new technologies. VS performs benchmarking of advanced vehicles and component technologies to evaluate the potential for significant improvements over current technologies. VS works with industry partners to accurately measure real-world performance of advanced technology vehicles using a testing regime developed in partnership with industry stakeholders. Baseline performance testing, fleet testing and accelerated reliability testing are carried out. Table 4 contains an overview of projects in each of the VS project areas for FY 2015. Detailed information on individual VS projects appears in the current VS Annual Progress Report [9].

VS groups its projects into focus areas that implement its systems engineering processes. In FY 2015, these focus areas were vehicle modelling and simulation, vehicle technology evaluations, codes and standards, industry projects, and vehicle systems efficiency improvements. Projects within each focus area typically produce outputs in one or more of the following forms: system designs, vehicle demonstrations, data, analysis, reports, tools, specifications, and procedures. As is typical of systems engineering work, the outputs from one task are often used as the inputs for one or more tasks in other focus areas. The performance of systems engineering addressing integrated vehicle systems performance for vehicle classes from light-duty (LD) to heavy-duty (HD) is unique to the VS program and critical to the VTO mission.

Table 4: An Overview of Vehicle Systems projects in FY 2015 (from [9])

Project Area	Project Topic	Participants
Industry Awards	Advanced vehicle testing & evaluation (AVTE)	Intertek Testing
	Wireless power transfer	ORNL, Hyundai America
	Thermal load reduction	MAHLE Behr Troy (2 projects), Hanon Systems, NREL
	Powertrain	Eaton Corp (2 projects)
	Friction and wear	Ricardo Inc.
	SuperTruck	Navistar, Daimler Trucks, Volvo
	Tires	Goodyear, PPG Industries
	Zero emission cargo transport	South Coast AQMD (2 projects), Houston-Galveston Area Council
Vehicle technology evaluations		ANL, INL, ORNL, NREL (11 projects)
Modelling and simulation		ANL (8 projects), NREL (5 projects), ORNL (2 projects)
Codes and standards		ANL (2 projects), INL, ORNL, PNNL
Vehicle systems efficiency improvements		ANL (5 projects), INL (2 projects), LBNL, NREL (2 projects), ORNL (3 projects),

6 Recent Highlights

The following is a brief summary of key highlights for HES-funded R&D technical accomplishments resulting from R&D funded by HES. Greater details on each project (as well as on other projects not listed here) are available in the VTO annual progress reports for the corresponding subprogram [see 6, 8, or 9].

6.1 Electric Drive Vehicle Market

6.1.1 U.S. Electric Drive Vehicle Sales

The U.S. represents the world's leading market for EVs and is producing some of the most advanced PEVs available today. Consumer excitement and interest in PEVs is growing, with sales continuing to increase, despite the recent drop in gasoline prices. In 2012, PEV sales in the U.S. tripled, with more than 50,000 cars sold. In 2013, PEV sales increased by 85% with over 97,000 vehicles sold. In 2014, PEV sales further increased by 20%, with annual sales of over 118,000 PEVs. In 2015, PEV sales remained steady with annual sales of 115,000 PEVs, even though oil prices have remained relatively low for the whole year.

6.1.2 Commercial Applications of DOE-supported Technologies

The 2015 DOE PEV Battery Cost Reduction Milestone of $275/kWh has been accomplished. DOE-funded research has helped reduce the current cost projection (from three DOE-funded battery developers) for a 40-mile range PHEV battery (PHEV-40 battery) to an average $264 per kilowatt-hour (of useable energy). This cost projection is derived by using the value for material costs and cell and pack designs as provided by those developers, which are then input into ANL's peer-reviewed public domain model "Battery Production and Cost (BatPaC)". The cost projection assumes a production volume of at least 100,000 batteries per year. The battery cost is derived for batteries that meet DOE/USABC system performance targets. The battery development projects usually focus on high voltage and high capacity cathodes, advanced alloy anodes, and processing improvements. DOE's goals are to continue to drive down battery cost to $125/kWh by 2022.

