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A Status Report on DOE Batteries & Electrification Program R&D for Fiscal Year 2021-22

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Summary

This paper provides a fiscal year (FY) 2021-22 status report on R&D projects funded by the batteries & electrification (B&E) program of the U.S. Department of Energy (DOE). B&E research covers electric drive technologies, grid integration, and advanced batteries. U.S. has had a significant long-term commitment to such R&D – the FY 2022 budget for it approached ~$200 million, plus additional commitments under the Bipartisan Infrastructure Law (also known as the Infrastructure Investment & Jobs Act). It describes recent key accomplishments for each area, programmatic structure, current research thrusts, and key activities under the Bipartisan Infrastructure Law.

Keywords: battery, electric drive, electric vehicle, government, charging

1 Introduction

The Vehicle Technologies Office (VTO) of the U.S. Department of Energy (DOE) conducts research and development (R&D) on advanced transportation technologies to reduce the nation's use of imported oil and also reduce harmful emissions. Technologies supported by VTO include electric drive components such as advanced energy storage devices (batteries), power electronics and electric drive motors, advanced structural materials, energy efficient mobility systems, advanced combustion engines, and fuels. VTO is focused on early-stage high-reward/high-risk research to improve critical components for more fuel efficient (and cleaner-operating) vehicles to enable U.S. innovators to rapidly develop the next generation of technologies that achieve the cost, range, and charging infrastructure necessary for widespread adoption of plug-in electric vehicles (PEVs). One of the ultimate goals of this research, consistent with the current vehicle electrification trend, is an EV which can provide the full driving performance, convenience, and price of an internal combustion engine (ICE) vehicle. To achieve this, VTO has established the following goals: reducing the production cost of a BEV battery pack to $80/kWh, increasing the range of electric vehicles (EVs) to 300 miles, and decreasing their battery charge time to 15 minutes or less [1]. This is a long-term R&D program, status reports for which have been presented in several prior EVS meetings (e.g., [2], [3]). VTO works with key U.S. automakers through the United States Council for Automotive

Research (USCAR) – an umbrella organization for collaborative research consisting of Fiat Chrysler LLC, the Ford Motor Company, and General Motors. Collaboration through the partnership known as U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability (US DRIVE) [4] attempts to enhance the relevance and the potential for success of the research portfolio. VTO competitively awards funding through funding opportunity announcement (FOA) selections; and directly funds work at the national laboratories based on annual appropriations. The FY2022 budget for battery and electrification (B&E) R&D was approximately $200 million. Stakeholders for the VTO R&D activities include universities, national laboratories, other government agencies and industry members (automakers, battery manufacturers, material suppliers, component developers, private research firms, and small businesses).

Battery & electrification program R&D includes research on electric drive technologies, advanced batteries, grid integration, and extreme fast charging (XFC). The FY2022 budget for battery and electrification (B&E) R&D was approximately $200 million (including $135 million for batteries, $40 million for electric drive technologies, and $25 million for grid and infrastructure). During fiscal year 2021-22, VTO continued to fund early stage R&D projects that address the U.S. transportation sector. The organizational structure of VTO is shown in Figure 1.

