Written Statement of

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Introduction

Chairman Bowman, Ranking Member Weber, and Members of the Subcommittee, thank you for the opportunity to participate in today's discussion on *Climate and Energy Science Research at the Department of Energy*.

My name is Fikile Brushett and I am an Associate Professor of Chemical Engineering at the Massachusetts Institute of Technology (MIT) where I hold the Cecil and Ida Green Career Development Chair. I am also a contributor to the Joint Center for Energy Storage Research (JCESR), an Energy Innovation Hub sponsored by the Department of Energy (DOE), Office of Basic Energy Science (BES) in the Office of Science. In JCESR, I currently serve as the Research Integration co-Lead and as a member of the Executive Committee.

My comments to the Committee will focus on my career development and the important role that science, technology, engineering, and mathematics (STEM) education and research opportunities, enabled by BES support of universities and national laboratories, have played in my growth as a scientist, mentor, and leader.

The Brushett Research Group

To provide some context to my testimony, let me briefly describe my educational background and current research activities.

I received my undergraduate degree in Chemical and Biomolecular Engineering from the University of Pennsylvania in 2006 and my graduate degree in Chemical Engineering from the University of Illinois at Urbana-Champaign (Illinois) in 2010. My doctoral thesis, under the supervision of Professor Paul J.A. Kenis, focused on microfluidic fuel cells as portable power sources and diagnostic platforms for analyzing the performance of catalysts and electrodes. From 2010-2012, I was a Director's Postdoctoral Fellow at Argonne National Laboratory (Argonne) in the Electrochemical Energy Storage Group working under the supervision of Dr. John T. Vaughey. I began my independent career in the Department of Chemical Engineering at MIT in 2012, rising from an assistant professor (2012 – 2018) to an associate professor without tenure (2018-2020), to now an associate professor with tenure (2020 – present).

The objective of my research program is to advance the science and engineering of electrochemical technologies, such as advanced batteries, needed for a sustainable energy economy. My group seeks to understand and control the fundamental processes that govern the performance, cost, and lifetime of present day and next-generation electrochemical systems for energy storage and conversion. Our approach combines synthesis and characterization of redox active materials, design and engineering of electrochemical reactors, and techno-economic modeling of electrochemical systems. We place a strong emphasis on connecting system-level performance and cost goals to materials-level property requirements and on leveraging this knowledge to guide exploration of new chemistries and reactor designs. Ultimately, we aim to develop robust and portable guiding principles for the design of materials, processes, and devices that harness electrochemical phenomena. Pursuant to this goal, I have established and continue to grow a diverse and innovative research portfolio. The students and postdoctoral associates in my group, together with JCESR colleagues and other collaborators, are tackling important challenges in grid energy storage and environmental stewardship. We are also expanding our work to include the role of electrochemical processes in manufacturing to reduce energy use and to enable transformations infeasible via traditional methods. My teaching and service contributions focus on educating and empowering engineers to conceive, develop, and implement electrochemical solutions to critical global energy and sustainability challenges.

During my pre-tenure career, the bulk of my research activities focused on the development of redox flow batteries (RFBs) for stationary energy storage. In brief, electrochemical energy storage has the potential to play an important role in enabling a sustainable, resilient, and cost-effective electric power system by facilitating the integration of intermittent renewable resources (e.g., wind, solar) as well as by extending the lifetime and improving the efficiency of existing grid infrastructure. Redox flow batteries are rechargeable batteries where the charge-storing materials (redox species) are dissolved in liquid electrolytes which are stored in external tanks and pumped to a power-converting reactor where they are oxidized and reduced to alternately charge and discharge the battery. As compared to other rechargeable batteries (e.g., lithium(Li)-ion batteries), RFBs have several key advantages that are particularly relevant for grid energy storage including independent power (reactor size) and energy (tank size) specification, long operational lifetimes and easy maintenance, simplified manufacturing, and improved safety characteristics. While state-of-the-art RFB technologies have achieved success in niche applications, present embodiments are too expensive for ubiquitous adoption. In general, these limitations arise from a combination of high materials costs and low cell voltages, due to the small electrochemical stability window of aqueous electrolytes. Opportunities exist for transformative advancement through the discovery of inexpensive redox couples and associated electrolyte formulations, the development of high-performance electrochemical reactors, and the establishment of manufacturing capabilities for charge-storing materials and battery systems. To date, my research activities have focused on the former two.

