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Introduction

Vehicle Technologies Office Overview

Automotive Battery R&D Overview

I. INTRODUCTION

I.A Vehicle Technologies Office Overview

The Department of Energy's (DOE's) Vehicle Technologies Office (VTO) develops advanced transportation technologies that would reduce the nation's use of imported oil. Technologies supported by VTO include electric drive components such as advanced energy storage devices (batteries and ultracapacitors), power electronics and drive motors, advanced structural materials, advanced combustion engines, and fuels.[1] VTO is focused on funding high-reward/high-risk research by national laboratories, universities, and industry partners promising improvements in critical components needed for more fuel efficient (and cleaner) vehicles.

VTO works with U.S. automakers through the United States Council for Automotive Research (USCAR)—an umbrella organization for collaborative research consisting of Chrysler LLC, the Ford Motor Company, and the General Motors Company.[2] Collaboration with automakers through the US DRIVE (Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability) Partnership enhances the relevance and the success potential of such programs.

During the past year, the U.S. government continued its strong R&D support of plug-in electric vehicles (PEVs) such as plug-in hybrids, extended range electric vehicles and all-electric vehicles. Earlier, in March 2012, President Obama announced the *EV Everywhere* Grand Challenge. One of its primary objectives is to enable U.S. innovators rapidly develop/commercialize the next generation of technologies achieving the cost, range, and charging infrastructure necessary for widespread adoption of PEVs. Their significant penetration into the transportation sector would reduce our dependence on foreign oil and any negative economic impacts associated with crude oil price fluctuations, as well as our greenhouse gas emissions.

An important step for the electrification of the nation's light duty transportation sector is the development of more cost-effective, longer lasting, and more abuse-tolerant PEV batteries. In fiscal year 2013 the DOE VTO battery R&D funding totaled nearly $88 million. R&D continued to focus on the development of high-energy batteries for PEVs and very high power devices for hybrid vehicles. This document summarizes the progress of VTO battery R&D projects supported in FY 2013. An electronic version of this report can be accessed at http://www1.eere.energy.gov/vehiclesandfuels/resources/fcvt_reports.html.

I.B Vehicle Technologies Battery R&D Overview

I.B.1 DOE Battery R&D Goals and Technical Targets

The *EV Everywhere* Grand Challenge[3] establishes a vehicle-level framework in which the technological progress toward achieving the Grand Challenge objectives can be evaluated. To meet those objectives, batteries, power electronics, motors, lightweight materials and vehicle structures must see dramatic advances. Performance and cost targets have been established for all the key technical areas associated with a PEV. Achieving those targets will meet the needs for a range of vehicle types including plug-in hybrids as well as short and long range all-electric vehicles. Some of the technology

[1] See http://www1.eere.energy.gov/vehiclesandfuels/ for more information.

[2] For more information, please see http://www.uscar.org/guest/view_partnership.php?partnership_id=1.

[3] For more information, please see http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/ev_everywhere.html.

targets, derived from modeling and hardware-in-the-loop simulations of batteries operating in PEVs under multiple drive cycles, are shown in Figure I - 1.