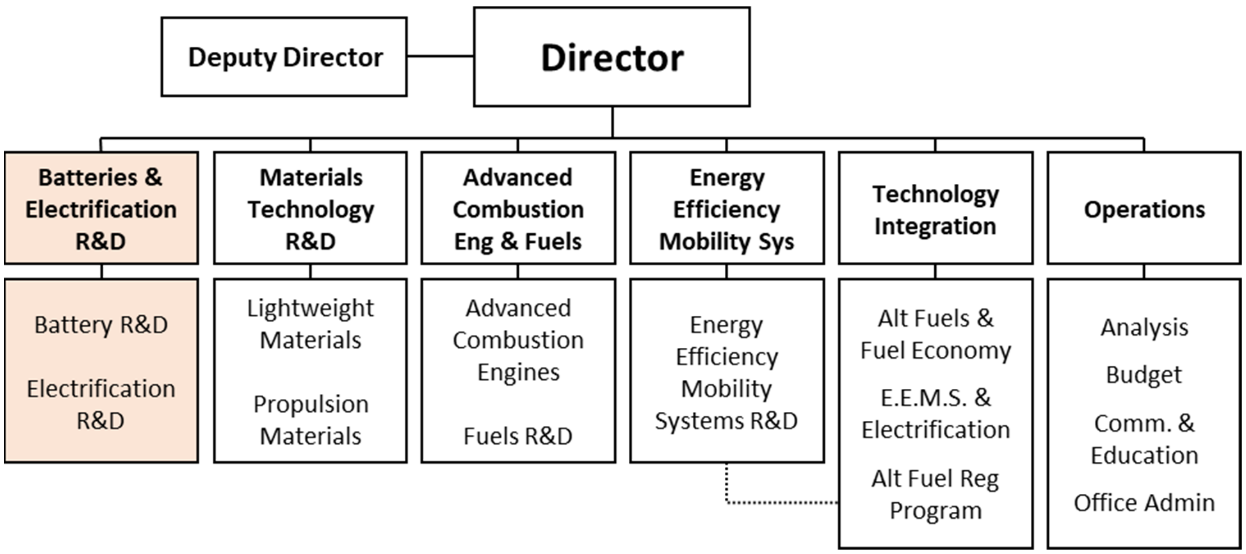

Figure 1: Organization chart for the DOE Vehicle Technologies Office (VTO).

2 Battery & Electrification (B&E) Program Areas

2.1 Electrification Technologies

The VTO Electrification Sub-Program is composed of *electric drive technologies*, and *vehicle-grid integration* activities. The *electric drive technologies* group conducts R&D projects that advance electric motors and power electronics technologies. The *vehicle-grid integration* group conducts R&D projects that advance cybersecurity and electric vehicle charging technologies. More information on electrification technologies is available in the FY2020 VTO annual progress report for electrification [5].

The *electric drive technologies* activities conduct early stage R&D on transportation electrification technologies that accelerate the development of cost-effective and compact electric traction drive systems meeting or exceeding performance and reliability requirements of internal combustion engine (ICE) vehicles, thereby enabling electrification across all light-duty vehicles. Its goal is to develop an electric traction drive system at a cost of $6/kW for a 100 kW peak system by 2025. In addition, the program has a 2025 power density target of

33 kW/L for a 100 kW peak system. While achieving these targets will require transformational technology changes to current materials and processes, it is essential for enabling widespread electrification across all light-duty vehicle platforms.

The objective of *vehicle-grid integration* R&D is identifying systems pathways and conducting R&D to facilitate a robust, interoperable, and cyber secure, EV charging and grid infrastructure which incorporates advanced charging technologies, distributed energy resources, grid, and grid services. Its areas of research include EV grid integration and services, high-power static/dynamic wireless charging, EV/electric vehicle service equipment (EVSE)/grid interoperability & control, extreme fast charging (XFC) hardware, and cyber security.

2.2 Battery Technologies

The Battery Sub-Program activities focus on the development of robust batteries to significantly reduced battery cost, increased life and performance. This effort occurs in close partnership with the automotive industry, through a cooperative agreement with the U.S. Advanced Battery Consortium.

To quantify the improvements needed to accelerate large-scale adoption of PEVs and HEVs, certain performance and cost targets have been established. Some sample performance and cost targets for EV batteries, both at cell level and at system (pack) level, are shown in Table 1. An overview of the main battery R&D activities appears in Figure 2. More information on individual activities appears in the FY 2020 VTO annual progress report for batteries [6].

Table 1: Subset of EV requirements for advanced high-performance EV batteries and cells

Energy Storage Goals (by characteristic)	Pack Level	Cell Level
Cost @ 100k units/year (kWh = useable energy)	\$125/kWh*	\$100/kWh*
Peak specific discharge power (30s)	470 W/kg	700 W/kg
Peak specific regen power (10s)	200 W/kg	300 W/kg
Useable specific energy (C/3)	235 Wh/kg*	350 Wh/kg*
Calendar life	15 years	15 years
Deep discharge cycle life	1,000 cycles	1,000 cycles
Low temperature performance	>70% useable energy @C/3 discharge at -20°C	>70% useable energy @C/3 discharge at -20°C