Without my postdoctoral experience at Argonne National Laboratory, my collaborations with other academics, national laboratories, and industry enabled by DOE BES funding, my progress in this area would have been significantly slower and I would have sought other “safer” but less impactful research directions closer to my graduate training.

Postdoctoral Research at Argonne National Laboratory

As I neared the completion of my Ph.D. at Illinois, I realized that I wanted to learn more about energy storage, in particular rechargeable batteries. In searching for a postdoctoral position that would allow me to do that, I considered working under the supervision of a leading battery scientist at a top-tier academic institution, but ultimately decided to pursue an opportunity in the Electrochemical Energy Storage group in the Chemical and Engineering Sciences Division at Argonne. There were several professional and personal reasons for this decision. I will limit my comments to the former.

From the professional development perspective, Argonne offered a rapid and broad introduction to the battery field. At an academic institution, there are typically 1-2 faculty studying energy storage, each typically pursuing fundamental research on a narrow aspect of a particular battery system. Thus, while I would have had an opportunity to learn from a leading expert, the breadth of knowledge to be gained was limited. In contrast, the battery research group at Argonne was composed of dozens of professional researchers of diverse scientific backgrounds pursuing a wide variety of interconnected problems in battery systems, ranging from modeling atomistic phenomena to "building-and-breaking" battery packs. This breadth of research activities within a single group provided an opportunity for a neophyte like me to immerse in battery science and engineering. Furthermore, Argonne offered access to cutting-edge science tools and facilities (e.g., Advanced Photon Source, Center for Nanoscale Materials) which could not be housed at research universities. As a postdoctoral associate I had easy, informal access to experts within the laboratory (e.g., grabbing a coffee with a beamline scientist). These engagements both strengthened my existing research activities and inspired exciting new scientific directions. Finally, working within a professional research environment gave me an opportunity to develop important non-research-related skills that have served me well in my faculty career including project management, environment, health & safety management, and laboratory hazard assessment.

My postdoctoral appointment was supported by a Director's Postdoctoral Fellowship from the Division of Education (now, Educational Programs and Outreach) at Argonne. This funding allowed me to do exploratory research that diverged from the group's primary focus on lithium (Li)-ion batteries. It was through this opportunity that I starting studying RFBs, trying to translate knowledge gained from and materials developed for Li-ion batteries to high-voltage, high-efficiency flow batteries. This became the foundation of my research as an independent faculty member at MIT, and led directly to my engagement with BES funded programs through JCESR. In addition, my knowledge of the educational and scientific opportunities DOE offers within Argonne and other national laboratories has informed my mentoring of undergraduate, graduate, and postdoctoral associates at MIT. This includes recommending that undergraduate students apply to the science undergraduate laboratory internship (SULI) program and other lab-specific opportunities as well as advising graduate students of the benefits of career trajectories that pass through the national laboratories.

Career development enabled by BES-funded programs

Toward the end of my postdoctoral appointment at Argonne, BES announced the competition for an innovation hub focusing on energy storage. I had the opportunity to participate in the writing process for what became the winning proposal, JCESR. Specifically, I was a key writer for the nonaqueous redox flow thrust, one of three discovery science thrusts in the proposal. I developed the scientific narrative for that thrust and coordinated with other writers, typically tenured faculty at academic institutions. When JCESR ramped up around the same time I started at MIT, I was able to secure research funding for my group, pursue research activities that I had helped to develop, and gain immediate visibility both at MIT and within the energy research community.

While I have undoubtedly benefitted from the MIT community in terms of student education, faculty mentoring, research funding and fruitful collaborations, among many other things, my engagement with JCESR has accelerated my career development. JCESR has been my primary source of DOE BES-funding to date and, hence it is the focus of my testimony. Below I will try to emphasize the unique benefits for a junior faculty member of working in a hub, and how this funding modality has influenced my own research directions and those of the broader community. For interested Committee members, I have provided a more extensive overview of JCESR at the end of this document as an appendix.

Scientific Development:

The collaborative environment established by the hub allowed me to rapidly expand my breadth of expertise in energy storage, to develop differentiating skills through engagement with experts in academia, national labs, and industry, and, ultimately, to pursue research activities I could not have achieved as an individual PI in an academic environment. Further, JCESR provides access to frontier tools and facilities within the member national laboratories (e.g., Argonne, Lawrence Berkeley, Pacific Northwest, and Sandia) including advanced light sources, leadership computing, nanoscience centers, and other state-of-the-art facilities. Engagement with these cutting-edge resources not only accelerates research progress but also promotes education and development for academics along with their graduate students and postdoctoral associates. Below, I provide two examples of this drawing from my own experiences.

