Written Statement of

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Innovation in Battery Storage for Renewable Energy

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Introduction

Chairman Weber, Ranking Member Grayson, and Members of the Subcommittee, thank you for the opportunity to testify in today's hearing on *Innovations in Battery Storage for Renewable Energy*.

My name is Jud Virden, and I am the Associate Laboratory Director for Energy and Environmental research at Pacific Northwest National Laboratory (PNNL) in Washington State. PNNL is a U.S. Department of Energy, Office of Science multi-program national laboratory operated by Battelle.

My comments will focus on four main areas:

1. The current state of the grid energy storage research at PNNL, including the primary areas of battery technology and chemistry being explored.
2. Key technology breakthroughs achieved through PNNL's work on grid energy storage and how we have transferred those breakthroughs to the private sector.
3. Next steps in research and development (R&D) and technology deployment necessary to meet stated goals for grid energy storage performance.
4. The impact that these new technologies can have on the energy market, particularly renewable power, if stated goals are met.

Current State of Grid Energy Storage Research at PNNL

PNNL's Grid Energy Storage program covers a broad spectrum of research and development. Our scientists focus on the development and application of unique scientific tools and computational models to understand fundamental material and chemical processes in batteries. Our material scientists and engineers develop new battery materials, and perform testing and evaluation of novel prototype battery systems. Our grid system engineers perform system analysis to predict the cost and performance requirements for energy storage grid applications, along with the development of consistent testing protocols, safety codes, and standards. We collaborate with universities, utilities, battery providers, software developers, and state governments. These integrated efforts are focused on creating energy storage technologies that will enable our future grid to be more resilient, reliable, secure, and flexible so that it can incorporate more renewable energy, utilize loads as a resource, and provide enhanced resilience against energy outages.

Our primary sponsors for grid energy storage research are the Department of Energy's Office of Electricity and Office of Science. PNNL supports the Office of Electricity through research and development of next-generation cost-competitive energy storage technologies, and validated reliability, safety, and industry acceptance of those technologies. With support from the Office of Science's Basic Energy Science (BES), PNNL is a key member of the Joint Center for Energy Storage Research (JCESR) led by Argonne National Laboratory. In JCESR, we collaborate with Lawrence Berkeley National Laboratory and Sandia National Laboratories, University of Michigan, Stanford, Massachusetts Institute of Technology, and many other partners. The Office of Science also supports an Energy Frontier Research Center (EFRC) at PNNL: the Center for Molecular Electrocatalysis. This center aims to develop low-cost catalysts to replace precious metals for energy conversion and storage. We utilize the Environmental Molecular Science Laboratory (EMSL) at PNNL, which is a Department of Energy, Office of Biological and Environmental Research national scientific user facility. EMSL's mission is to enable molecular-level discoveries that translate to predictive understanding and accelerated solutions for national energy and environmental challenges. Through the DOE Office of Energy Efficiency and Renewable Energy's (EERE) role in the DOE Grid Modernization Laboratory Consortium, PNNL evaluates integration of renewable on the grid including energy storage. PNNL evaluates a variety of energy storage options through EERE's Building Technology Office in combination with transactive control of buildings to mitigate renewable generation variability.

PNNL's scientific R&D is focused on electrochemical energy storage (batteries). Specifically, we are involved in the scientific understanding and development of a variety of next-generation low-cost battery chemistries including aqueous and nonaqueous redox flow (vanadium, zinc-iodine), lithium ion, lithium-sulfur, and sodium batteries.

Technology breakthroughs and their transfer to private industry

Since 2009, PNNL's grid-scale energy storage research has led to more than 298 publications, 216 invention reports, 91 U.S. patents filed, 19 patents granted to date, and seven licenses to U.S. based companies. It is our outstanding technical staff, in combination with state-of-the-art characterization tools, modeling and simulation capabilities, and testing protocols that allows us to rapidly transform fundamental discoveries into practical applications.

PNNL scientific research and development. Today, we cannot predict — based on scientific principles — the performance of new battery systems. Understanding the atomic- and molecular-level processes that govern their operation, performance limitations, and failure processes is one of critical areas of battery research being addressed by scientific institutions around the world. To develop this understanding will require advances in situ tools and techniques that, in combination with advanced modeling and simulation, allow us to first see and then predict how atoms and molecules change structures and react under real-world operating conditions.

With Office of Science funding, and by taking advantage of the scientific capabilities at EMSL, PNNL is pioneering in situ transmission electron microscopy (TEM) to attack this challenge. TEM allows scientists to see the atomic and molecular processes that influence battery performance and lifetime. In situ characterization techniques allow scientists to see how battery materials are changing under real operating conditions while charging and discharging — as opposed to the old approach where we had to charge and discharge a battery, then take it apart and characterize the materials to try to figure out what happened. We are applying this new technique to several battery materials under a variety of DOE projects and, with additional improvements to the approach, will provide the world with some of the first views of fundamental material and chemical processes in a battery while the battery is charging and discharging. Using this technique, scientists at PNNL recently published the first in situ study of why lithium ion batteries short out and fail. This groundbreaking work also has confirmed a new approach that might dramatically extend the lifetime of lithium batteries.