6.2 Electric Drive Technologies

6.2.1 Ribbon Electrical Interconnects to Enable Increased Current Density in Power Electronics

NREL, in collaboration with Kulicke & Soffa, confirmed that ribbon electrical interconnects display good reliability and allow for high-current-density power electronics packaging. A transition from round wire interconnects to ribbon interconnects allows for higher current densities, lower parasitic inductances, and lower loop heights. This transition is essential for the larger transition to wide bandgap devices. An insulated gate bipolar transistor (IGBT) with wire interconnects from a 2012 Nissan Leaf inverter is shown in Figure 3. A representation of ribbon interconnects at equivalent current density results in a 40% reduction in required bondable area.

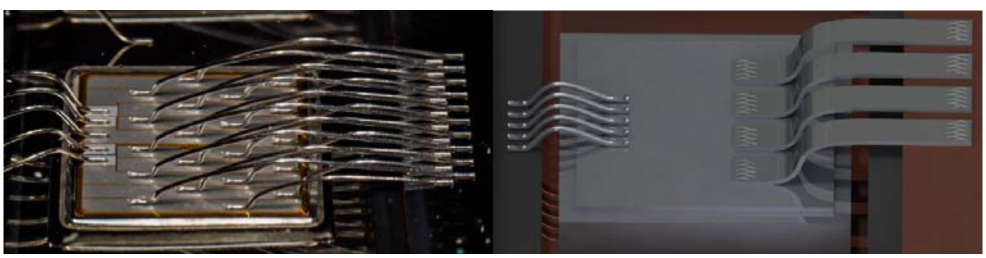

Figure 3: IGBT with wire interconnects (left) and ribbon interconnects (right).

Ribbon interconnects exhibited similar reliability to wire interconnects under thermal aging, cycling, and corrosion tests. Minimizing span length is key to maximizing the lifetime of ribbon interconnects under vibration conditions. This work validates and supports the shift to ribbon interconnects as a route to enable high-current-density packaging and wide-bandgap-device-based components.

6.2.2 Thermal Stackup to Enable the Full Potential of WBG Devices

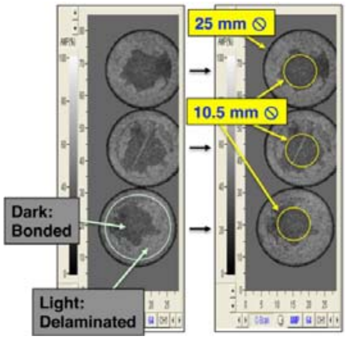

Figure 4: Scanning acoustic microscopy images of delaminated sintered-Ag interconnects. Dark patches represented undelaminated bonding. ORNL and NREL are using such analysis to improve understanding of sintered-Ag reliability.

The power module is the heart of power electronics and its thermal stack up is the second most important determining factor in performance and second only to the device itself. Joints of the thermal stack up are critical to reliability and thermal performance. Current state-of-the art interconnects are primarily soldered or brazed. New sintered-silver technology holds promise, but the ability to consistently and effectively create them is not well understood. The goal of this ORNL research, funded jointly with VTO's propulsion materials program, is to determine all the elements needed to produce a consistent and reliable sintered joint. One pathway to hasten sintered-silver utilization is to fundamentally prove its anticipated higher reliability. ORNL developed custom sintered test coupons whose thermal cycling testing are providing needed data for this (Figure 4). ORNL is processing and characterizing the sintered-Ag coupons while NREL is performing thermal cycling (e.g., -40 to 170°C) to excite failure mechanisms.