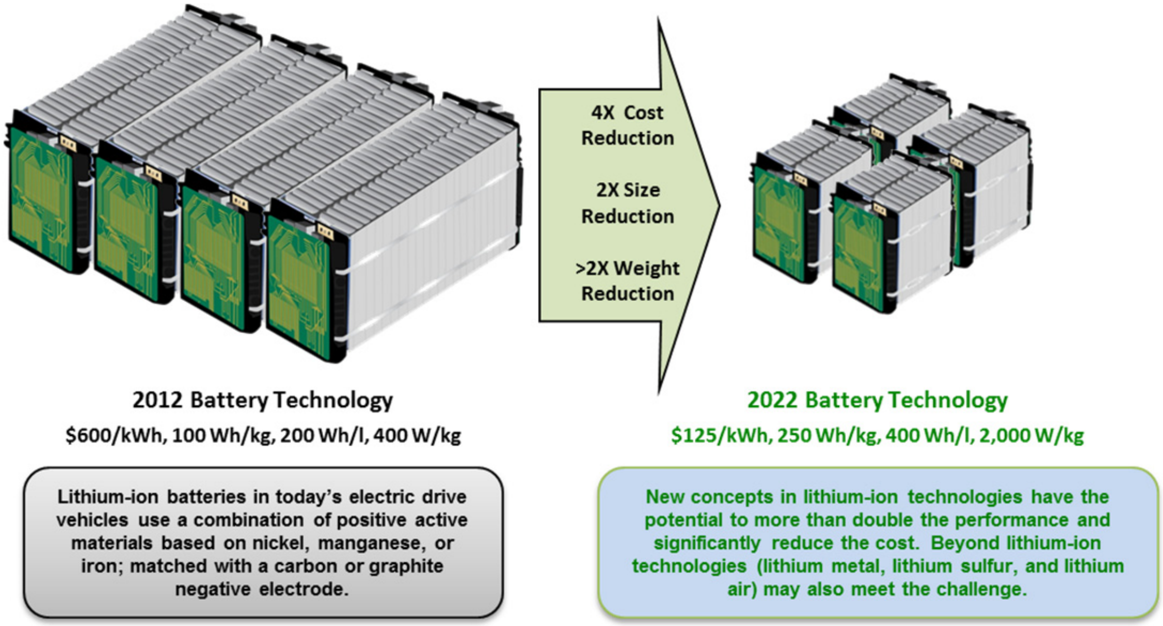

Figure I - 1: Battery advancements needed to enable a large market penetration of PEVs

I.B.2 DOE Battery R&D Plans

The objective of the VTO battery R&D effort is to advance the development of batteries to enable a large market penetration of hybrid and electric vehicles. Program targets focus on overcoming technical barriers to enable market success and they include: (1) significantly reducing battery cost, (2) increasing battery performance (power, energy, durability), (3) reducing battery weight & volume, and (4) increasing 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 (2012-2017), 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 graphite anodes. Despite recent promising advances, much more R&D is needed to achieve the performance and lifetime requirements for deploying those advanced technologies in PEVs.

In the longer term (2017-2027), battery chemistries "beyond Li-ion", such as lithium-sulfur, magnesium-ion, zinc-air, lithium-air, and certain other advanced chemistries; offer the possibility of specific energy levels significantly greater than those for current lithium-ion batteries and they also have the potential of greatly reducing battery cost. However, major shortcomings in cycle life, power density, energy efficiency, and/or other critical performance parameters, including cost, currently hinder commercial introduction of state-of-the-art "beyond Li-ion" battery systems. Therefore, some kind of innovative breakthroughs would be needed for those new battery technologies to enter the market.

The energy density increases described above are critical to achieving the *EV Everywhere* cost and performance targets. Additional R&D efforts, including those related to pack design optimization and simplification, manufacturing improvements at cell/pack levels, production cost reduction for battery materials, and novel thermal management technologies will also help reduce battery cost. The major associated technical challenges and potential solutions to those challenges are listed in Table I - 1.

Table I - 1: Major Li-ion technology technical challenges and potential pathways to address them

Barrier/Challenge	Potential Solutions
• Reduce the cost and improve the performance of lithium-ion battery technology	• Improved material and cell durability • Improved energy density of active materials • Reduction of inactive material • Improved design tools/design optimization • Improved manufacturing processes
• Develop higher energy battery technology such as next generation lithium ion, lithium-sulfur and lithium-air ○ Issues with these materials include poor cycle life, low power, low efficiencies, and safety	• Improved electrolyte/separator combinations to reduce dendrite growth for Li metal anodes • Advanced material coatings • New ceramic, polymer, and hybrid structures with high conductivity, low impedance, and structural stability
• Improve abuse tolerance performance of battery technology	• Non-flammable electrolytes • High-temperature melt integrity separators • Advanced materials and coatings • Improved understanding of reactions • Battery cell and pack level innovations such as improved sensing, monitoring, and thermal management systems