As a first example, my postdoctoral work in RFBs was focused on the discovery of new redox species and associated electrolytes. At the time, our approach was to page through the chemical catalogs to identify small molecules with aromaticity and heteroatoms, purchase what seemed promising and evaluate the compound in a set electrolyte. At the onset of JCESR, organic chemists and electrochemists, who did not necessarily have a background in RFB science but possessed deep knowledge of molecular design and functionalization, joined the efforts. They allowed us to rapidly expand the materials design space by leveraging years of prior knowledge and chemical intuition obtained in different fields. However, we soon found that experimental screening for redox materials was limited by throughput. We could not mine the vast chemical design space without advanced computing tools, which could screen thousands of materials and make connections between seemingly-disparate molecular structures that would be challenging to realize through intuition, experience, or experiment alone. To this end, the Electrolyte Genome Project at Lawrence Berkeley National Laboratory, which was developed to search for better liquid electrolytes for battery systems, allows us to streamline the discovery / screening process by evaluating thousands of materials by simulation on the computer and choosing only the most promising few to synthesize and test in the laboratory. Today, such advances have enabled the identification, synthesis, and testing of several valuable molecular families for charge storage in RFBs. Emerging machine learning and artificial intelligence tools have the potential to further refine computational materials discovery.

As a second shorter example, prior to JCESR, I had no knowledge in techno-economic modeling of electrochemical systems, and while I recognized the importance of those activities, the topic was distinct enough from my academic training that I would have hesitated to pursue it as a pre-tenure faculty member. Through JCESR, I was able to collaborate with and learn from leading experts at Argonne National Laboratory and United Technologies Research Center, and later to apply my new-found capabilities to a range of problems in my own research. Indeed, the uniqueness of my expertise in techno-economic modeling of electrochemical systems was a foundational piece of my successful tenure case at MIT.

Student Mentorship:

For a junior faculty member, successfully recruiting and mentoring students can be challenging. New faculty are almost always inexperienced in research and personnel management. Their scientific direction and funding are uncertain. JCESR provided my students with a community, a professional network of graduate students, postdoctoral researchers, scientists, and faculty from diverse institutions working on battery-related energy science. Instead of having a single mentor (myself), my students benefitted from multiple supportive voices and, at times, I was able to lean on the expertise or experience of others. This environment allowed my students to address research problems which would have been unsolvable in my own laboratory, by leveraging expertise and capabilities of JCESR colleagues and by making use of frontier facilities and tools at partner institutions. For example, I have had students leverage the Electrochemical Discovery Laboratory at Argonne (which houses specialized equipment featuring simultaneously chemical and electrochemical measurements) to analyze complex and transient electrolyte transformations that we cannot interrogate either in my own laboratory or through standard equipment in shared facilities at MIT. Finally, the multi-year JCESR funding provided support and stability for student growth and development as well as the pursuit of more complex high risk-high payoff research problems which require time to unravel.

Leadership development:

Beyond advancing technical skills, the hub environment offered opportunities to learn scientific leadership and project management under the mentorship of senior personnel. Since the outset of JCESR, I have held various leadership roles, with increasing responsibility, including "Solutions Group" leader within the Nonaqueous Redox Flow thrust (01/13 – 11/14), Cell Design & Prototyping Principal Investigator (03/14 – 06/15), and Grid Arc Lead Technologist (06/15 – 06/18). Since the renewal (06/18-present), I have served as the Research Integration co-Lead and a member of the Executive Committee. The knowledge gained and lessons learned from these experiences have extended to my service and leadership at MIT.

Thank you for the invitation to testify to the Subcommittee on Energy. I would be happy to answer any questions you or other members of the Committee may have.

Appendix: An Overview of the Joint Center for Energy Storage Research

JCESR is led by Argonne National Laboratory, whose mission is to accelerate science and technology that drives U.S. prosperity and security. At its core, JCESR is comprised of 19 leading battery research and development institutions, including national laboratories, universities, and industry. These institutions have been working collaboratively to create the battery science and technology needed to enable deep decarbonization of the electricity grid, automotive transportation, and aviation. Such a breadth and diversity of talent cannot be found in any single institution. The battery challenge requires a major effort, combining the frontiers of electrochemistry, high-performance computing, atomic-level materials characterization, and advanced discovery and synthesis of new materials. Each of these frontiers has its own group of specialized techniques and leading researchers. Bringing them all together in a single collaborative organization is the only way to make the rapid progress needed in battery technology to avoid the worst consequences of climate change.