*Current commercial cells and packs not meeting the goal

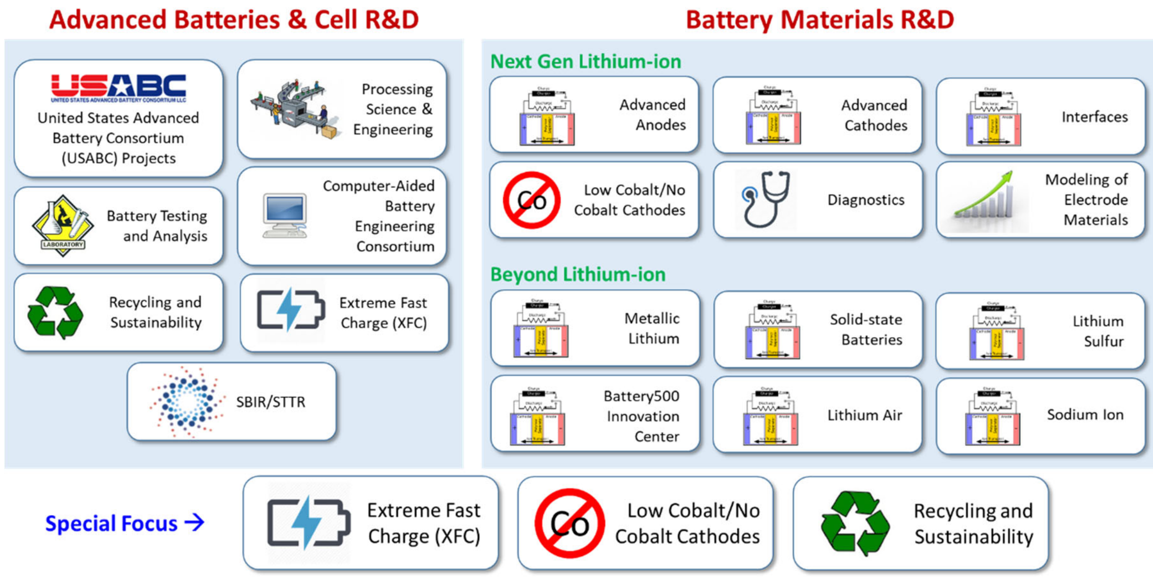

Figure 2: Battery R&D Program Structure.

The *advanced battery & cell R&D* focuses on the development of robust battery cells and modules to significantly reduce battery cost, increase life, and improve performance. This effort occurs in close partnership with the automotive industry, through a cooperative agreement with the USABC. In FY 2021-22, the USABC continued to support multiple cost-shared contracts with developers to further the development of batteries and battery components for PEVs and HEVs. In addition, DOE supported battery and material suppliers via contracts administered by the National Energy Technology Laboratory (NETL). Other projects in this area include performance, life and abuse testing of contract deliverables, laboratory- and university-developed cells, and benchmarking new technologies from industry; thermal analysis, thermal testing and modeling; cost modeling; secondary usage and life studies; and recycling studies for core materials. The *processing science & engineering* activity supports the development and scale-up of manufacturing technologies needed to enable market entry of next-generation battery materials and cell components – emphasizing disruptive materials and electrode production technologies that could significantly reduce cost and environmental impact while increasing yield and process control relative to existing production technologies. Several *small business innovation research* (SBIR) projects, supported by VTO, are focused on the development of new battery materials/components and provide a source of new ideas and concepts.

The *battery materials R&D* addresses fundamental issues of materials and electrochemical interactions associated with rechargeable automotive batteries. It develops new/promising materials and it makes use of advanced material models to discover such materials (and their failure modes), utilizing scientific diagnostic tools and techniques to gain insight into the failure process. The researchers belong to various national labs, universities, and industry partners. The work spans mainly two general areas – "next generation" chemistries (which employ an alloy anode and/or a high voltage cathode) and beyond lithium-ion (BLI) chemistries (which employ a lithium metal anode). More recently, it is funding the Battery500 Consortium, with the aggressive goal of developing a battery cell with a specific energy of 500Wh/kg. VTO also sponsors research to develop recycling processes for battery materials.

The current *special focus* targets three areas of battery research: enabling extreme fast charging (XFC) in enhanced lithium-ion systems, developing and optimizing low-cobalt cathode materials, and a set of recycling and sustainability projects.

3 B&E Program Highlights for FY 2021-22

This section includes brief descriptions of recent R&D highlights from the B&E program. More details for specific projects are available in the associated annual progress reports ([5], [6]).

3.1 A new class of cobalt-free materials. (ANL)

Novel cathode-oxides based on a lithiated spinel framework have been discovered at ANL that can reversibly cycle >200 mAh/g. Initial results show promising stability at high voltages with close to zero-strain behavior (<3% expansion). The unique properties of these materials are enabled by controlling the degree of atomic-scale disorder within the overall, ordered framework. (See Figure 3.)