I.B.3 Energy Storage R&D Programmatic Structure

The energy storage effort includes multiple activities, ranging from focused fundamental materials research to battery cell and pack development and testing. The R&D activities can involve either short-term directed research by commercial developers and national laboratories or exploratory materials research generally spearheaded by the national laboratories and universities. These consist of four major program elements which are inter-related and complementary, namely:

- Advanced Battery Development.
- Battery Testing, Analysis, and Design.
- Applied Battery Research (ABR).
- Focused Fundamental Materials Research, or Batteries for Advanced Transportation Technologies (BATT).

The *Advanced Battery Development program*'s goal is to support the development of a domestic advanced battery industry whose products can meet electric drive vehicle performance targets. Such R&D activity focuses, for example, on the development of robust battery cells and modules to significantly reduce battery cost, increase life, and improve performance. It takes place in close partnership with the automotive industry, through our cooperative agreement with the United States Advanced Battery Consortium (USABC). DOE works in close collaboration with USABC to develop battery and ultracapacitor requirements for various vehicle types[4] and test procedures.[5] In FY 2013, the USABC supported

[4] See http://www.uscar.org/guest/article_view.php?articles_id=85

[5] See http://www.uscar.org/guest/article_view.php?articles_id=86

9 cost-shared contracts with developers to further the development of batteries for PEVs and HEVs. Also, DOE often works directly with battery and material suppliers via National Energy Technology Laboratory (NETL) contracts. In FY 2013, NETL managed 14 battery R&D contracts. Chapter III focuses on the battery development program.

The Battery Testing, Analysis, and Design activity supports certain complementary aspects of the battery development program. The high-level projects pursued in this area include cost modeling; secondary and other energy storage use and life studies; analysis of the recycling of core materials; requirements analysis for PEVs and HEVs; performance, life and abuse testing of contract deliverables, those of laboratory and university developed cells, and also those of benchmark systems from industry; thermal analysis, thermal testing and modeling; development of new test procedures and maintenance of current test procedures; and finally the development of tools for computer aided engineering of batteries. Battery technologies are evaluated according to USABC Battery Test Procedures. The manuals for the relevant PEV and HEV applications are available online.[6,7,8] A benchmark testing of an emerging technology would be performed to remain abreast of the latest industry developments. Within this report, Chapter IV focuses on the *Battery Testing, Analysis, and TestingDesign* activity.

The *Applied Battery Research* (ABR) activity is focused on the optimization of next generation, high-energy lithium-ion electrochemistries that incorporate new battery materials. Its emphasis is on identifying, diagnosing, and mitigating issues that impact the performance and life of cells containing advanced materials. It investigates interaction between all cell components (including the cathode, anode, electrolyte, binders, conductive additives, and separator) which impact performance and life. Typical issues associated with incorporating new material developments into working PEV cells can include: (1) inadequate power capability needed to meet the requirements of PEVs, (2) insufficient cycle life stability to achieve the 1,000 to 5,000 "charge-depleting" deep discharge cycles, and (3) poor performance at lower temperatures. It is conducted by a team which is headed by the Argonne National Laboratory (ANL) and includes five other national labs and several universities. Chapter V lists all the projects under the Applied Battery Research activity.

The *Focused Fundamental Materials Research* activity, also called the Batteries for Advanced Transportation Technologies (BATT) activity, addresses fundamental issues of materials and electrochemical interactions associated with lithium batteries. It attempts to develop new and promising materials, to use advanced material models to discover new materials and predict failure modes, and scientific diagnostic tools and techniques to gain insight into why material and systems fail. Battery chemistries are monitored continuously with periodic substitution of more promising components based on advice from within this activity, from outside experts, and from the 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. The program is also studying issues critical to the realization of beyond Li-ion technologies. Two of the most promising such technologies are Lithium/Sulfur and Lithium/Air. Some of the main areas of focus are to devise new methods to understand and stabilize lithium metal anodes; to contain Li polysulfides to enable the use of sulfur cathodes; and to develop electrolytes that support Li air and Li/sulfur cells. Chapter VI lists all the projects which are part of the Focused Fundamental Research activity.