From the outset, JCESR determined to work in the "beyond-lithium (Li)-ion" space, meaning we focus on inventing and enabling technologies that can surpass the limits inherent to today's Li-ion batteries. This approach is important because, although revolutionary, Li-ion batteries alone cannot meet all of the required applications of energy storage, such as powering heavy trucks and long-duration storage of renewable energy for grid firming. It is also important because Li-ion battery production is firmly established overseas, and teams like JCESR foster the ingenuity required for America to capture the next generation of battery manufacturing leading to new jobs, economic growth and energy security.

JCESR First Five Years

In its first five years, JCESR's vision was to transform transportation and the electricity grid with high performance, low cost energy storage. The mission was to deliver electrical energy storage with 5× the energy density and 1/5th the cost of 2012 commercial batteries within 5 years. The three legacies were (1) to establish a fundamental science library of the materials and phenomena of energy storage at atomic and molecular levels; (2) to deliver two prototypes, one for transportation and one for the electricity grid, that, when scaled up to manufacturing, have the potential to meet JCESR's transformative goals; and (3) to demonstrate a new paradigm for battery research and development that integrates discovery science, battery design, and research prototyping and manufacturing collaboration in a single highly interactive organization [1].

JCESR introduced comprehensive techno-economic models which quantify and compare the performance and economic potential of the diverse set of established and conceptual grid and automotive battery systems. This modeling framework was used across JCESR in three ways: (1) to "back-translate" from system-level performance and price goals to materials and component-level targets, (2) to "forward evaluate" the challenges, costs, and ultimate performance of different technology approaches, and (3) to chart progress and allocate limited resources most effectively. Further, JCESR advanced computer simulation of battery materials to a new level permitting comprehensive atomic- and molecular-level prediction of capacity, voltage, and mobility of ions in solid electrode and liquid organic electrolytes. For example, JCESR simulated 1800 combinations of working ions and cathodes for a magnesium battery, finding five promising candidates which were synthesized and proven to work in the laboratory. Exploring this many combinations of materials could never have been achieved in the laboratory alone without computer simulation, even with an army of graduate students solely dedicated to the task. JCESR's high-throughput computer simulation dramatically accelerated the pace of materials discovery.

Highlights of JCESR's many other significant advances include:

- invention of inexpensive nanoscale polymer membranes that selectively transmit or block organic molecules on the basis of size,
- introduction of the Electrolyte Genome, a comprehensive database of predicted properties of liquid organic molecules for next-generation batteries,
- development of the concept of redox active polymers or "redoxmers" for a new kind of high-performance, low-cost flow battery,
- discovery of high mobility pathways for doubly charged ions, such as magnesium in crystalline electrodes and electrolytes, and
- pursuit of a promising new direction for lithium-air batteries with high energy density and low cost.

At the end of five years, JCESR delivered four prototypes, two for transportation and two for the grid. For the former, we demonstrated innovative batteries based on magnesium, zinc, and calcium, each of which carries two charges instead of the single charge on lithium, doubling the energy stored or released per ion on each charge or discharge cycle. We also developed the concept of sparingly solvating lithium-sulfur batteries to raise their energy density while prolonging their cycle life. For the latter, JCESR's new concept of redox-active polymers or "redoxmers" promises flow batteries with low cost, high capacity, and self-healing properties to extend their life. JCESR's invention of inexpensive aqueous air-breathing sulfur batteries for long duration storage fills a long-standing and challenging gap in grid storage technologies.

JCESR spun out three startups in its first five years. Blue Current is pursuing solid state electrolytes. Sepion Technologies is commercializing inexpensive size-selective polymer membranes. Form Energy is commercializing JCESR's long-duration inexpensive flow battery based on sulfur, water, and oxygen. Working together, JCESR and Form Energy took the idea of an aqueous, air-breathing sulfur battery for long duration storage from initial concept to commercialization in less than five years.

At the end of its first five years, JCESR won the Secretary of Energy Achievement Award for its development of new strategic and operational concepts for large collaborative projects, such as Energy Innovation Hubs. This confirmation of our success inspired us to push our research boundaries even more aggressively going forward.