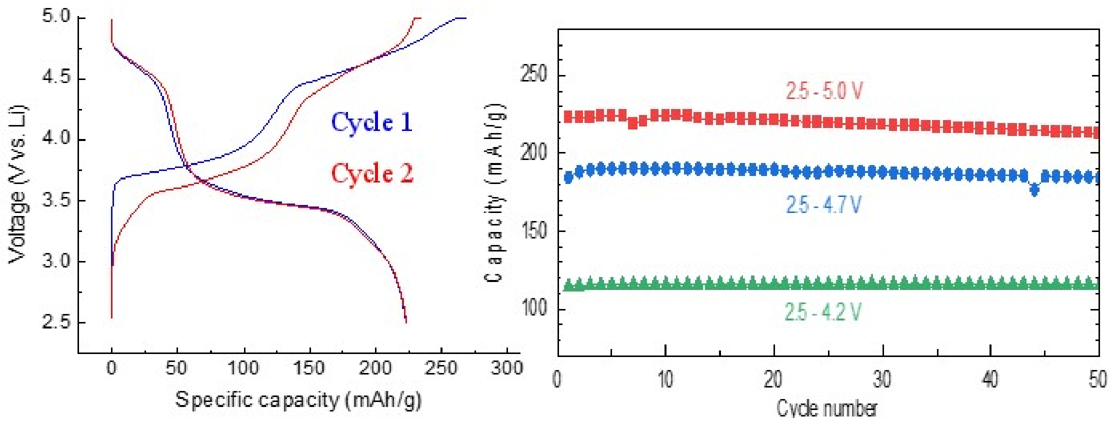

Figure 3: (left) Unique charge/discharge profiles of the novel, lithiated spinel between 5.0-2.5 V. (right) Cycling capacity at three upper cutoff voltages highlighting the stability of the cathode material, the electrolyte is 1.2M $LiPF_6$ EC/EMC 3/7 wt% (Source: Argonne National Laboratory).

3.2 Towards stable cycling of cost-effective DRX cathodes via fluorination (LBNL)

A highly fluorinated Mn-Ti DRX (cobalt and nickel free) cathode material has been synthesized at LBNL through the use of ammonium fluoride. This DRX material exhibits excellent cycling performance, with an initial capacity of 233 mAh/g and 90% capacity retention after 200 cycles. More importantly, this material exhibits a stable average voltage after it undergoes an initial structural rearrangement leading to the stable cycling at an energy density of 760 Wh/kg. These recent advancements highlight the great promise of cost-effective DRX cathodes for high-energy lithium-ion batteries. (See Figure 4.)