Several *Small Business Innovation Research* (SBIR) contracts are also supported by VTO, in addition to the R&D described above. SBIR projects have been the source of new ideas and concepts. These SBIR projects are focused on the development of new battery materials and components.

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[6] United States Advanced Batteries Consortium, USABC Electric Vehicle Battery Test Procedure Manual, Rev. 2, U.S. Department of Energy, DOE/ID 10479, January 1996.

[7] U.S. Department of Energy, PNGV Battery Test Procedures Manual, Rev. 2, August 1999, DOE/ID-10597.

[8] United States Council for Automotive Research, RFP and Goals for Advanced Battery Development for Plug-in Electric Vehicles, http://www.uscar.org/.

Dramatic improvements in battery performance and cost will require a well-coordinated effort across all of the DOE complex and with America's most innovative researchers and companies. Coordination within DOE and with other government agencies is a key attribute of the VTO energy storage R&D effort. VTO coordinates efforts on energy storage R&D with the DOE Office of Science, the DOE Office of Electricity, and the Advanced Research Projects Agency – Energy (ARPA-E). Innovations in battery technology occur as a result of fundamental investigations carried out at national labs and universities supported by the DOE Office of Science, through translational research sponsored by ARPA-E, and through applied research and development at labs, universities and industry supported by VTO. Innovations coming from R&D on pre-competitive technologies will be transferred to and implemented by industry partners as a business case develops for these technologies through the US DRIVE public/private partnership. The USABC makes cost-shared, competitively awarded projects to industry to facilitate commercialization of pre-competitive technologies and introduce them into the marketplace.

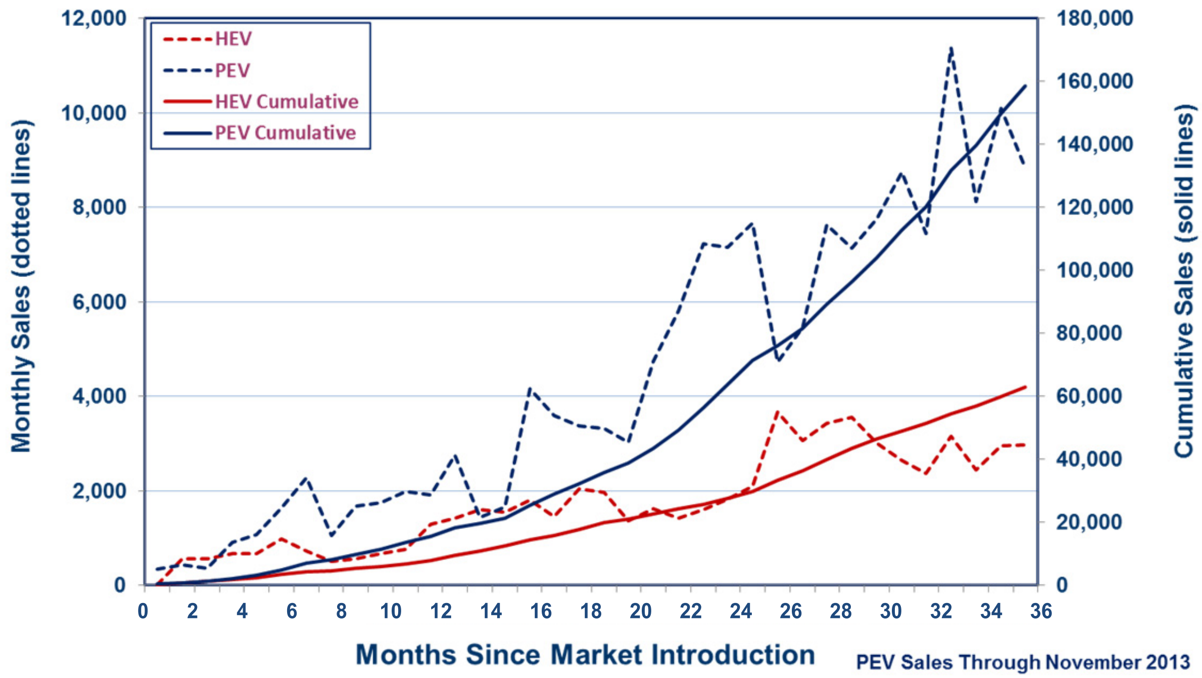
VTO also has established extensive and comprehensive ongoing coordination efforts in energy storage R&D with other government agencies. Such efforts include membership and participation in the Chemical Working Group of the Interagency Advanced Power Group (IAPG), active participation in program reviews and technical meetings sponsored by other government agencies, and coordinating the participation of representatives from other government agencies in the contract and program reviews of DOE-sponsored efforts. DOE also coordinates with the Department of Transportation/National Highway Traffic Safety Administration (DOT/NHTSA), the Environmental Protection Agency (EPA), and with the United Nations Working Group on Battery Shipment Requirements. Additional international collaboration occurs through a variety of programs and initiatives. These include: 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.

