Spotlight

Solving Challenges in Energy Storage

August 2018

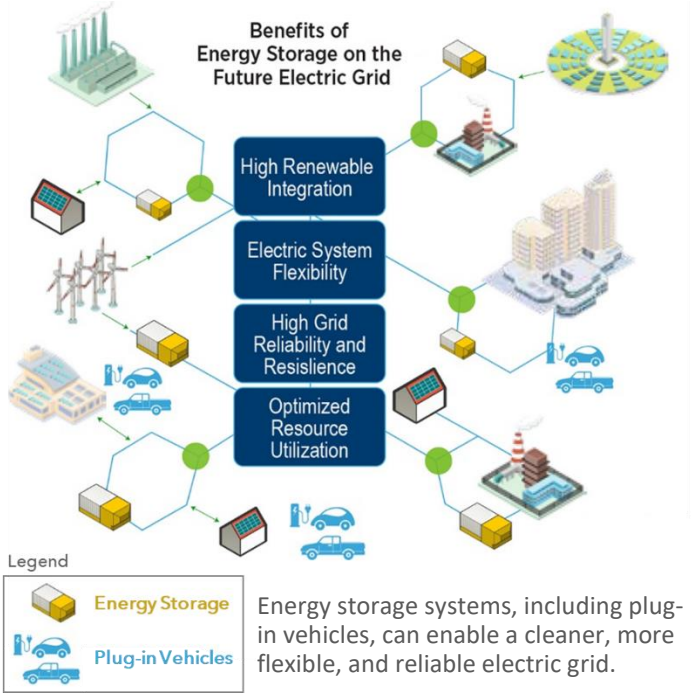
U.S. DEPARTMENT OF ENERGY | Office of TECHNOLOGY TRANSITIONS

energy.gov/technologytransitions

Critical Need for Energy Storage

Advanced energy storage provides an integrated solution to some of America's most critical energy needs: electric grid modernization, reliability, and resilience; sustainable mobility; flexibility for a diverse and secure, all-of-the-above electricity generation portfolio; and enhanced economic competitiveness for remote communities and targeted micro-grid solutions.

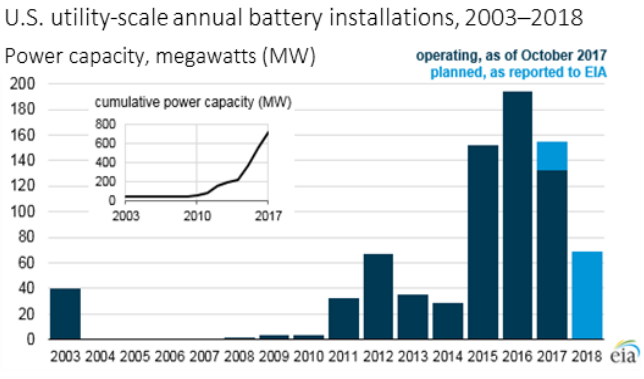
Storage technologies strengthen and stabilize the U.S. grid by providing backup power, leveling loads, and offering a range of other energy management services. Electric vehicles (EVs) are also poised to become an integral part of this new grid paradigm as their batteries both draw power from and supply it back to the grid (when beneficial) – while eliminating tailpipe emissions.



Energy storage systems, including plug-in vehicles, can enable a cleaner, more flexible, and reliable electric grid.

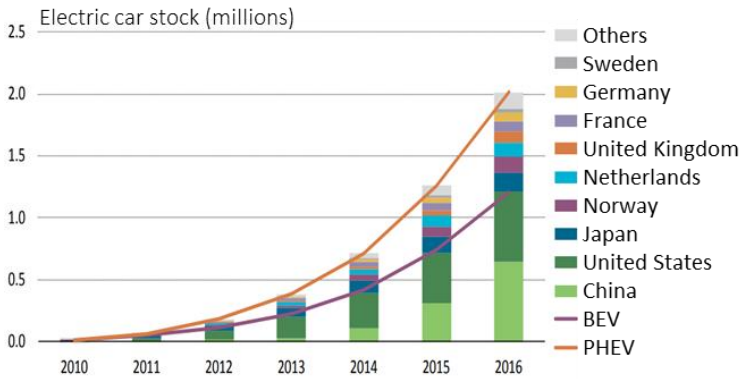
Recognizing that specific storage technologies best serve certain applications, the U.S. Department of Energy (DOE) pursues a diverse portfolio of energy storage research and development (R&D) to assure a continuous, affordable, and sustainable electricity supply. DOE forms R&D partnerships to leverage resources and accelerate progress throughout the entire technology development cycle. To address partner needs, DOE and its National Laboratories offer various arrangements and agreements for research. This approach has facilitated effective teamwork by the labs, industry, academia, other federal and state agencies and organizations—helping increase the commercial adoption of grid energy storage and EVs.

Growing Utility-Scale Energy Storage



Growing U.S. utility-scale battery installations, 2003–2018
Source: EIA. January 8, 2018.
eia.gov/todayinenergy/detail.php?id=34432

Rising Global EV Stocks



Rising global electric car stocks, 2010–2016,
Source: IEA. 2017.
iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf

Challenges Facing Energy Storage Adoption

DOE investments in early-stage research have helped to significantly advance energy storage technologies that industry is unlikely to have developed on its own. Continued research activities with industry at specialized DOE facilities hold significant potential to further improve energy storage performance and cut costs. Continued R&D efforts target further progress to boost industry acceptance and enable the next generation of energy storage systems. Advances could accelerate growth in both utility-scale storage and EV ownership. As energy storage systems demonstrate their viability, policies and regulations may encourage broader deployment while ensuring systems maintain and enhance their resilience.[1]

DOE recognizes four key challenges to the widespread deployment of electric energy storage:[2]

Atomic structure of a solid electrolyte for safer batteries.

