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Energy Landscape. The energy landscape must rapidly change to address the urgent needs for environmental sustainability and greater resiliency of our energy infrastructure. Two major opportunities are electrification of transportation and integration of renewable forms of energy generation into the electric grid. Both of these changes depend on energy storage. Electric vehicles require high power portable energy where drive distance, charge time, lifetime, safety, and vehicle cost are all considerations. The broad implementation of renewable energy sources such as solar and wind is challenged by their intermittency. Thus, methods to reliably and safely store the energy and allow later release are needed to enable integration of renewables into the electric grid.

Energy Storage. Batteries function by taking chemical energy and turning it into electrical energy and serve key functions as sources of portable power. As applications evolve, new batteries must be invented or adapted to meet the needs of the new use condition. For example, while in industry, my main project was the development and launch of the battery for the implantable cardiac defibrillator. The battery that we developed was the first that provided the needed power and longevity with the requisite safety and reliability to make the device clinically viable and thus, it enabled the widespread deployment of implantable defibrillators. These devices are life-saving as they can respond quickly if the patient has onset of ventricular fibrillation that is often fatal without intervention.

As a second example, lithium ion batteries were critical to the widespread adoption of portable electronics such as laptop computers and cell phones, due to their high energy content and lightweight. This application demands batteries that may last 3-5 years as the devices become obsolete quickly. In contrast, electric vehicles demand batteries that are much larger and last up to 10 years so that they do not need to be changed for the life of the car. Considering grid level storage, the desired lifetimes are 10-20 years such that the installed infrastructure does not need to be changed frequently. These differences in lifetime as well as specifics in function require that new generations of batteries be developed. It is the evolution of the applications that are motivating the investigation and development of new generations of batteries.

Research and Development Structure. Complex problems, such as energy storage systems, are best addressed by teams of people from different backgrounds brought together for a purpose. An example I use here is the structure of the Energy Frontier Research Centers (EFRCs), funded by the Basic Energy Sciences program in the Department of Energy (DOE) Office of Science. With funding of approximately $2-4 million per year and a term of 2 to 5 years, each Center provides a vehicle to assemble scientists, talented in their own right, to focus on issues beyond the ability of one scientist to deliver on their own, bringing experts from universities and national laboratories together. When led by visionary and insightful leaders the outcomes can be remarkable. As an analogy from the Arts, imagine a symphony orchestra. Each musician is a virtuoso, with distinct talent and expertise. Brought together by a knowledgeable conductor who understands the music a grandeur of sound results beyond that possible from an individual. This holds for science as well when the leader has the deep knowledge and understanding of the problem and the opportunity to bring the collective solutions forth from synergistic engagement of the participants, remarkable scientific and technical achievements can result.

As a specific example, I direct the EFRC, The Center for Mesoscale Transport Properties. Over the first fours years 2014-2018, our mission was to establish a comprehensive understanding of ion and electron transport mechanisms over multiple length scales in energy storage systems. To reach our goals, the center investigators included experts in materials synthesis, characterization over multiple length scales from the atomic scale to the full battery, electrochemistry, and multilength scale theory and modeling. Through effective interaction, the center was highly effective at determining transport limitations at the atomistic, particle, aggregate, electrode, and system levels. This information provides the fundamental insights needed to move toward optimal design and synthesis of active materials, formulation and processing of electrodes, and battery design. From 2018-2022 our mission is to build the scientific knowledge base necessary to enable future creation of scalable electrochemical energy storage systems. Existing materials and electrode constructs suffer transport limitations that inhibit design of scalable electrodes necessitating compromise of either energy content or power delivery. Thus, we are considering the constructs needed for deliberately scalable architectures as well as materials suitable for low cost and safe large-scale energy storage.