I.B.4 Recent Highlights

Chapter II of this report contains brief summaries of some key accomplishments resulting from the VTO Energy Storage R&D and associated efforts in support of the *EV Everywhere* Grand Challenge – each one selected from many active projects and representing a significant technical breakthrough. In addition, the following highlights specifically pertain to the U.S. electric drive vehicle market during FY 2013.

U.S. sales of electric drive vehicles nearly doubled in 2013. The *EV Everywhere* Grand Challenge remains focused on overcoming barriers to widespread market acceptance of PEVs, with cost reduction being a primary component. Despite obstacles, the electric-drive vehicle market is growing. Evidence of this can be seen in vehicle sales and increased investment by auto makers (see Figure I - 2).

- Total U.S. PEV sales in model year 2013 nearly doubled those of 2012, approaching 100,000 sold for the year alone.
- Additionally, PEVs reached nearly 160,000 cumulative sales in November 2013.



(Source: HybridCars.com)

Figure I - 2: New PEV sales compared to hybrid electric vehicle (HEV) sales over their respective 36 month introductory periods

Commercial applications of DOE-supported technologies. Several technologies, developed partially under VTO-sponsored projects, have moved into commercial applications. Hybrid electric vehicles on the market from BMW and Mercedes are using lithium-ion technology developed under projects with Johnson Controls Inc. (JCI). 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 also in the Ford Focus EV battery. LG Chem will also supply Li-ion batteries to Eaton for hybrid drive heavy vehicles. A123Systems is producing lithium-ion battery systems for the GM Spark EV.

PEV battery cost reduction. DOE-funded research has helped bring down lithium-ion battery costs from $1,000/kWh in 2008 to less than $325/kWh today. DOE's goals are to continue to drive down battery cost to $300/kWh by 2014 and to $125/kWh by 2022.

I.B.5 Organization of this Report

This report covers all the projects currently ongoing or starting up as part of the energy storage R&D effort in VTO. Chapter II contains the *EV Everywhere* Grand Challenge R&D Progress highlights, and chapters III through VI contain descriptions and progress of various R&D projects supported through VTO funding. A list of individuals who contributed to this annual progress report (or who are otherwise collaborating with the energy storage R&D effort) appears in Appendix A. A list of acronyms is provided in Appendix B.

We are pleased with the progress made during the year and look forward to continued work with our industrial, government, and scientific partners to overcome the remaining challenges to delivering advanced energy storage systems for vehicle applications.

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