PNNL scientists also have utilized a wide range of state-of-the-art nuclear magnetic resonance (NMR) spectrometers, including a unique micro-battery design for studying battery chemistry under realistic conditions. NMR allows researchers to measure how battery chemistry is changing under battery operation. Changes in materials chemistry often lead to loss of capacity and reduced battery life. PNNL applied NMR techniques to understand the fundamental chemistry in the novel mix acid redox flow battery, and we are currently applying NMR, TEM, and other techniques to help understand the electrolyte chemistry in advanced energy storage materials as part of the JCESR.

PNNL breakthrough transferred to the private sector. One of our most recent exciting breakthroughs coming out of PNNL is the development of a mixed acid vanadium redox flow battery that increased energy capacity by 70 percent with a much wider temperature range of operation, making it significantly more practical for real-world applications. The approach was especially exciting because the mixed acid chemistry in this battery went against mainstream thinking, opening a new and promising area of battery development. This research started with DOE Office of Electricity funding to explore new approaches to dramatically improve flow battery performance. The research leveraged scientific staff and advanced characterization tools at the Office of Science's EMSL user facility.

Through an approach that involved both theoretical computations and experimental validation, PNNL scientists and engineers evaluated many electrolyte options, ultimately determining that the mixed acid system promised the most dramatic improvements. Five small U.S.-based companies (based in Washington State, California, and Massachusetts) have subsequently licensed the PNNL technology and are further developing it for private sector grid applications. One of those companies, UniEnergy Technologies (UET), was started by two former PNNL scientists in 2012, and has grown to 50 employees. UET is deploying its novel flow battery technology in Washington, California, and Germany. UET's project with Avista Utilities in Pullman, Wash., was featured last week in the New York Times (*Liquid Batteries for Solar and Wind Power*, April 22, 2015). The $7 million demonstration project on the Schweitzer Engineering Laboratories campus is being tested as an uninterruptible power supply: In case of a power failure, the batteries in UET's storage containers can keep the company's manufacturing operations running for three hours.

PNNL testing, evaluation, and validation activities. PNNL is also involved in several regional activities to independently test and evaluate battery system performance in real grid applications. In the Pacific Northwest, as part of Washington State's Clean Energy Fund, PNNL has been asked to perform technical and economic use case analyses, dispatch optimization, and performance monitoring in collaboration with three regional utilities that are deploying energy storage technologies in the field. In another example, PNNL worked with Puget Sound Energy to address four questions relative to the practical deployment of energy storage on the grid: 1) Where should energy storage be sited and at what scale to maximize value in the Puget Sound Energy system? 2) What services can energy storage provide and what values are derived from these services? 3) How do we build and test an energy storage control strategy to maximize value? And, 4) When optimized to maximize value, do the modeled benefits exceed the revenue requirement for the battery system? Our analysis of several sites determined a single site where a 3MW (9-12 MWh) battery system would yield a positive return based on reducing outage mitigation, capacity value, deferral upgrades, and inter-hour balancing.

Energy storage and renewable generations. Energy storage also can smooth out the fluctuations in power flow caused by the variable nature of wind and solar sources. PNNL performed a high level study (PNNL report 21388) for the DOE Office of Electricity, determining that more than 18.6GW of additional inter-hour balancing capacity is needed if renewables represented 20 percent of U.S. generation capacity by 2020. Energy storage would be key to enabling high market penetration. The study also highlighted the need for lower cost energy storage technologies to compete effectively against other technologies such as combustion turbines and demand response.

Finally, PNNL is working with DOE and Sandia National Laboratories to develop proposed testing and evaluation protocols (*Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems*, PNNL-22010). PNNL also is actively involved in the development and deployment of codes, standards, and regulations affecting energy storage system safety (PNNL reports 23578 and 23618). These DOE Office of Electricity activities are critical to building consistency and uniformity in evaluating and ultimately deploying new battery technologies

What next steps in R&D and technology deployment are necessary to meet stated goals for grid energy storage performance?

The key research and development issues that need to be addressed for near-term deployment of advanced batteries and for longer-term next-generation energy storage include:

1. *Key Scientific Challenges*. Sustained fundamental science and applied research continues to improve the tools and techniques available to develop the next generation of safe, low-cost, high-performance grid energy storage technologies.
2. *Key Development Challenges*. Independent evaluation and validation of next-generation energy storage technologies to validate cost, performance, and safety over and the continued development of uniform codes and standards that allow interoperability between different technologies and software.

3. *Key Demonstration Challenges*. Regional demonstrations of energy storage for multiple grid applications that validate the life-cycle cost, performance, safety and overall impact of batteries on grid reliability, resilience, and renewable integration.