6.2.3 Integrated WBG Onboard Charger and DC-DC Converter

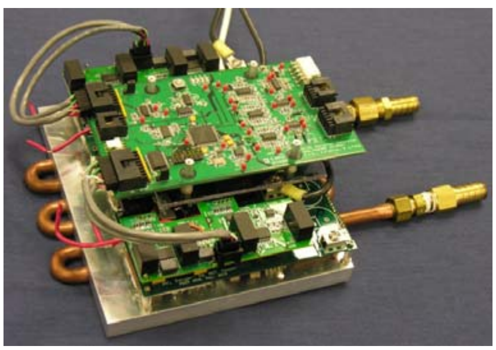

Figure 5: A 6.8 kW SiC charger converter with a built-in 2 kW 14V buck converter tested in an integrated SiC bidirectional OBC with a 100 kW segmented traction inverter.

Stand-alone onboard battery chargers (OBC) and 14V DC-DC converters used in current PEVs are bulky, costly and have a relatively low efficiency (85-92%) due to limitations of current semiconductor and magnetic materials. This project leapfrogs the present silicon (Si) -based charger technology by using WBG silicon carbide (SiC) devices; advanced magnetic materials; and a novel integrated charger architecture and control strategy. ORNL has developed a new bidirectional integrated OBC and DC-DC converter architecture that reduces the number of components significantly (a 47% reduction in power circuit components alone, not counting savings in the gate driver and control logic circuits, translating to 50% reduction in cost and volume compared to existing standalone OBCs). ORNL has built and tested an all-SiC 6.8 kW bidirectional OBC prototype that integrates a 6.8 kW isolation converter into a 100 kW segmented traction inverter (Figure 5). ORNL has also developed a control strategy for the charger isolation converter to reduce the battery ripple current of twice the AC main.

6.2.4 Next Generation Inverters

Figure 6: The next generation inverter prototype.

GM collaborated with ORNL, NREL, and some other technology and equipment suppliers to develop its next generation inverter which achieved DOE's 2020 traction inverter power density target of 13.4kW/L and specific power target of 14.1kW/kg. Further, scaled up to its highest power configuration, it was projected to meet DOE's 2020 cost target of $3.30/kW with 100,000 units annual volume (assuming GM's internal cost targets for the components and other manufacturing targets could be achieved). The performance of the inverter prototype (Figure 6) was verified under active load in GM's dynamometer lab. Figure 7 shows the inverter efficiency maps in motoring and regeneration.

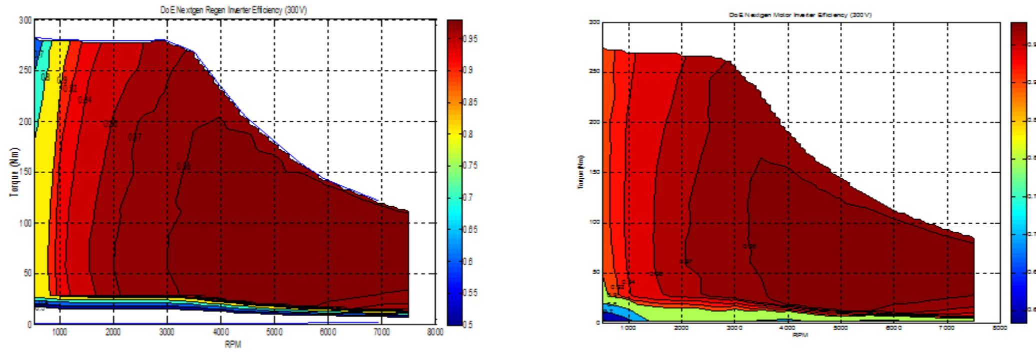

Figure 7: Next generation inverter efficiency map during regeneration (left) and motoring (right).

6.3 Advanced Batteries

6.3.1 Commercial Applications

Several technologies developed under partially VTO-sponsored projects have moved into commercial applications. HEVs on the market from BMW and Mercedes are using lithium-ion technology developed under DOE projects with Johnson Controls Inc. (JCI). JCI will also supply such batteries to Land Rover for hybrid drive sport utility vehicles. Also, lithium-ion battery technology developed at LG Chem partially with DOE funding of a USABC project is being used in GM's Chevrolet Volt extended-range electric vehicle (EREV), the Cadillac ELR EREV, the Chevy Bolt EV, and the Ford Focus EV battery. LG Chem will also supply lithium-ion batteries to Eaton for hybrid drive heavy vehicles.

