Written Statement of
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Chairman Murkowski, Ranking Member Cantwell, and Members of the Committee, thank you for the opportunity to testify in today's hearing on energy storage technologies.

My name is Dr. Vincent Sprenkle, and I manage the Electrochemical Materials and Systems Group at Pacific Northwest National Laboratory (PNNL) in Washington State. PNNL is a U.S. Department of Energy (DOE) multi-program national laboratory stewarded by the Office of Science. At PNNL, my group is focused on developing the next generation of battery technologies for energy storage applications and this will be the focus of my testimony.

My comments today will focus on three main areas:

1. Key technology breakthroughs achieved through PNNL's work on grid energy storage and how we have transferred those breakthroughs to the private sector.
2. Energy storage materials research being conducted at PNNL for next-generation electric vehicles.
3. Future research and development (R&D) directions for energy storage.

Background

The past decade has seen tremendous growth in the energy storage market, with significant increases in the number of energy storage systems sold for both the electric vehicle and stationary energy storage markets. Even with this growth, battery energy storage for transportation and grid-scale storage is still an early-stage application market. For example, in 2016, 160,000 electric vehicles were sold in the U.S.—accounting for roughly 1 percent of the 17 million vehicles sold. After a year of record growth, battery solutions for the stationary energy storage market are projected to reach 395 megawatts by the end of 2017 but will still only account for less than 0.1 percent of U.S. generation capacity. While additional robust growth in both battery storage markets is anticipated, significant R&D needs and opportunities remain for innovations across the technology-readiness spectrum that can lower the cost of energy storage while increasing performance, safety, and reliability.

The research being conducted at PNNL is at the forefront of energy storage R&D. It includes fundamental characterization of battery materials, development of next-generation materials to improve the desired performance of the battery, and creation of analytical models that can accurately represent the technical and economic impacts of real-world applications on battery performance.

DOE's Office of Electricity Delivery and Energy Reliability (OE) and Office of Science are the primary sponsors of grid energy storage research at PNNL. OE funds R&D of next-generation, cost-competitive energy storage technologies and works with industry stakeholders to ensure these systems are safe, reliable, and can meet the technical and economic needs of industry—all of which are essential to moving energy storage technologies to market. The Office of Science supports fundamental research in cutting-edge in situ characterization tools and first-principle materials design efforts, which are foundational to the development of the next generation of energy storage systems. These systems can ultimately cost less and perform better than the technology that is deployed today.

Energy storage R&D for next-generation electric vehicle batteries is supported at PNNL primarily by the DOE Energy Efficiency and Renewable Energy's Vehicle Technologies Office and is focused on developing and demonstrating new battery chemistries that can deliver two to three times greater energy density—resulting in longer driving range and lower cost compared to today's lithium-ion batteries.

Scientists at PNNL are able to leverage a unique suite of tools and facilities—from the advanced materials characterization instruments at the Environmental Molecular Sciences Laboratory (a DOE user facility) to PNNL's Advanced Battery Facility—to develop, prototype, and validate the performance of next-generation battery systems. For example, using the Environmental Molecular Sciences Laboratory's capabilities, PNNL is pioneering in situ characterization techniques that enable real-time evaluation of functioning electrochemical couples under transmission electron microscopy imaging and Nuclear Magnetic Resonance spectroscopy. These tools allow scientists to see the atomic and molecular processes that influence battery performance and lifetime, and they help us understand how battery materials are changing under actual charging and discharging conditions. These techniques are being applied today to several new battery materials being developed for DOE and industry clients and will provide the world with unparalleled insight into how various battery chemistries change during operation.

This research already is benefiting the nation. Since 2009, PNNL energy storage researchers have issued 375 peer-reviewed scientific publications and have been awarded 45 U.S. patents, which have been licensed to more than 20 companies. This research has been instrumental in accelerating the development of technologies that will enable storage to play a greater role in improving the reliability, efficiency, and resiliency of the electric grid and increase the driving range of electric vehicles.

Grid Energy Storage Research

Electric energy storage has long been a "holy grail" for grid operators—technology that can cost effectively improve the resiliency, reliability, security, and robustness of the power grid. Grid-scale energy storage presents a distinct set of opportunities and technical challenges. OE's Energy Storage Program supports a wide range of R&D and has identified four development priorities in its 2013 ***DOE Grid Energy Storage*** report.