Start Small, Think Big

Today's energy storage devices are limited by the performance of their constituent materials. Overcoming these limitations requires understanding the myriad interactions that transfer ions or electrons in these devices and the physical and chemical processes that degrade them.

Powerful new computational, imaging, and characterization tools are illuminating the inner workings of energy storage at the atomic and molecular scales. Integration of this new knowledge will enable the scientific design of a new generation of energy storage devices that radically increase charge density and last longer by minimizing degradation from charge-discharge cycles.

Learn more about DOE Office of Science research priorities: science.energy.gov/~/media/bes/pdf/reports/2017/BRN_NGEES_rpt.pdf

Performance and Safety

Grid operators must be confident that energy storage systems will perform as intended within the larger network. Advanced modeling and simulation tools can facilitate acceptance—particularly if they are compatible with utility software.

Cost-Competitive Systems

Actual energy storage technology (e.g., the battery) contributes 30%-40% to total system cost; the remainder are attributed to auxiliary technologies, engineering, integration, and other services.

Regulatory Environment

Energy storage systems provide different functions to their owners and the grid at large, often leading to uncertainty as to the applicable regulations for a given project. Regulatory uncertainty poses an investment risk and dissuades adoption.

Industry Acceptance

Energy storage investments require broad cooperation among electric utilities, facility and technology owners, investors, project developers, and insurers. Each stakeholder offers a different perspective with distinct concerns.

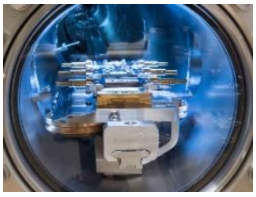
[1] "Energy Storage: Possibilities for Expanding Electric Grid Flexibility." National Renewable Energy Laboratory. February 2016. nrel.gov/docs/fy16osti/64764.pdf

[2] *Quadrennial Technology Review 2015*. U.S. Department of Energy. September 2015. energy.gov/quadrennial-technology-review-2015

Toward a More Robust U.S. Electric Grid

For grid applications, electricity must be reliably available 24 hours a day. Even second-to-second fluctuations can cause major disruptions that could potentially cost billions of dollars. New approaches to maximize energy storage capacity are essential to bring intermittent renewables into the grid and effectively manage electricity generation to meet peak demand.[3] DOE seeks to enable a smarter, more flexible electric grid by advancing research on novel materials and system components that resolve key challenges for energy storage systems.[4]

DOE's R&D Focus Areas for Energy Storage


Collaborative Center for ES Science, ANL


Concentrating solar tower at Crescent Dunes, LPO


Post-Test Facility, ANL

Materials. Improved energy storage system costs, service life, durability, and power density are made possible by innovative materials that enable new battery chemistries and component technologies, such as low-cost membranes for flow batteries, sodium-based batteries, high voltage capacitors, wide bandgap materials, and devices for power electronics.

Power Technologies. Storage systems can be designed with a broad portfolio of technologies, each with its own performance characteristics that makes it optimally suitable for certain grid services. Established large-scale technologies, such as pumped hydro and compressed air energy storage, are capable of long discharge times (tens of hours) and high capacity. In contrast, various electrochemical batteries and flywheels are positioned around lower power applications or those suitable for shorter discharge times (a few seconds to several hours).

Power Electronics. Power electronics, such as switches, inverters, and controllers, allow electric power to be precisely and rapidly controlled. Energy storage and power electronics improve a power supply reliability and responsiveness.

Grid Analytics and Policy. Analytical and multi-physics models to understand risk and safety of complex systems, optimization, and efficient utilization of energy storage systems in the field. Validated data sets support development of codes and standards to optimize use of storage resources across the U.S. electricity infrastructure.

Safety and Reliability Testing. Advanced simulation and modeling and real-world demonstration projects increases the understanding of safety and reliability of energy storage systems.

Key Grid Energy Storage Technologies

Batteries. Electrochemical battery types include lithium-ion, sodium sulfur, lead acid, and flow batteries. These batteries vary in energy density, power performance, lifetime charging capabilities, safety, and cost.

Pumped Hydroelectric Storage. Water pumped from a low reservoir to a high one is later released through a hydroelectric turbine to generate electricity as needed.

Compressed Air Energy Storage. Compressed air is stored in an underground cavern until it is heated and expanded in a turbine to generate electricity.

Thermal Storage. Heat is captured and stored in water, molten salts, or other working fluids for later use in generating electricity, particularly when intermittent resources (e.g., solar) are unavailable.

Hydrogen. Hydrogen can be stored and used later in fuel cells, engines, or gas turbines to generate electricity without harmful emissions.

Flywheels. Electric energy is stored as kinetic energy by spinning a rotor in a frictionless enclosure. Flywheels are useful for applications such as power management.

[3] DOE, Basic Energy Sciences, "Science for Improving U.S. Energy Flow." science.energy.gov/~/media/bes/images/placemats/Back_3103x2024.jpg

[4] DOE, Office of Electricity, "Energy Storage." energy.gov/oe/activities/technology-development/energy-storage


AES Energy Storage, LLC

Advanced Energy Storage Projects Boost U.S. Technology Leadership

DOE and its National Laboratories have worked with industry, academia, other federal and state agencies and organizations for decades to develop and optimally integrate innovative storage technologies, power electronics, and controls into complete energy storage systems. Advanced energy storage benefits the power industry, its customers, and the nation:

Affordability. Meet system needs at minimal costs

Efficiency. Optimize assets and reduce delivery losses

Flexibility. Handle dynamic supply and demand and accommodate diverse technologies

Reliability. Consistently deliver high-quality power

Resiliency. Maintain critical functions/quick recovery

DOE RDD&D projects are helping U.S. businesses deliver these benefits while solidifying America's leadership in global energy storage technology.