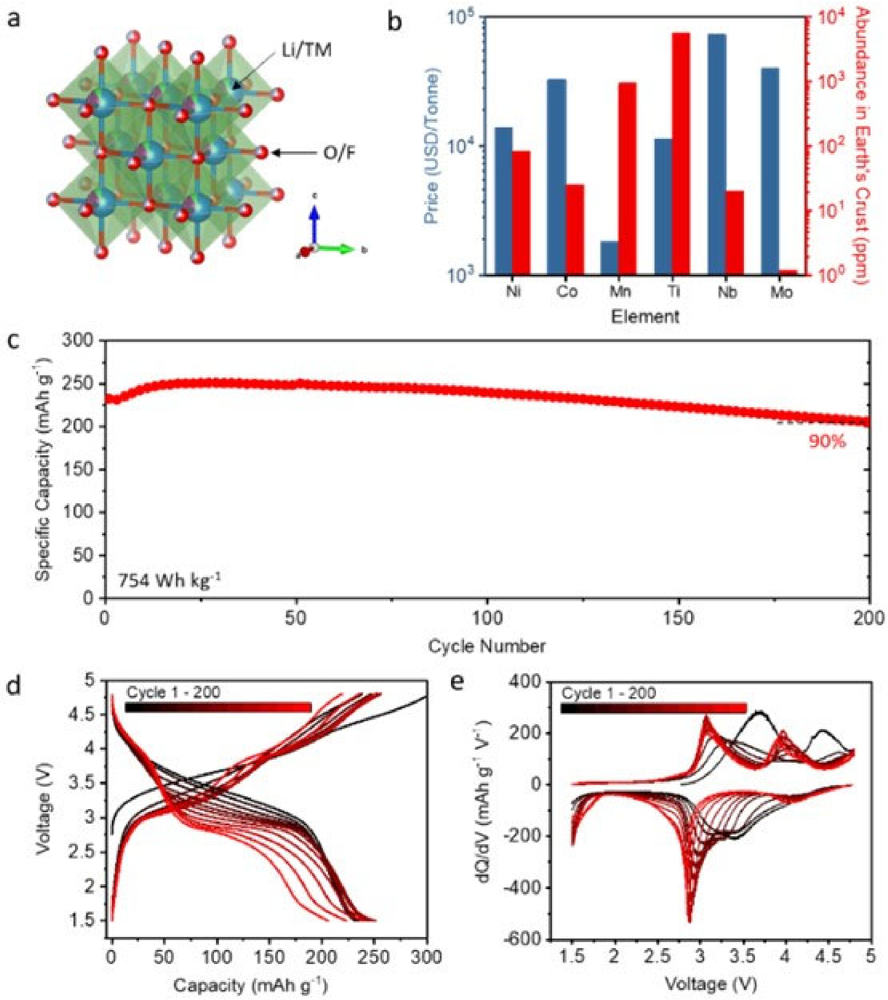

Figure 4: Battery performance of a highly fluorinated DRX, $Li_{1.2}Mn_{0.6}Ti_{0.2}O_{1.8}F_{0.2}$. (a) Crystal structure, (b) price and abundance of selected transition metals, (c) specific capacity, (d) voltage profiles, and (e) differential capacity plot. DRX cell is cycled at 16 mA g^{-1} within 4.8 and 1.5 V (Source: Lawrence Berkeley National Laboratory).

3.3 Stable Ni-rich $LiNi_xMn_yCo_{1-x-y}O_2$ material synthesized with fast-charge capability (LBNL)

LBNL has developed synthetic approaches to produce Ni-rich $LiNi_xMn_yCo_{1-x-y}O_2$ single-crystal samples with well-controlled morphologies and surfaces. $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ crystals with (104)-family surface were found to deliver much better fast-charging performance than the conventional polycrystalline counterpart. The improvement is attributed to enhanced chemical and structural stabilities, faster Li^+ diffusion, suppressed side reactions with electrolyte and excellent particle cracking resistance found of single crystals. (See Figure 5.)

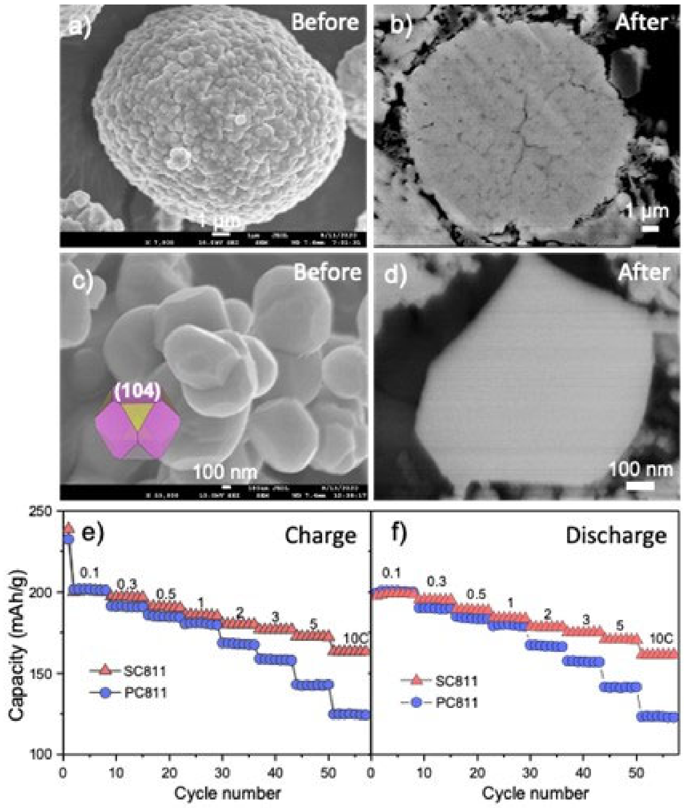

Figure 5: (a-d) SEM images of PC (a, b) and SC (c, d) NMC811 before (a, c) and after (b, d) cycling. Enhanced cracking resistance in SC is clearly shown. e-f) Electrochemical testing confirms superior charge and discharge rate capability of SC (Source: Lawrence Berkeley National Laboratory).