Those priorities, which guide OE's investments in this area, are:

- The development of ***cost-competitive technologies*** through targeted scientific investigations of key materials and systems.
- ***Validated reliability and safety*** by independent testing of prototypic devices and understanding of degradation.
- Enabling ***standardization of energy storage valuation*** through industry, utility, and developer collaborations to quantify benefits and provide input to regulators.
- ***Industrial acceptance*** by facilitating highly leveraged, early-stage field demonstrations and development of storage system design tools.

Cost-Competitive Technologies: Falling costs of lithium-ion batteries and redefinition of market rules have enabled a significant increase in the amount of energy storage deployed for grid applications, such as short-duration frequency regulation. While lithium-ion chemistries were not designed specifically for grid services—and we don't fully understand the impacts of these services on their lifetime—they have proven the technical and economic viability of energy storage on the grid. Other battery technologies, like redox flow systems, may ultimately be a lower-cost alternative and contain sufficient energy capacity to enable these systems to meet multiple grid applications.

PNNL's pioneering work in vanadium redox flow batteries, which enabled a 70 percent increase in energy density and an 83 percent increase in temperature stability, overcame several of the barriers limiting flow battery commercialization, including cost competitiveness. Variations of this successful technology already have been licensed to eight companies. One such company, UniEnergy Technologies (UET), was started by two former PNNL scientists in 2012 and currently employs more than 60 workers at its facility, north of Seattle, Washington. To date, UET has installed 18.5 megawatt hours of commercial systems in the U.S. and abroad, and has an additional 365 megawatt hours under contract or award. This technology is starting to achieve cost parity with lithium-ion at a systems level after only five years of development—compared with the more than 25 years that lithium-ion cells have been in production. PNNL is currently developing the next generation of redox flow batteries, focused on replacing the vanadium species with engineered aqueous-soluble organic molecules that could further decrease the cost of flow battery systems by another 50 percent.

Validated Safety and Reliability: For energy storage systems to be ubiquitously accepted, the technology must be demonstrated to be safe and reliable. A scientifically-derived knowledge base must be developed and disseminated to industry that improves our understanding of the predictability of storage systems under a wide variety of conditions and enables the engineering of safer and more reliable systems. These efforts form the basis of new protocols, codes, and standards that ensure large-scale grid storage can be deployed safely and reliability.

At PNNL, researchers are evaluating the impact of grid services on battery performance and understanding how changes in the materials and interfaces are impacting the expected lifetime and safety of the systems. Along with Sandia National Laboratories, PNNL leads an Energy Storage Safety Working Group with stakeholders in the storage industry to focus R&D activity related to safety and to facilitate the development and deployment of codes, standards, and regulations affecting energy storage system safety. These efforts are critical to building consistency and uniformity in evaluating and ultimately deploying new battery technologies.

Enabling standardization of energy storage valuation: Science and technology efforts are critical to the deployment of energy storage, but alone cannot achieve the end state goal. Utilities at all levels—consumer-owned, investor-owned, municipalities—must have the capacity to understand the value of energy storage. State regulators need the same tools and data sets with which to evaluate energy storage, so they can provide the type of policy environment that leads to deployment.

Value propositions for grid storage often depend on identifying the institutional and regulatory hurdles to deployment and understanding how storage benefits can be evaluated when compared to other grid resources. At PNNL, staff are working with public service commissions across the country to provide the technical information needed to accurately evaluate the net benefits storage can provide to the system. In Washington and Oregon, PNNL is working with utility commission staff to develop planning tools that can both capture the monetized and non-monetized benefits of storage and provide an analytics framework for integrated resource planning that can accurately evaluate storage benefits.

This work complements research undertaken by the Grid Modernization Laboratory Consortium (GMLC), a strategic partnership between DOE and 12 national laboratories. The GMLC is developing a framework for valuation of the new grid technologies and concepts, including energy storage, so that government and industry stakeholders can work together to assess the benefits and costs of resilience improvement strategies. This partnership between DOE, national laboratories, states, and industry is an important collaboration in charting a timely path to a more resilient U.S. power system.