1976-1991

DOE labs research alternative energy and utility energy storage technologies, including rechargeable batteries.

1991-2011

Scope expands to RDD&D of integrated energy storage systems, power electronics, and controls—winning R&D 100 awards

2011-2015

16 stationary storage projects demonstrate technology readiness to deliver backup power and auxiliary utility services; onboard technologies improve range, price, and efficiency

2015-2018

DOE licenses technologies to industry; provides data and modeling to support commercialization; explores novel storage approaches (e.g., flywheels, compressed air); and helps pave the way for interconnections and further market growth.

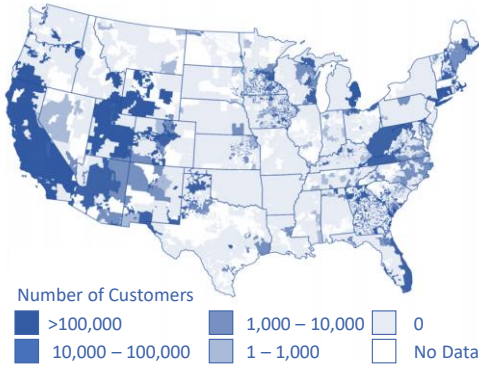
DOE Office of Electricity Partners as of 2018

43 Industry

26 Academia

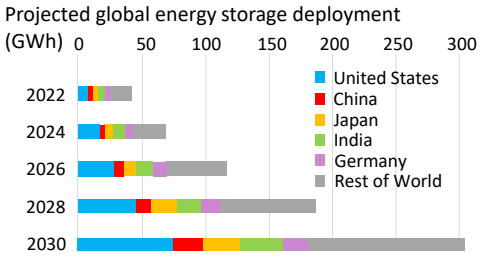
15 Agencies & National Laboratories

Markets for Behind-the-Meter Battery Energy Storage



Number of commercial electricity customers who can subscribe to tariffs with demand charges in excess of $15/kW. [nrel.gov/docs/fy17osti/68963.pdf]

Projected Global Deployment of Energy Storage



[Adapted from Bloomberg New Energy Finance 2017]

Improving Onboard Vehicle Energy Storage

Improved batteries and hydrogen fuel cells (HFCs) for electric-drive vehicles will assure their economic, environmental, and market sustainability. Transitioning to a vehicle fleet powered by these devices could eliminate tailpipe emissions and cut emissions overall, depending on the technology mix. While a variety of EVs and HFCs are now available, research developments could further enhance their consumer appeal. RDD&D focuses on reducing the cost, volume, weight, and charging time of batteries and fuel cells, while simultaneously improving performance (power, energy, durability, and tolerance in harsh conditions).[5]

Strategic DOE R&D Areas for On-Vehicle Energy Storage

Battery chemistry research, NREL

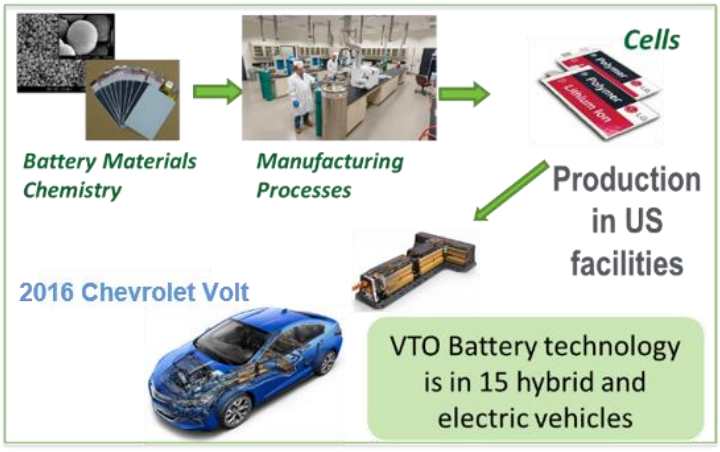
INL's Battery Test Center

Advanced Cell Materials. Researchers apply scientific tools and models in exploring electrochemical interactions and developing novel materials to improve energy storage capacity and efficiency while lowering costs.

System Integration, Analysis, and Testing. New battery and cell systems that integrate novel materials and technologies are carefully analyzed and tested to assess their performance and potential to reduce cost, weight, and size while improving performance and safety. This research aims to ensure these systems meet specific goals for particular vehicle applications.

Electrification R&D. Research on Extreme Fast Charging tackles the challenges in developing a convenient and affordable grid and charging infrastructure that will enable low-effort energy replenishment in 15 minutes or less.

EV Batteries Extend Range at Lower Cost



DOE is developing new chemistry and cell technologies to push EV battery costs below $100/kWh, increase range to over 300 miles, and charge in under 15 minutes.[5]

Second Use for EV Batteries on the Grid

EV batteries are typically retired from vehicle use when they no longer meet the high standard performance thresholds for that application. These batteries still offer significant storage capacity and can be economically reconditioned and redeployed to store energy for the stationary grid—such as peak-shaving services. The National Renewable Energy Laboratory is exploring this reuse to help increase EV ownership and reduce the cost of grid-connected energy storage systems.

"Energy Storage: Possibilities for Expanding Electric Grid Flexibility." National Renewable Energy Laboratory. February 2016.