6.3.2 Novel and Inexpensive Manufacturing Process

24M is developing a novel and inexpensive manufacturing process that requires fewer unit operations for a higher process yield and results in electrode and stacked cell fabrication taking 80% less time compared to conventional methods. The semisolid electrodes require no drying activity and no organic solvents. The process is able to make thick electrodes (200-1,000 microns), increasing the energy density and potentially reducing the cost of stacked cells. Their enhanced areal capacity (i.e., the amount of capacity/energy stored per unit area of the electrode) is two to four times higher than conventional electrodes.

6.3.3 Next Generation Battery Materials

ANL teamed with Strem Chemicals, a manufacturer/distributor of specialty chemicals, to develop certain next-generation battery materials. Strem licensed 23 separate intellectual property (IP) items from ANL and will distribute 9 battery solvents and additives via its own networks. All materials were invented at ANL's Electrochemical Energy Storage Center and scaled at its Materials Engineering Research Facility (MERF).

6.3.4 Internal Short Circuit (ISC) device

NREL developed and patented an internal short circuit (ISC) device to emulate defects that cause short-circuits and thermal runaway failure in lithium-ion cells. The intent of the device is to enhance the design of lithium-ion batteries by testing ISC effects. The device is made from small discs of copper and aluminum, a copper puck, separator, and thin layer of wax and it can be placed in any location within a cell to produce four different types of shorts. Upon implantation in a cell, heating melts the wax layer, which is wicked away, allowing the metal components to come into contact and induce an ISC. NREL delivered over 300 ISC devices to NASA and some industry partners for evaluating abuse tolerance of new cell designs and materials. (See Figure 8.)

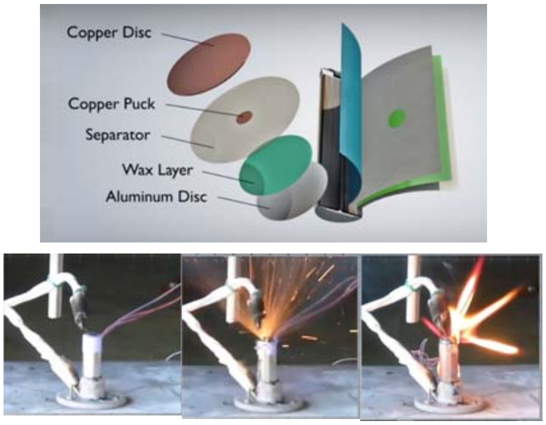

Figure 8: Top: Components of ISC device that can be placed anywhere in a cylindrical or prismatic cell. Bottom images left to right: A lithium-Ion cell with ISC device, a few minutes after melting the wax, and going into thermal runaway.

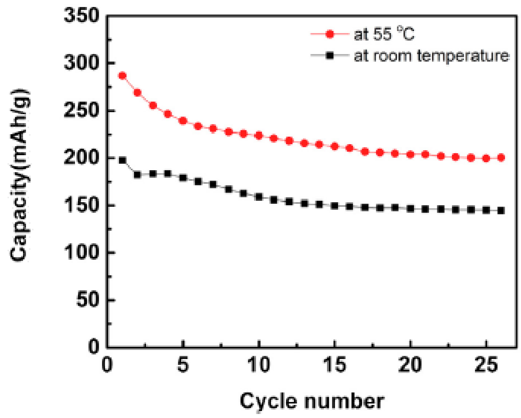

Figure 9: Discharge capacity of $Li_{1.25}Nb_{0.25}Mn_{0.5}O_2$. vs Li metal half cells cycled at 55 °C and room temperature versus cycle number

6.3.5 Variable Frequency Microwave (VFM) Drying Technology

Lambda Technologies is developing variable frequency microwave (VFM) drying technology which employs penetrating energy that selectively targets the solvent in the entire volume of the wet electrode. (In contrast, convection dryers only heat the electrode surface and solvent removal proceeds layer by layer which takes much longer.) VFM is estimated to result in a 30-50% reduction in the operating cost of the electrode drying procedure. This process has been applied to NMC electrodes placed into graphite/NMC cells by the partner, Navitas Systems. The cycle life for these cells was not any different from those from traditional drying. In addition, this technique would potentially permit the drying of much thicker electrodes than at present.