JCESR Renewal

In September 2018, the Office of Basic Energy Science in DOE renewed JCESR for a second five-year term. In the renewal, JCESR shifted its focus from particular battery systems to transformational battery materials, chemistries and architectures. Towards the end of the first term, we realized that even if all four of our prototypes were commercialized, this would not come close to satisfying the urgent need for a diversity of new batteries to match a diversity of emerging applications in the electricity grid, automotive transportation, and electric flight. Moreover, while techno-economic modeling provides insight to what materials property sets are desirable, the discovery, synthesis and validation of these materials is typically the roadblock in creating new battery technologies. To address these challenges, JCESR shifted its focus in its renewal to transformational battery materials, chemistries and architectures for electrodes, electrolytes, and interfaces that will enable a diversity of purpose-designed batteries for a diversity of uses [2].

JCESR's renewal introduces a new approach to transformational battery innovation: building batteries "from the bottom up", atom by atom and molecule by molecule, where each atom or molecule plays a prescribed role in achieving targeted overall materials behavior. This kind of atomic- and molecular-level materials design would not have been possible ten years ago because our knowledge of the atomic and molecular origins of electrochemical behavior was incomplete. The advanced atomic-level computer simulation and experimental characterization of battery materials in JCESR's first five years are part of the foundation for our new bottom-up materials design approach. Introducing such innovative approaches is critical to secure America's energy future and deliver economic—and scientific—competitiveness and growth.

JCESR's renewal provides a natural platform for strengthening broader research alignment among its partner institutions. JCESR's partners are working to ensure that their broader lab strategies and capabilities beyond the JCESR program are complementary and closely aligned with long-term DOE goals, such as research challenges for future U.S. battery manufacturing needs. This fostering of research alignment raises the effectiveness of the labs as a whole, collectively champions engagement with U.S. industry, and serves as a role model for cooperation across the national lab and university systems.

Overall, JCESR's short-term strategy is to significantly advance our atomic and molecular understanding of battery phenomena to enable rapid new materials discovery in liquid and solid electrolytes, redoxmers, and multivalent electrodes, electrolytes and interfaces. JCESR's long-term strategy is to initiate strategic new directions with the promise of disruptive impact that will set ten-year directions for energy storage and lay a firm foundation for the research community to grow and prosper in energy storage after JCESR ends. These short- and long-term strategies will ensure that America regains the international leadership in next generation battery innovation, manufacturing and marketing.

JCESR's Impact on Workforce Development

Since its inception, JCESR has made important contributions to developing the US workforce including the publication of >680 high-quality, high-visibility battery science papers in peer-reviewed journals, 59 total patent applications and 26 total issued patents, the education of >200 early career scientists, and the nucleation of three start-up companies.

JCESR is also actively engaging with the research community by hosting workshops (in person and, due to the pandemic, virtual) to discuss important research activities including artificial intelligence and machine learning for energy materials discovery, synthesis, and characterization, as well as computational and experimental techniques to study battery interfaces, the origin of many battery degradation processes. These workshops enable workforce development by bringing a multidisciplinary lens to pivotal research challenges to inspire scientists and engineers beyond JCESR's core team. In addition, JCESR is working to connect external graduate students to member national laboratories through mentorship webinars and panel discussions regarding career trajectories and guidance on applying to postdoctoral openings. This concept was piloted in April 2021 and we are gathering feedback from graduate student attendees to inform future events for HBCUs and minority-serving institutions.

Within the hub, the development of early- and mid-career scientists at member institutions is furthered in several meaningful ways. Junior researchers benefit from nurturing, mentoring, and collaborating with many of the world's preeminent battery and electrochemical scientists. This environment offers opportunities to expand their technical skills but also to learn scientific leadership and project management. Further, JCESR provides access to frontier tools and facilities within the national laboratory system including advanced light sources, leadership computing, nanoscience centers, and other state-of-the-art laboratories. Engagement with these cutting-edge resources and their associated research staff promotes education and development for not only academics but their graduate and postdoctoral students. The culture of innovation and critical thinking fostered by JCESR drives rapid advancement and refinement of ideas from inception to publication. Finally, the visibility and credibility of the JCESR "brand" in the global research community provides platforms for dissemination (e.g., papers in high-impact journals, invited presentations at prestigious conferences). Importantly, the knowledge gained and lessons learned from working with JCESR extend to other areas of our professions including scholarship in non-JCESR-related areas, teaching and mentorship of undergraduates, graduates, and postdoctoral associates, and service and leadership at our individual institutions.

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