[5] DOE, Vehicle Technologies Office. "Batteries, Charging, and Electric Vehicles." energy.gov/eere/vehicles/batteries-charging-and-electric-vehicles

Researchers at Argonne National Laboratory (ANL) and other National Labs explore strategies to shorten EV charging time. (Image: ANL)

Advanced Battery Research Boosts U.S. Electric Vehicle Sales

Major advances in battery technologies are driving U.S. sales of electric vehicles. Through December 2017, 757,445 plug-in electric vehicles have been sold in the United States. DOE has been a leader in battery R&D investment, investing $1.6 billion dollars in battery R&D between 1992 and 2017. Nearly all battery technology on the road today can be traced to DOE research.

Research: Since 1976, DOE funded scientists have built a broad foundation for advances in energy storage technologies ranging from nickel-metal hydride batteries to lithium-ion battery technologies and beyond lithium-ion chemistries. In 2017, VTO developed and verified innovative lithium-ion technology with the potential to reduce battery pack cost to $219/kWh of useable energy, an approximately 80% reduction since 2008.

Disclosure and IP Protection: This research yielded valuable technologies, resulting in 222 patents for batteries, ultracapacitors, and supporting components by 2009.

Jobs: Nearly 80% of the 260,000 alternative fuel vehicle jobs in the USA focus on hybrids and plug-in electric vehicles.

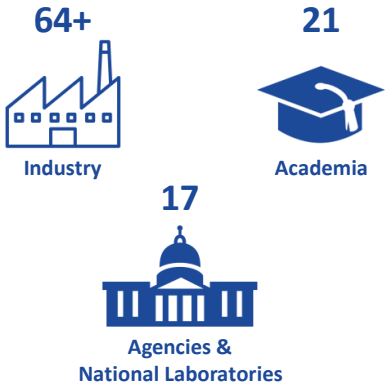
Learn more at: energy.gov/revolution-now

Research Example: Together with the United States Advanced Battery Consortium (USABC), DOE research enabled the core battery cell technology used in vehicles such as the Chevy Bolt and Ford Focus EV.

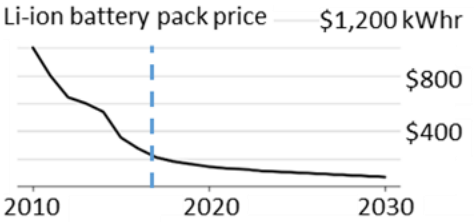
The cell, which contains a graphitic anode and a mixture of layered nickel-manganese-cobalt and manganese spinel oxides, was developed in collaboration with LG Chem Michigan from early 2004 through 2012.

It also contains promising cathode technology that can improve energy density by 30-40% over conventional cathode materials. The innovative, “lithium-rich” nickel-manganese-cobalt oxide cathode material, originally developed at Argonne National Laboratory, has been licensed to GM, LG Chem, BASF, Toda America, and Envia. Members of this cathode material “family” can operate at higher voltages and achieve much higher capacities than conventional cathode materials, leading to batteries with higher energy density.

DOE Vehicle Technologies Office Partners as of 2018

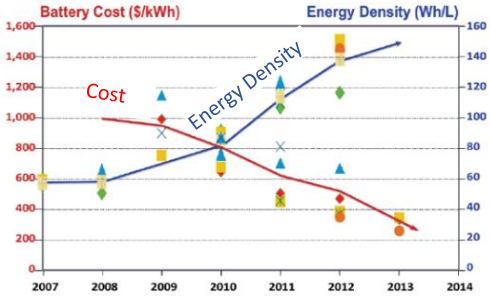


Novel Materials Lower Battery Costs



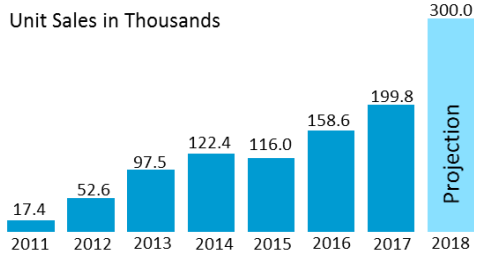
[Adapted from Bloomberg New Energy Finance 2018]

EV Batteries Increase Energy Density to Extend Range at Lower Cost



“EV Everywhere Grand Challenge.” DOE Energy Efficiency and Renewable Energy Office. January 2014. energy.gov/sites/prod/files/2014/02/f8/eveverywhere_road_to_success.pdf

Rising Annual EV Sales



[Data from Inside EV Sales Scorecard]

Partners Advance Energy Storage with DOE

DOE invests in energy storage R&D to stimulate significant technology progress—boosting U.S. competitiveness in global markets. Through an array of Program Offices that oversee energy storage R&D, DOE has stimulated significant progress in energy storage over the past several decades.

DOE supports de-risking energy storage technology through R&D partnerships among its National Laboratories with industry, academia, federal and state agencies, and a range of public-private consortia.[6] These multi-institutional partnerships support the advancement of energy storage technologies for applications in vehicles and the electric power sector and the commercialization of new energy technologies. The consortia involving industry leave participants free to build on shared information to create proprietary outcomes of commercial value. Each consortium is focused on a vision or goal to attain specific technology performance and cost thresholds for industry uptake and commercialization, while basic research partnerships sustain leading-edge science and discovery.

USABC	Develop electrochemical energy storage technologies that support commercialization of fuel cell, hybrid, and electric vehicles.
PowerAmerica	Transition existing silicon-based systems to wide bandgap technology for enhanced power and efficiency.
Battery 500 Consortium	Build a battery pack with a specific energy of 500 watt-hours per kg, compared to the 170-200 watt-hours per kg in today's typical EV battery.
GRID Modernization Initiative U.S. Department of Energy	Established a strategic partnership between DOE and the National Laboratories to modernize the nation's electric grid.
JCESR Joint Center for Energy Storage Research	Deliver transformational understanding, new concepts, and innovative materials for high performance, next generation batteries for the grid and transportation.
Energy Frontier Research Centers	Several of the Office of Science Energy Frontier Research Centers address use-inspired basic research for electrochemical energy storage.