3.4 Development of Advanced Electrolyte for Fast Charging (INL)

As part of the XCEL program INL developed the B26 electrolyte which improves ion transport properties and enables increased charge rates and higher charge acceptance during fast charge. When combined with other advances, B26 has allowed XCEL to increase the charge accepted prior to the constant voltage portion of a charge by a factor of three. (See Figure 6.)

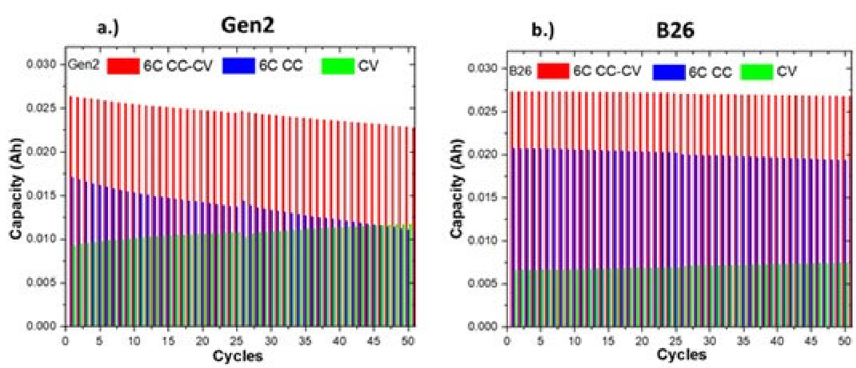

Figure 6: Comparison of Gen2 (a) versus B26 (b) electrolytes in cells with NMC 532 cathodes and graphitic anodes (ANL CAMP Pouch cells) (Source: Idaho National Laboratory).

3.5 Balancing interfacial reactions to achieve long cycle life in high-energy lithium metal batteries (PNNL)

Battery500 consortium researchers discovered that ultra-thin lithium metal foil as the anode serve to extend the lifespan of lithium metal pouch cells. The 350Wh/kg pouch cell achieved over 600 cycles. (See Figure 7.)

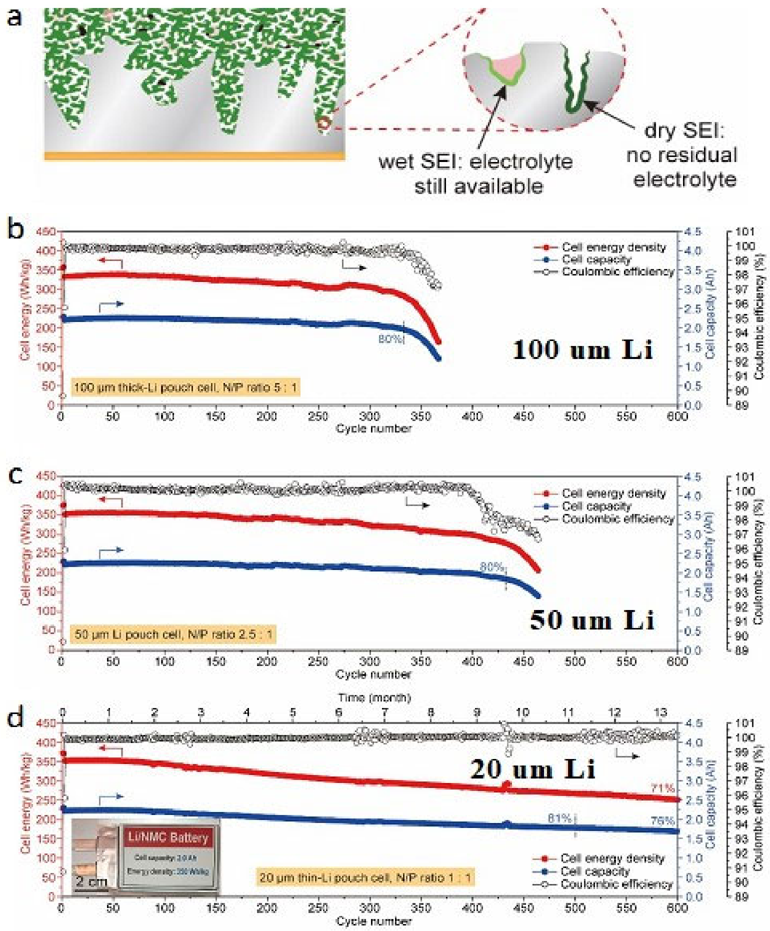

Figure 7: 350 Wh/kg pouch cells achieve more than 600 cycles in research from the Battery500 Consortium. (a) Illustration of wet and dry SEI layers in lithium metal anode. (b)-(d) Cycling performances of 350 Wh/kg lithium metal pouch cells using 100, 50 and 20 µm lithium foils as anodes, respectively. Cathode: $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$; Electrolyte: 1.54 M lithium bis(fluorosulfonyl)imide (LiFSI) in 1,2-dimethoxyethane (DME) and 1,1,2,2-tetrafluoroethyl-2,2,3,3-tetrafluoropropyl ether (TTE) (Source: Pacific Northwest National Laboratory).