Knowledgeable leadership and a talented team also require cutting edge instruments and tools to be successful. Historically, batteries were developed using an Edisonian approach based on trial and error. New successful battery types are not introduced often as the changes and implementation of new designs, materials, and manufacturing processes may take decades. Even after the batteries are deployed in the marketplace, full understanding of how they work lags behind. Only 10-15 years ago the best way to understand the function of the battery was destructive analysis - to test it then cut it open and examine the parts. The limitation is that the battery components may change significantly, limiting the usefulness of the resulting data. Today, synchrotron devices such as the National Synchrotron Light Source II at Brookhaven National Laboratory supported by the DOE's Basic Energy Sciences program provide high energy x-rays that can be tuned to very small beams, often smaller than the diameter of a human hair. These x-ray beams are powerful enough that they can penetrate battery housings, including special configurations and commercially built batteries. The x-ray beams are then used to follow the reactions of the battery as it is working. This can be done in real time to capture time-dependent mechanisms and it can also be done where spatial location or mapping are conducted to determine the location of the reaction or the transformation. These operando measurements conducted on functioning batteries are allowing unprecedented insight into mechanisms that are taking place. Thus, we can now deliberately design the next generation of battery based on the knowledge that we have gained through the ability to track its internal function. We can move ahead in a more deliberate way based on the insights that were obtained.

The fundamental insights provide a path by which the knowledge can be used to advance product development. The concepts first demonstrated in the laboratory can then be targeted to the specific needs of the applications. The information then becomes relevant to the private sector where adoption for commercialization can proceed.

I elaborate here three categories of the impact of scientific research. The first is the scientific impact as it lays the foundational understanding needed for new energy technologies. The second is broader scientific impact where the fundamental scientific findings foster interest and interaction beyond basic science and the third is impact beyond the research arena where benefits to society can be realized. I provide several examples from our own research. Research as part of our EFRC demonstrated that synthetic control of material physiochemical properties can have significant impact on the resultant electrochemistry. As a result of our findings, we were able to initiate a program with the Department of Energy Office of Electricity Delivery and Energy Reliability through Sandia National Laboratory to exploit synthetic material tuning in systems directly applicable to large scale storage. The second example is an outgrowth of our demonstrated ability to modify material surfaces to favorably influence their electrochemistry. Based on the insights, we attracted funding from the Vehicle Technology Office of the Department of Energy's Energy Efficiency and Renewable Energy organization to enable fast charge, less than 10 minutes, of lithium ion electric vehicle batteries. Based on our patented approach, we were then able to attract funding from the Office of Technology Transfer through the Technology Commercialization Fund to demonstrate the process at scale. A third example stems from our EFRC findings where we demonstrated the ability to measure the heat generated by an active battery to probe reactions of electrolyte at the electrode surface as a function of the battery voltage. These sensitive and precise measurements were recognized as industrially relevant where we could understand material and battery stability in a relatively short timeframe compared to many months or years of testing. We are pursuing this topic more expansively funded by an electric vehicle company for systems relevant to their application.

<u>Workforce development</u>. The time that I spent in industry was highly rewarding as the battery that powered implantable cardiac defibrillator devices has saved millions of lives. However, my direct interaction with those that were impacted was limited. One of the motivations in my transition from industry to academics was the ability to impact the next generation of scientists and leaders more directly. The graduate students and post-doctoral researchers in our research group represent the future. They are diverse in terms of scientific, cultural, gender, and ethnic backgrounds. They leave our research group well educated and have moved to a variety of careers including faculty at universities and colleges, scientists at National Laboratories, and Industrial scientists and engineers. They will contribute to solving the issues of the future.

The structure of the EFRCs also provides a venue for young investigators to participate in addressing significant and complex science questions. In the Center that I direct, the young investigators interact with the established scientists, gain exposure to both academic and national laboratory research environments, and witness first-hand the benefits of research conducted in a cohesive collaborative manner. These young investigators gain the needed skills to become the scientists and leaders of tomorrow.

Importance of the Field. In many ways, the pursuit of technology relevant to the energy sector is a race where the entire energy landscape will change quickly over the next 10-20 years. This is recognized internationally and thus, there is significant investment taking place worldwide. It is known that access to reliable energy is directly tied to standard of living and quality of human life. It is also recognized that unlimited burning of fossil fuels cannot continue forever. Thus, transformation of how energy is generated, stored, and used is imperative. Decisions in this arena will determine who leads and who follows in the new global energy economy.

Summary. The funding for the Department of Energy Basic Energy Science has proven to be critical on multiple fronts. The research support has proven exceptionally valuable to gain fundamental scientific insights. The support of young investigators as part of the research initiatives is imperative to ensure the availability of an educated workforce. Further, Department of Energy Basic Energy Science funded research facilities are enabling unprecedented insights into energy related systems. Thus, the funding remains critical for the talent development, research, and facilities/tools that will help the nation realize if not lead the energy revolution through many diverse applications of energy storage and batteries.