Advancing the State of the Art through Strategic Investments in Innovative Energy Storage Technologies

In May 2018, Advanced Research Projects Agency-Energy (ARPA-E) announced up to $30 million in funding for projects as part of a new program: Duration Addition to electricitY Storage (DAYS). DAYS project teams will build innovative storage systems that can provide power to the electric grid for durations of 10 to 100 hours—opening new prospects to increase grid resilience and integrate intermittent renewable resources.

Learn more at: arpa-e.energy.gov/?q=news-item/department-energy-announces-funding-support-long-duration-energy-storage

The DOE Loan Programs Office has helped launch and finance many innovative energy storage projects in the United States. Key examples: (1) concentrating solar power plants with thermal energy storage, (2) Nissan North America's construction of one of the largest advanced battery manufacturing plants in the country, and (3) Tesla Motors' production of specially designed, all-electric plug-in vehicles and battery packs in Fremont, California.

Learn more at: energy.gov/lpo/tesla

[6] "Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing—Supplemental Information." Quadrennial Technology Review 2015. DOE. 2017. energy.gov/sites/prod/files/2017/02/f34/Ch6-SI-Public-Private-Consortia-and-Technology-Transition-Case-Studies.pdf

DOE Leverages Unique Energy Storage Capabilities

DOE's scientific and technical capabilities are rooted in its system of National Laboratories—world-class institutions that constitute the most comprehensive research and development network of its kind.

The DOE National Laboratories possess a unique collection of scientific expertise and highly specialized facilities. Collectively, these assets play a vital role in helping the United States maintain the science and technology leadership needed to sustain economic superiority in a dynamic and innovative global economy.

Researchers at the National Laboratories and other DOE-funded facilities actively collaborate with partners in industry, academia, and government to develop transformational technologies, including those essential to energy storage.

Partnership Agreements with DOE National Laboratories

Industry, academia and other entities can access the specialized expertise and facilities of the DOE National Laboratories by entering into collaborative research agreements. A variety of partnership mechanisms are available to suit the diverse needs of the broad U.S. research community. Types of partnership agreements include:

- Agreements for Commercializing Technology (ACT)
- Cooperative Research & Development Agreements (CRADA)
- Material Transfer Agreements
- Strategic Partnership Projects (SPP)
- Technical Support Agreements
- Technology Licensing Agreements
- User Agreements

In fiscal year 2016, partners using the ACT, CRADA, or SPP mechanisms for energy storage research included 63 unique non-federal partner organizations working on 80 active agreements. These partners contributed $4.5 million to this work covered by agreements included 30 CRADAs, to which DOE contributed $2.1 million. In addition, three other federal agencies engaged the labs on 16 active agreements and contributed $2.9 million to this work.

For more information on how to work with the National Laboratories, please refer to the 2016 *Guide to Partnering with DOE's National Laboratories*, inl.gov/wp-content/uploads/2016/05/Revised-Guide-Partnering-with-National-Labs-Final.pdf

Core Capabilities in Energy Storage

Our National Laboratory System uses its world-class expertise and facilities to lead basic discovery research, technology development, and demonstrations. The following laboratories hold core capabilities in energy storage R&D:

- Ames Laboratory
- Argonne National Laboratory
- Brookhaven National Laboratory
- Idaho National Laboratory
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory
- Sandia National Laboratories
- Savannah River National Laboratory
- SLAC National Accelerator Laboratory

Learn more at energy.gov/downloads/annual-report-state-doe-national-laboratories

DOE's System of National Laboratories has tens of thousands of square feet of laboratory space dedicated to accelerating the development of the next generation of energy storage technologies.

The Labs are home to multiple facilities and collaborative research groups that solve energy storage problems through multidisciplinary research.

IP Bundling of Energy Storage Technologies Available for Licensing

To expedite technology partnerships in energy storage, DOE piloted an IP Bundling Project. Under this project, six DOE National Laboratories develop technology bundles that identify complementary intellectual property (IP), scientific expertise, and technological capabilities across multiple laboratories and offer them to industry partners under one partnership agreement.

Laboratory Partnering Service (LPS)

LPS is an online platform that enables public access to world-leading DOE National Laboratory energy experts, project marketing summaries, and licensing opportunities.

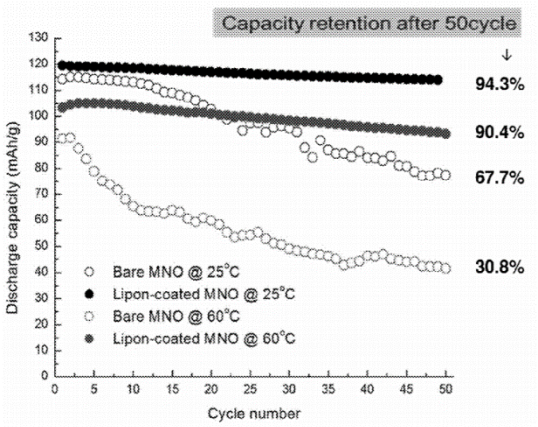
For additional and up-to-date all DOE available technologies and more information visit: labpartnering.org/

Three Energy Storage IP Bundles are available for commercialization:

1. High-Energy, High-Voltage, Lithium-Ion Batteries

Materials research continues to be critical to widespread adoption of Li-ion batteries. In particular, efforts seek to increase cathode voltage while minimizing capacity losses at the lowest possible system cost. Current cathodes perform at approximately 150–180 mAh/g at 3.5–3.8 V (Li), giving <700 Wh/kg oxide energy. The USABC goal for the price vs. cost of Li-ion batteries is $125/kWh.