3.6 Aqueous sequential separation of anodes and cathodes from spent lithium-ion batteries (ORNL)

Scientists at the Oak Ridge National Laboratory have developed a low cost and highly selective method to recycle anodes and cathodes from spent lithium-ion batteries. The method relies on an aqueous sequential separation to successfully recover both electrode materials and current collectors upon the use of buffer solutions and surfactant additives in one single pot. The ORNL team has engineered this novel recycling method to practice leading the way to demonstration. (See Figure 8.)

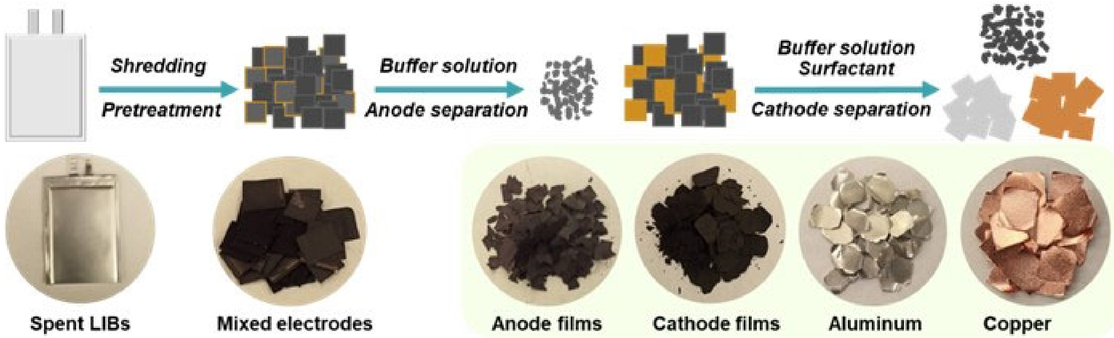

Figure 8: Two-step process to recover electrode material and current collectors from spent Li-ion batteries, developed in the ORNL ReCell Program (Source: Oak Ridge National Laboratory).

3.7 High-performance traction motors free of permanent magnets (Illinois Institute of Technology)

Researchers at the Illinois Institute of Technology optimized, prototyped, and dynamometer-tested a third-generation high-power-density wound field synchronous machine (WFSM), a potentially attractive electric vehicle traction motor topology free of permanent magnets and having a controllable field excitation, which allows for easy field weakening, reduced iron losses at high speed, and a high power factor that enables a lower stator inverter volt-ampere rating. (See Figure 9.)

Figure 9: Square WFSM rotor (left) and overall WFSM rotor with brushes and slip rings mounted on the dynamometer for testing (right) (Source: Illinois Institute of Technology).

3.8 Vertical Gallium Nitride MOSFETs for Electric Drivetrains (SNL)

A Sandia research team has developed a process to fabricate vertical gallium nitride (GaN)-based trench MOSFETs (metal–oxide–semiconductor field-effect transistors) for use in electric drivetrains. The vertical GaN trench MOSFET differs from Si or SiC alternatives in that the doped layers comprising the source and body regions are grown by epitaxy rather than formed by ion implantation. In addition, GaN lacks a high-quality native oxide, so the gate dielectric must be deposited rather than thermally grown. The devices produced at Sandia rely on atomic layer deposited thin films for the gate dielectric (primarily Al_2O_3 or SiO_2). This work provides a foundational platform for development of next-generation power electronics that employ wide-bandgap GaN semiconductors. (See Figure 10.)