Key scientific challenges and next steps. We cannot predict, based on scientific principles alone, the performance of new battery systems. Battery systems consistently perform well below their theoretical potential. In 2007, the Department of Energy assembled experts from throughout the U.S. and the world to assess the basic research needs for electrical energy storage. While many advances have been made in the last eight years, the primary conclusions of the report (*Basic Research Needs for Electrical Energy Storage, Department of Energy, Office of Science, Basic Energy Sciences, 2007)* are still valid and represent the key challenges to be addressed over the next several decades:

> *…Although electrical energy storage devices have been available for many decades, there are many fundamental gaps in understanding the atomic- and molecular level processes that govern their operation, performance limitations, and failure. Fundamental research is critically needed to uncover the underlying principles that govern these complex and interrelated processes. With a full understanding of these processes, new concepts can be formulated for addressing present electrical energy storage technology gaps and meeting future energy storage requirements.*

The report also calls out four critical crosscutting research directions required to meet future technology needs for electrical energy storage: advances in characterization, nanostructured materials, innovations in electrolytes, and theory, modeling, and simulation. In addition to EMSL, other scientific user facilities play an important role in advancing this research, including: National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory, Integrated Center for Nanotechnologies (CINT) at Sandia National Laboratories, and Advanced Photon Source at Argonne National Laboratory.

PNNL strongly supports the continued and focused efforts of the scientific community to address these scientific challenges and research directions. New breakthroughs based on an improved fundamental understanding will take many years to ultimately yield low-cost, high-performance, safe batteries for all grid applications. There must also be a focus on the applied sciences to accelerate the transfer of fundamental understanding to new battery systems. This is best accomplished by testing new materials systems in small-scale prototypes under real-word grid operating conditions. The information gained from this small system testing capability provides the feedback loop needed for scientists and engineers to rapidly close 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.

Key development challenges and next steps. There are more than 3,000 utilities in the U.S. with different grid challenges (transmission and distribution congestion, peak demand, renewable integration, severe weather events, etc.), depending on location, energy mix, and infrastructure. Most have little or no R&D capacity, and cannot assume the large amount of risk inherent in developing and testing new energy storage materials or in validating their performance or safety without passing those costs on to consumers. We consistently hear from utilities and state governments that an independent evaluation and validation of next-generation energy storage technologies is needed to provide confidence in new battery performance and safety. Along with this is a need for uniform codes and standards that allow interoperability between different technologies and software interfaces. This is key to ensure that new technologies can plug and play into the existing grid operations system.

We believe that more efforts need to focus on independent testing and validation of new battery technology for grid applications. This would involve independent testing at a cell level, stack level and system level. Testing and evaluation also needs to include validation of both the power control system and the software that interfaces to existing utility management systems. Consistent codes and standards that allow multiple technology options (there are many types of batteries) while still providing interoperability between all technologies (i.e., plug and play) are important for an emerging market.

Key demonstration challenges and next steps. Energy storage demonstrations are taking place around the country, but we will need more. Most are supported by federal or state funding, sharing the risk with utilities. Most demonstrations are for higher value grid applications. As new lower cost energy storage technologies are developed over the next decade, demonstrations will still be important to build confidence in performance, lifetime, safety, and benefit to multiple low-cost grid applications.

Continued demonstrations of energy storage for multiple grid applications are needed, in different regions of the U.S., to build confidence that energy storage is a viable technology option. 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. Ideally, lessons learned would be shared across the entire utility community to enable utilities with limited resources and opportunity to more effectively and efficiently determine where energy storage can contribute to their grid applications.

What impact could these new technologies have on the energy market, particularly renewable power, if stated goals are met?

Electric energy storage has long been the "holy grail" for grid operators. The ability to store electrons at the distribution and transmission level would allow an unprecedented ability to fully utilize both centralized and distributed renewable energy. Energy storage will also allow grid to improved reliability and resiliency, by meeting a variety of services. Grid energy storage can improve both grid reliability and resilience by providing a local "cushion" against shocks to the system caused by interruption of generation or by loss of circuit connection at either the bulk (transmission) system level or in the more local distribution system. Local energy storage can buffer users from short-term power problems by supplying the necessary energy and ancillary services needed to provide "ride-through" during system events and help in re-stabilizing the grid. Finally, energy storage adds flexibility in how we collect and use electric energy, even providing energy usage time shifting where needed in order to better match variable sources to variable loads. Overall, the industry has identified more than 30 uses for electric storage on the grid, making the combination of storage, power electronics, and advanced controls into a new general-purpose grid component that is as fundamental as a transformer or a circuit breaker.

There are a variety of analyses in the public literature that estimate the size of the future global energy market. A 2010 report by the Electric Power Research Institute (*Electric Energy Storage Technology Options; A Primer on Applications, Costs & Benefits*) describes a 50GW market size (roughly ranging from $5 billion to $25 billion) if low-cost ($100/kWh to $500/kWh) energy storage technologies can be developed and deployed. Other estimates forecast worldwide markets exceeding $100 billion over the next five years.

Summary

The U.S. electric grid and U.S. citizens would benefit greatly from the widespread use of low-cost, reliable, and safe energy storage. It will truly enable distributed and centralized renewable energy, while increasing transmission and distribution reliability and resiliency. While there are early high-value-added market grid applications for energy storage along with an emerging collection of U.S. battery providers, there still is a need to dramatically reduce the cost of effective energy storage over the long-term. 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 new technologies are U.S. born and raised.

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