This IP bundle emphasizes novel materials that will yield high-voltage, high-energy batteries. The included technologies stem from research at Argonne, Lawrence Berkeley, and Oak Ridge National Laboratories funded by the EERE Vehicle Technologies Office.



Patent No. US 9837665

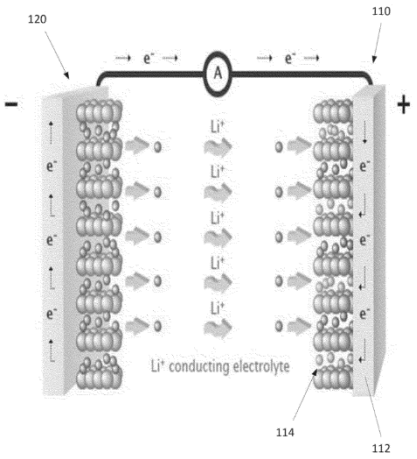
Intellectual Property Included in this Bundle

- Electroactive materials for rechargeable batteries. US 9478794B2
- Lithium ion battery incorporating heat-treated carbon black that limits the reactivity of the carbon black and electrolyte. US 9368798
- Cathode material having an alkaline source for improved specific capacity, energy density, cycle life, and stability for rechargeable batteries including, but not limited to Li-S. US 9012091
- Lithium phosphorus oxynitride protective layer of coating between the cathode and electrolyte to allow Li-ion operation at high temperature and high voltage. US 9837665B2
- Electrolyte solvent enabling high-temperature operation of Li-ion battery. US 9005822
- Non-aqueous electrolyte solution preventing solid electrolyte interface films on carbonaceous electrodes for improved performance. US 9246187
- High-voltage lithium-ion battery with fluorinated electrolytes and lithium additive for improved performance at high temperature and voltage. US 2015-0050561
- Electrolyte composed of lithium hexafluorophosphate for high-voltage applications providing longer life stability and better cycling performance. US 2016-0099484

2. Lithium-Sulfur Batteries

Poor conductivity and rate capability based on sulfur are intrinsic characteristics of the Li-S battery system that limit performance. Current challenges include Li-polysulfide formation due to dissolution of sulfur in the electrolyte and the formation of dendrites in the lithium-metal anode.

This IP bundle combines advanced materials in all components of the battery to mitigate these challenges. Sulfur is a low-cost raw material, and Li-S batteries could obtain specific energy densities of nearly five times that of Li-ion technology. The included technologies stem from research at Argonne and Lawrence Berkeley National Laboratories, funded by the EERE Vehicle Technologies Office.



Patent No. US 2016-0308209

Intellectual Property Included in this Bundle

Porous graphene nanocages for battery applications. US 9590248

Ultra-stable cathodes for Lithium-Sulfur batteries. US 2016-0308209

Sulfur cathode hosted in porous organic polymeric matrices. US 2014-0255794

Lithium-Sulfur batteries. US 2017-0033406

Lithium-Sulfur electrolytes and batteries. US 2014-0023936

Non-aqueous electrolytes for electrochemical cells. US 9368832

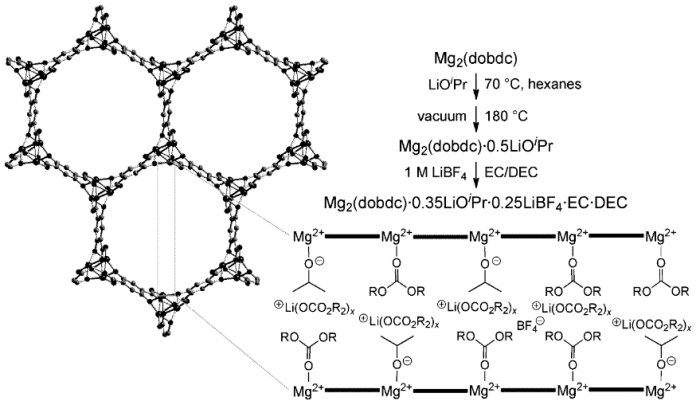
Core-shell structured nanoparticles for Lithium-Sulfur cells. US 2015-0311508

Durable carbon-coated Li2s core-shell materials for high-performance lithium/sulfur cells. US 2016-0248084

3. New Materials for Solid State Li-Ion Batteries

This bundle provides Li-ion producers strategic pathways to increase battery power, energy density, lifetime, and safety with novel alternatives that exhibit excellent electrochemical performance.

The available technologies, developed at Argonne and Lawrence Berkeley National Laboratory, include clean anodic Li films for longer life in rechargeable Li-ion batteries, solid Li electrolytes for increased safety, and block copolymer-based cathodes that can transport electronic charge and ions. Technologies developed with support from the EERE Technologies Office.