6.3.6 New Disordered Rock-Salt Material with Lithium-excess

MIT designed, prepared, and tested a new disordered rock-salt material with lithium-excess, $Li_{1.25}Nb_{0.25}Mn_{0.5}O_2$. It shows a high capacity of 287 mAh/g and specific energy density of 909 Wh/kg (vs. 650Wh/kg for the best current cathodes) in the first cycle at 55°C. Combined *in situ* x-ray diffraction (XRD) and electron energy loss spectroscopy (EELS) measurements indicate that Mn and O both reversibly contribute to the charge transfer with oxygen providing almost half of that capacity. Together with previous work on understanding lithium transport in lithium-excess and disordered materials, this material is an important new direction to create high capacity cathode materials. (See Figure 9.)

6.3.7 High-capacity Prelithiation Reagent

Stanford University developed Li_xSi-Li_2O core-shell nanoparticles (NPs) as a high-capacity prelithiation reagent to compensate the first cycle irreversible capacity loss of various anode materials, such as Si. Li_xSi NPs were synthesized by mechanical stirring of a mixture of Si NPs and lithium metal at elevated temperature inside argon atmosphere. A dense passivation layer is formed on the Li_xSi NPs after exposure to trace amounts of oxygen, preventing the Li_xSi from further oxidation in dry air. First cycle voltage profiles of Si NPs/Li_xSi-Li_2O composite and Si NPs show that the incorporation of this prelithiation reagent compensates the capacity loss of Si NPs. The composite shows an initial loss of only 10%, whereas the Si NPs show an initial loss of 30%. (In full cells, that initial loss of lithium must be compensated by excess cathode, which effectively reduces the cell energy.)

6.3.8 DOE R&D Funding Awards

In January 2015, DOE released a funding opportunity announcement (FOA) that solicited proposals in the areas of advanced light-weighting, advanced battery development, power electronics, advanced combustion technology, and natural gas utilization in transportation. In September 2015, DOE announced the selection of 24 new projects (worth nearly $55 million) to develop and deploy cutting-edge vehicle technologies that will strengthen the U.S. clean energy economy. Through the Advanced Vehicle Power Technology Alliance with DOE, the Department of the Army is contributing an additional $2.26 million in co-funding to projects focused on battery modelling technologies and computational fluid dynamics. Specifically, in the area of advanced batteries, 10 projects totaling $26.1 million were awarded for existing and next-generation battery material manufacturing processes, advances in electrode and cell fabrication manufacturing, and electric drive vehicular battery modelling for commercially available software. In January 2015, VTO issued an "Incubator" FOA, which would support innovative technologies and solutions that could help meet existing goals that are not represented in a significant way in the EERE offices' existing Multi-Year Program Plans (MYPPs) or current R&D portfolios. In august 2015, 8 new "incubator" projects (worth $10.4 million) were selected, of which 3 projects were in the advanced battery area (worth $3.3 million).

6.4 Vehicle Systems

A partial snapshot of VS project highlights for FY 2015 is provided in Table 5. These accomplishments are intermediate steps to realizing the potential real world benefits of advanced vehicle systems technologies. More detailed information on those projects appears in the subprogram's annual progress report [9].