Industrial Acceptance: Demonstrating the economic value, performance, and reliability of early-stage energy storage systems in both controlled and fielded deployments is critical to achieving new technology validation. As part of Washington State's Clean Energy Fund, PNNL is performing technical and economic use case analyses, dispatch optimization, and performance monitoring in collaboration with five regional utilities that are deploying energy storage technologies for improved renewables integration and enhanced resiliency. This analysis will form the framework for systems-level analysis tools that can be used by utilities, regulators, and industry to accurately capture the locational value (monetized benefits and avoided costs) of energy storage deployments.

Most of the 3,000 utilities, municipalities, and cooperatives located in the U.S. have limited—or no—R&D budget to examine the benefits of storage. PNNL, along with partners at Sandia National Laboratories and Oak Ridge National Laboratory, is actively engaged in helping utilities understand the locational benefits energy storage can provide to their systems by developing analytical models that accurately capture the entire benefit proposition. As part the GMLC, PNNL staff recently completed a detailed analysis with Portland General Electric (PGE) on its 5 megawatt/1.25 megawatt hour Salem Smart Power Energy Storage Demonstration project. This study showed that PGE could utilize the facility for the Western Energy Imbalance

Market to derive an additional $150,000 in revenue every year, and that additional benefits could be realized as the energy capacity of the battery was increased to 10 times its current duration—resulting in clear economic value and performance increase while providing additional reliability to the system. Under the same project, our partner laboratories are working with Electric Power Board of Chattanooga, Tennessee to add energy storage to its automated power management system to form one of the most advanced smart grids in the country and serve as a living laboratory for future grid modernization technology.

Energy Storage Research for Electric Vehicles

Making electric vehicles with smaller, lighter, less expensive batteries requires research across multiple DOE programs. The Joint Center for Energy Storage Research (JCSER), funded through DOE's Office of Science, undertakes fundamental research to serve as a foundation to develop game-changing, next-generation battery technologies. Argonne National Laboratory leads JCSER, which includes other national laboratories, universities, and industry partners. DOE's Battery500 Consortium, funded through DOE's Energy Efficiency and Renewable Energy Office, is focused on doubling the energy storage of existing battery materials while also producing a high-performance battery that is reliable, safe, less expensive, and can be easily adopted by manufacturers. This is a significant challenge requiring technical expertise across the U.S. R&D sectors and PNNL, as lead of the Consortium, has the support of partners including other national laboratories, universities, and industry.

DOE's investments in advanced energy storage technologies will transform vehicle transportation. Today, lithium-ion batteries are the dominant technology for electric vehicles. On average, it takes 4.5 pounds of batteries to travel one mile. Meeting the Battery500 goals would enable that same 4.5 pounds of batteries to travel 2.5 miles, thereby increasing the overall range—or decreasing the cost of the electric vehicle when the range is kept constant. To accomplish this goal, the Consortium's aim is to double the "specific energy" of electric vehicle batteries. "Specific energy" measures the amount of energy packed into a battery based on its weight. Current batteries contain approximately 200 watt-hours per kilogram and will need to achieve 500 watt-hours per kilogram by the end of the program.

To meet the goals of the Battery500 Consortium, a novel approach is being used that integrates the best materials and battery researchers across the country to solve some of the most difficult science and technology challenges. For example, the Consortium will require replacing graphite with lithium-metal as the battery's negative electrode. Fundamental research will aim to understand how this new electrode interacts with other battery components and how to control those interactions to achieve the desired performance with a lifetime comparable to today's technology.

Future Research Directions

The U.S. pioneered the development of modern battery technologies, including the widely used lithium-ion batteries. Our leadership in this area is constantly challenged as the appetite for energy storage is growing around the world. Maintaining a leadership position in the next generation of energy storage technologies requires a continued commitment across the following areas:

- ***Science and technology investments:*** Sustained fundamental science and applied research is necessary to improve the tools and techniques available to develop the next generation of safe, low-cost, high-performance energy storage technologies. We cannot predict, based on scientific principles alone, the performance, safety, and reliability of new battery systems. Continued and focused research capable of understanding new energy storage systems at the component and interfacial level is required to address these challenges. New breakthroughs, based on these fundamental understandings, will take many years to ultimately yield low-cost, high-performance, and safe batteries for all applications. Ongoing developments in applied sciences—including sophisticated capabilities in materials synthesis, battery design/agile manufacturing, testing validation, and predictive computational tools, such as are available at DOE's national laboratories—are also required to move these technologies closer to practical realization. Integrated science and technology investments across the spectrum of fundamental science and applied research will ultimately yield technologies that can meet the cost and technical requirements of the market.