Patent No. US 9525190B2

Intellectual Property Included in this Bundle

Clean anodic Lithium films for longer life, rechargeable Lithium-Ion batteries. US 2017-0110714A1

Modified metal organic framework (MOF) as a solid Lithium electrolyte for safer Lithium-ion batteries. US 15083029, US 9525190B2

Block copolymer cathode binder to simultaneously transport electronic charge and ions. US 8552144

Materials for solid-state electrolytes and protective electrode coatings for Lithium batteries. US 2015-0364747A1

Individual Energy Storage Patents Available for Licensing

Anodes

Lithium air battery having a cross-linked polysiloxane separator
US 9478782, Argonne National Laboratory

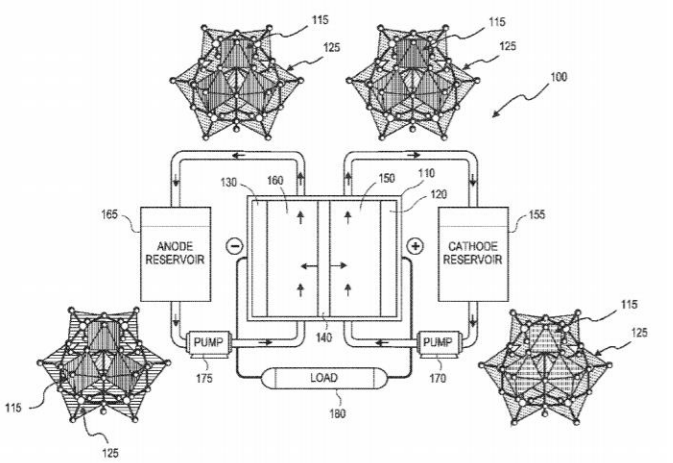
Modified carbon black materials for lithium-ion batteries
US 9368798, Lawrence Berkeley National Laboratory

Multi-layer coatings for bipolar rechargeable batteries with enhanced terminal voltage
US 9673478, Lawrence Livermore National Laboratory

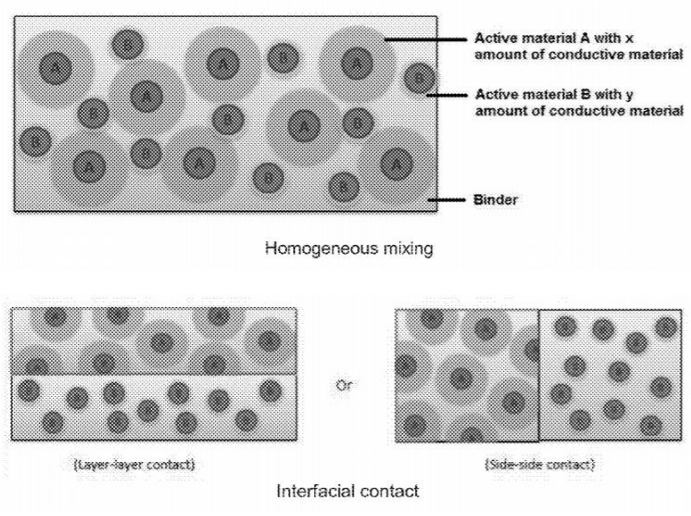
Planar high density sodium battery
US 9276294, Pacific Northwest National Laboratory

Polyoxometalate flow battery
US 9287578, Sandia National Laboratories

Lipon coatings for high voltage and high temperature Li-ion battery cathodes
US 9570748, Thomas Jefferson National Accelerator Facility and Oak Ridge National Laboratory



Patent No. 9287578



Patent No. 9444096

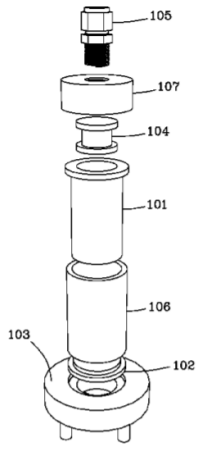
Batteries

Advanced separators based on aromatic polymer for high energy density lithium batteries
US 9598545, Argonne National Laboratory

High-rate overcharge-protection separators for rechargeable lithium-ion batteries and the method of making the same
US 9525160, Lawrence Berkeley National Laboratory

Method of fabricating electrodes including high-capacity, binder-free anodes for lithium-ion batteries
US 9543054, National Renewable Energy Laboratory

Organometallic-inorganic hybrid electrodes for lithium-ion batteries
US 9444096, Thomas Jefferson National Accelerator Facility, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory



Patent No. 9444091

Cathodes

Hybrid radical energy storage device and method of making
US 9324992, National Renewable Energy Laboratory

Gradient porous electrode architectures for rechargeable metal-air batteries
US 9293772, Thomas Jefferson National Accelerator Facility and Oak Ridge National Laboratory

Apparatuses for making cathodes for high-temperature, rechargeable batteries
US 9444091, Thomas Jefferson National Accelerator Facility, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory

Electrolytes

Electrolytes comprising metal amide and metal chlorides for multivalent battery
US 9601801, Argonne National Laboratory

Means of introducing an analyte into liquid sampling atmospheric pressure glow discharge
US 9536725, Lawrence Berkeley National Laboratory and Pacific Northwest National Laboratory

Methods for separating particles and/or nucleic acids using isotachophoresis
US 9285340, Lawrence Livermore National Laboratory

Anti-perovskite solid electrolyte compositions
US 9246188, Los Alamos National Laboratory

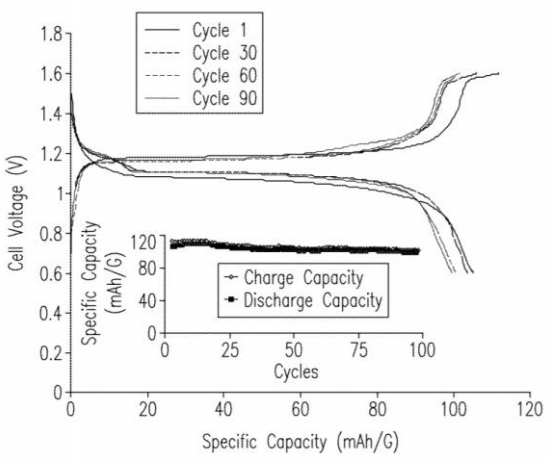
Electrochemical cell structure including an ionomeric barrier
US 9685684, Sandia National Laboratories