Table 5: FY 2015 VS Selected Accomplishment Highlights (partial table, extracted from [9])

R&D Team member	Accomplishment	Significance
Daimler Trucks	SuperTruck project team demonstrated 115% improvement in vehicle freight efficiency (12.2 mpg average).	Far exceeded the SuperTruck Project's goal to improve freight efficiency by 50%.
INL	Published PEV and Infrastructure Analysis Report addressing driving and charging behaviour throughout the U.S., and five multi-year demonstrations of PEVs and charging infrastructure.	Analysis of the largest PEV and charging infrastructure demonstrations ever conducted (2010-2015).
INL	Completed first-of-a-kind benchmark testing on the efficiency and power quality of plug-in electric vehicle charging systems.	Help industry accelerate vehicle and charging equipment product development and understand potential impacts of vehicle/grid power quality interaction.
NREL	Prototyped a novel big data analytical methodology to estimate fuel savings of 'off-cycle' technologies.	Facilitates adoption of fuel and CO2 reduction technologies. This methodology provides a way to objectively quantify the aggregate benefit of such technologies to inform claims for new earned 'off-cycle' credits.
ANL	Developed and demonstrated a Common Integration Platform (CIP), a universal electronic module with embedded open source software to connect EVSE and other devices to the grid.	The CIP is an enabling technology to support grid integration studies. The studies will demonstrate it as a common interface for communication between and integrated control of grid-connected devices.
ANL	Invented several test method approaches for finding the maximum powertrain power for a wide variety of vehicle configurations.	Public and independent data to support the SAE Vehicle Powertrain Power Rating Standard.

7 Conclusions

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

References

[1] Vehicle Technologies Office, *Vehicle Technologies Multi-Year Program Plan, 2011-2015* http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf, accessed 2016-03-18.

[2] Howell, D., *An Overview of Current U.S. DOE Hybrid Electric Systems R&D Activities*, the 28th International Electric Vehicle Symposium and Exhibition (EVS28), Goyang, Korea, May 3-6, 2015.

[3] Howell, D., *Current Fiscal Year (2012 – 2013) Status of the Hybrid and Electric Systems R&D at the U.S. – DOE*, the 27th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium (EVS27), Barcelona, Spain, November 17-20, 2013.

[4] Howell, D., *Hybrid and Electric Systems R&D at DOE: Fiscal Year 2011-2012 Status*, the 26th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium (EVS26), Los Angeles, California, May 6-9, 2012.

[5] U.S. Council for Automotive Research, *USABC Goals and Requirements*, http://uscar.org/guest/article_view.php?articles_id=85, accessed on 2016-03-18.

[6] Vehicle Technologies Office, *Energy Storage R&D, Fiscal Year 2015 Annual Progress Report*, U.S. Department of Energy, Washington, DC, March 2016.

[7] *The EV Everywhere Grand Challenge Blueprint*, http://energy.gov/eere/vehicles/downloads/ev-everywhere-grand-challenge-blueprint, accessed on 2016-03-18.

[8] Office of Vehicle Technologies, *Electric Drive Technologies R&D, Fiscal Year 2015 Annual Progress Report*, U.S. Department of Energy, Washington, DC, March 2016.

[9] Office of Vehicle Technologies, *Vehicle Systems R&D, Fiscal Year 2015 Annual Progress Report*, U.S. Department of Energy, Washington, DC, March 2016.

[10] U.S. Council for Automotive Research, *USABC Manuals*, uscar.org/guest/article_view.php?articles_id=86, accessed on 2016-03-18.

[11] United States Advanced Batteries Consortium, *USABC Electric Vehicle Battery Test Procedure Manual, Rev. 2*, U.S. D.O.E., DOE/ID 10479, January 1996., http://avt.inl.gov/battery/pdf/usabc_manual_rev2.pdf

[12] U.S. Department of Energy, *PNGV Battery Test Procedures Manual, Rev. 2*, August 1999, DOE/ID-10597, http://avt.inl.gov/battery/pdf/pngv_manual_rev3b.pdf

[13] U.S. Council for Automotive Research, *RFP and Goals: Advanced Battery Development for PEVs*, http://www.uscar.org/, accessed on 2016-03-18.

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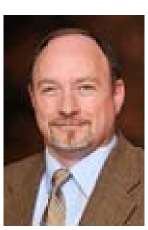

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