- ***Advanced Manufacturing/Prototyping:*** To accelerate the commercialization of breakthrough technologies, new manufacturing R&D is required to quickly move ideas from innovation to energy storage systems that are manufactured in the U.S. Common manufacturing architectures that provide a platform to accelerate the innovation coming out of universities, national laboratories, and small business can enable next-generation storage technologies to be validated and tested quickly and with minimal development time. There also must be a focus on the applied sciences to prototype and test these new systems at small-scale under real-word grid operating conditions. This is of particular importance for grid-scale storage, since the reliability and lifetime of new systems must be fully validated and understood before entering service on the grid. The information gained from this testing also provides the feedback loop needed for scientists and engineers to continue closing the gap between the often high theoretical potential of a new material and the much lower practical energy storage capacity and lifetime demonstrated in real-world systems.

- ***Technology Demonstrations***: Given the vast difference in expected lifetimes for grid storage (20-30 years) and transportation (5-7 years), additional technology demonstrations for grid technologies will be needed across the country to build confidence in the performance, lifetime, safety, and benefit to multiple low-cost grid applications. Energy storage demonstrations are taking place now with most new technologies receiving federal or state funding to share the risk with utilities. Continued demonstrations of energy storage in different regions of the U.S. builds confidence that energy storage is a viable technology option and can provide multiple grid services. Demonstrations that focus on validating life-cycle cost, performance, and safety for multiple grid applications, and that assess the overall benefit relative to grid reliability, resilience, and renewable integration, are critical to both long-term and near-term success in getting energy storage technology deployed on the grid. Additionally, with federal and state support, the lessons learned from these demonstrations can be shared across the entire utility community to enable those utilities with limited resources and opportunity to more effectively and efficiently determine where energy storage can contribute to their grid applications.

- ***Analysis and Control Systems****:* As the world moves towards a more decentralized electricity infrastructure, the impact of both electric vehicles and grid storage as a part of the suite of distributed energy resources (DER) must be analyzed and optimized to maintain desired reliability. Each of the more than 3,000 utilities in the U.S. will have different challenges and will recognize different benefits depending on the location and mix of these DER assets. Most utilities have little or no R&D capacity to fully analyze and determine the impacts of new energy storage systems or the increased adoption of electric vehicles. Uniform codes and standards—voluntarily accepted by industry—that allow interoperability between different technologies and software interfaces are required to ensure that new technologies can plug-and-play into the existing grid operations system when and where they are most needed. Advance controls must be developed that can autonomously determine the state of health of the energy storage system and determine the optimal energy dispatch parameters to reduce degradation and derive maximum value from the device. These control systems must be able to coordinate with other DER assets to aggregate for a specific service or function (e.g., islanding for resiliency). Finally, demonstration programs that can implement large-scale testing and validation of these control systems are needed to help instill user confidence and ensure the desired resiliency of the distributed energy assets.

Conclusion

While there is significant convergence of electric vehicles and grid storage as the grid utilizes a greater number of DER assets, the materials challenges for these systems are distinctive. While there are initial high-value-added market applications for energy storage today, there is a continuing need to reduce the cost and increase the performance to realize the full set of benefits energy storage offers. For large-scale battery systems to continue finding widespread application in the grid, they must ultimately reach costs and lifetimes comparable with other grid assets. This requires ultra-low-cost materials capable of being deployed for over 20 years. For electric vehicle applications, a different set of materials will provide the increased energy density needed to double their driving range in the future. Unlocking the full potential of U.S. researchers to address the fundamentals of energy storage, discover new materials, and rapidly translate these discoveries into practical applications is necessary to ensure that the U.S. remains a leader in energy storage technologies.

Thank you again for the opportunity to testify. I look forward to answering any questions you may have.