Magnesium-based energy storage systems and methods having improved electrolytes
US 9525191, Thomas Jefferson National Accelerator Facility, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory

Thermal Energy Storage

Nanoparticles for heat transfer and thermal energy storage
US 9080089, Argonne National Laboratory

Thermal energy storage apparatus, controllers and thermal energy storage control methods
US 9331483, Thomas Jefferson National Accelerator Facility, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory



Patent No. 9525191

Laboratory Partnering Service (LPS)

For up-to-date and additional information on all DOE available technologies, visit: labpartnering.org/

Technology-to-Market Programs Strengthen the Innovation Ecosystem

Energy I-Corps: Relevant Project Teams

CellSage: Idaho National Laboratory (Cohort 4). CellSage is an advanced research and development software tool that facilitates more comprehensive battery characterizations as well as diagnostics and prognostics of aging mechanisms.

GeoCAES: National Renewable Energy Laboratory (Cohort 4). This novel technology helps to identify additional locations for compressed air energy storage and lower costs by repurposing depleted hydraulically fractured gas wells for air storage.

Polymer Membranes: Sandia National Laboratories (Cohort 2). Polymer membranes play a crucial function in many energy and water technologies, including energy storage. The prototype poly (phenylene)-based hydrocarbon membrane separators are being tested for use in real-world applications by system customers and partner research institutions.

For additional and up-to-date Energy I-Corps project teams and more information visit: energyicorps.energy.gov/

Energy I-Corps

Energy I-Corps pairs teams of researchers with industry mentors for an intensive two-month training where the researchers define technology value propositions, conduct customer discovery interviews, and develop viable market pathways for their technologies.

Energy I-Corps is managed by DOE's National Renewable Energy Laboratory, which leads curriculum development and execution, recruits program instructors and industry mentors, and assembles teams from the following national labs:

Argonne National Laboratory; Berkeley Lab; Fermilab; Idaho National Laboratory; Lawrence Livermore National Laboratory; Los Alamos National Laboratory; NREL National Renewable Energy Laboratory; Oak Ridge National Laboratory; Pacific Northwest National Laboratory; Sandia National Laboratories

Technology Commercialization Fund

The Technology Commercialization Fund (TCF) leverages 0.9% of the Energy Department's annual budget for Applied Energy Research, Development, Demonstration, and Commercial Application to mature promising energy technologies with the potential for high impact.

The TCF helps businesses move promising technologies from DOE's National Laboratories to the marketplace. TCF projects receive at least an equal amount of non-federal funds to match the federal investment.

Select TCF Projects Relevant to Energy Storage

Earth Battery: Storing Energy with Compressed Air and Heated Brine in Porous Rock.
Lawrence Livermore National Laboratory.

Optimal, Reliable Building-Integrated Energy Storage.
National Renewable Energy Laboratory.

Low-Cost Battery Health Monitoring and Diagnosis System.
Pacific Northwest National Laboratory.

Evaluation of WattJoule's Vanadium Redox Flow Battery employing Sandia National Laboratories' membranes.
Sandia National Laboratories.

For additional and up-to-date TCF projects and more information visit: energy.gov/technologytransitions/services/technology-commercialization-fund

Learn More

Organizations may use several mechanisms to partner with the DOE National Laboratories in collaborative research and access the specialized capabilities of their facilities and experts.

The Office of Technology Transitions (OTT) engages with stakeholders, collects data, and evaluates impacts on DOE's partnering efforts. OTT uses this information to expand the commercial impacts of DOE research; implement the Energy Investor Center (EIC), the Technology Commercialization Fund (TCF), and Tech-to-Market initiatives; and streamline processes for partnering with the Labs.

Contact OTT to learn how to access technical experts, acquire the latest reports, identify promising energy projects, and locate DOE-funded technologies.

Email:
OfficeofTechnologyTransitions@hq.doe.gov

Website:
energy.gov/technologytransitions

Energy Investor Center (EIC)

The mission of the EIC, within OTT, is furtherance of America's technology leadership and economic competitiveness through targeted market engagement and commercialization of DOE's innovation portfolio. The EIC enables more and smoother technology hand-offs from the DOE Labs to market actors, as well as expanding the pool of potential capital providers to support these commercialization pathways.

- **Laboratory Partnering Service (LPS):** LPS is an online platform that enables public access to world-leading DOE National Laboratory energy experts, project marketing summaries, and licensing opportunities.
- **Laboratory-Investor Knowledge Series (LINKS):** EIC coordinates stakeholder meetings to connect DOE National Lab experts and technology program managers with investors to discuss market needs, DOE technology offerings, and resulting partnership opportunities.
- **Public Private Partnerships:** EIC works with market actors and investors to facilitate targeted partnerships with DOE Labs and Programs that maximize the nation's return on investment in the DOE innovation portfolio.

For more information visit: energy.gov/technologytransitions/eic

DOE-Led Webinars on Energy Storage

DOE and the National Labs often host webinars on many topics in Energy Storage. All past webinars are recorded and available on the internet.

To learn more about challenges, solutions, research areas, and technologies available for commercialization, visit: energy.gov/technologytransitions/eswebinars

Joint Center for Energy Storage Research,
jcesr.org/scientific-tools/electrochemical-discovery-laboratory/

Office of Technology Transitions
U.S. Department of Energy

The Office of Technology Transitions develops DOE's policy and vision for expanding the commercial impacts of its research investments and streamlines information and access to DOE's National Labs, sites, and facilities to foster partnerships that will move innovations from the labs into the marketplace.

U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

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