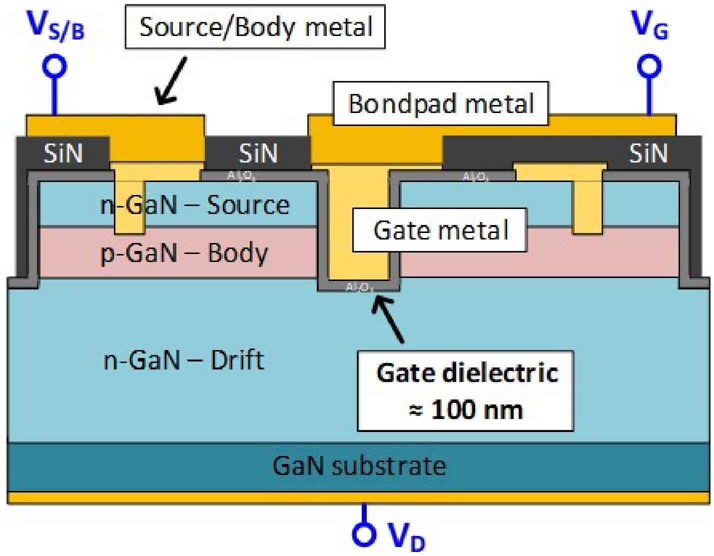

Figure 10: Representative structure of the vertical GaN trench MOSFETs fabricated at Sandia (Source: Sandia National Laboratories).

3.9 High-energy lateral mapping studies of inhomogeneity and failure mechanisms in pouch cells (BNL)

A high-energy density lithium metal battery was cycled until failure and then investigated using 2D synchrotron diffraction methods to resolve the inhomogeneity. From the observed phase behavior, it was possible to determine that the failure was primarily driven by electrolyte depletion. Partial depletion led to hindered cycling in most regions of the cell, while full depletion led to the complete inactivation of the cathode in three macroscopic spots.

4 The Bipartisan Infrastructure Law (BIL)

The Bipartisan Infrastructure Law (BIL) is a United States federal statute (Public Law 117-58) enacted by the 117th United States Congress and signed into law by President Joe Biden on November 15, 2021 [7]. BIL includes more than $62 billion for the U.S. Department of Energy (DOE) to deliver a more equitable clean energy future for the American people by investing in American manufacturing and workers, expanding access to energy efficiency and clean energy for families, communities and businesses, delivering reliable, clean, and affordable power to more Americans, and building the technologies of the future through clean energy demonstrations. BIL invests more than $7 billion in the supply chain for batteries. Among its various provisions, several are directed at revitalizing domestic supply chains and America's manufacturing leadership. BIL investment in clean energy technology supply chains would allow America to make the energy technologies of the future domestically, boosting competitiveness within a global clean energy market expected to reach $23 trillion by the end of the decade. These investments will create jobs up and down the supply chain—especially manufacturing jobs and skills-matched opportunities for fossil fuel workers.

5 Conclusions

The DOE Vehicle Technologies Office B&E program includes advanced batteries and electrification technologies. This research is focused on early-stage high-reward/high-risk research to improve critical components for more fuel efficient (and cleaner-operating) vehicles, so as to enable U.S. innovators to rapidly develop the next generation of technologies that achieve the cost, range, and charging infrastructure necessary for the widespread adoption of plug-in electric vehicles. The program has had a long-term, successful track record in advancing the state of the art of advanced automotive batteries and electric drives, in successful commercialization of numerous technologies, and in bringing down their cost. VTO has also established extensive and comprehensive ongoing coordination efforts in energy storage R&D across DOE and with other government agencies. The past successful commercialization of DOE-funded/developed technologies is a testimony to the success already achieved by its cooperative programs. The program continues to leverage its progress in various enabling technologies to accomplish challenging VTO goals and to reassess candidate technologies that promise performance, life, and cost benefits.

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Authors

As Program Manager for Batteries and Electrification, Steven manages federal funding and a research team dedicated to early-stage R&D across battery and electrification technologies. Focus areas include new battery chemistries and cell technologies with the potential to reduce the cost of batteries, technologies to address the impacts of vehicle charging on the electric grid, and high power density electric drive systems to enable new vehicle architectures. Steven received his Bachelor of Science and Master of Science degrees in Mechanical Engineering from Virginia Tech, and has participated in DOE's Advanced Technology Vehicle Competitions.

David Howell is the Acting Director of the Vehicle Technologies Office as well as the Acting Director and Principal Deputy Director of the Office of Manufacturing and Energy Supply Chains at DOE. Before starting at DOE in 2003, he was the Aerospace Technologies project manager at the Oak Ridge National Laboratory and before that, served on active duty for 6 years at the Wright Patterson AFB, Ohio, as the program manager for Advanced Materials for Space Structures at the Air Force Materials Laboratory. He received his B.S. degree in Aerospace Engineering from the University of Tennessee, Knoxville, TN.