U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0000673
on
Advanced Technologies for Robust Control of Energy Storage

Objective: ARPA-E seeks input from researchers and technologists of various backgrounds and representing a broad range of fields and disciplines, with the goal of evaluating novel approaches to providing diagnostic, prognostic, and control capabilities to significantly increase performance and accelerate adoption of energy storage systems. The information you provide may be used by ARPA-E in support of program planning. THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.

Background: Energy storage can significantly improve US energy independence, efficiency, and security, by enabling a new generation of electric vehicles and by enhancing the capabilities of our electricity grid[1]. While rapid advances are being made in research and development of new battery materials and storage technologies, few transformational innovations have emerged in management of energy storage systems[2]. Batteries are complex systems and developing means to cost-effectively monitor, predict, and manage important performance measures such as capacity, life, and stability limits during real-world operations remains a key technological challenge. As a result, many battery systems are built and operated well below their theoretical energy and power capacities, incorporating excess storage capacity and significant balance of systems to meet operational requirements while minimizing the risk of premature or catastrophic failure. Many energy storage systems suffer from uncertain or inadequate lifetimes, and concerns over life and safety prohibit dual-use and secondary application, such as vehicle-to-grid dispatch. These drawbacks increase initial acquisition cost, life-cycle cost, and risk of deployment.

The challenge of battery management stems from the complexity of battery devices, compounded by the aggressive operational demands and severe cost constraints of practical applications[3]. Even the simplest charging and discharging scheme of an electrochemical battery depends on a wide range of processes that include chemical and electrochemical reactions, phase change reactions, electronic and ionic transport through liquids, solids, and complex composites, etc. – all of which are coupled and influenced by the operating parameters of the device[4]. While theoretical models can represent these phenomena, even the best models cannot capture and predict many of the degradation and failure mechanisms that emerge from the confluence of highly coupled reactions with unpredictable operating and environmental stresses, defects, chemical impurities and other physical realities[5].

Consider just one environmental factor – temperature. Elevated temperatures in a cell generally accelerate the rate of irreversible chemical reactions that lead to capacity fade and cell degradation. Meanwhile, reduced temperatures, which kinetically limit primary cell processes, can result in over-potentials that are electrochemical drivers for unwanted reactions. Beyond affecting transport and chemistry, temperature can affect mechanical stresses on electrodes, solubility of salts and additives, and the robustness of heterogeneous interfaces - all possible sources of degradation and failure. While temperature is an illustrative example, similar observations can be made for other state parameters. To compound the problem, it is difficult to identify the degradation mechanisms that lead to poor lifetime or pre-mature failure[6,7]. Some such mechanisms are universal, but many are specific to each unique battery chemistry or specific composition. Industry thus relies on empirical testing to identify and validate failure mechanisms. In many cases, years of testing is required to provide an adequate confidence period for deployment, and even after a failure mode has been observed, significant time can be required to identify and confirm the cause of failure.

As a result of the high degree of complexity in cell physics and the lack of information on degradation mechanisms, physical-based models of battery device have been of limited utility in setting operational constraints and managing control of these systems. One might then imagine that control of cells could instead leverage real-time state information. Unfortunately, we lack the ability to rapidly and efficiently measure parameters that accurately reflect physical changes related to degradation and failure of batteries. State estimation in current battery management is based on simple voltage, current, and temperature measurements of the cell. None of these provides direct information on the physical and chemical state internal to the cell. Voltage provides a composite measure of changes in potentials, but does not provide critical information on the individual state of either electrode. Temperature measurements in today's systems only probe the surface temperature of a cell, not sensing localized temperatures that internally drive degradation and failure.

A number of approaches have been investigated to improve this situation. The idea of embedding a third reference electrode into a commercial battery has captivated the imagination of battery developers. However, integration of a reference electrode in a high-volume commercial product remains an elusive goal given the impact on cost and energy density and interference with the operation of the device. Other electrical measurements, such as AC impedance spectroscopy, are frequently used for battery diagnostics, but the cost of performing such measurements in-situ is prohibitive. These long sought-after solutions may merit revisiting, and insights from other fields may offer new means of accurately probing the physical internal state of battery cells. ARPA-E seeks breakthrough concepts and approaches to battery sensing, which can significantly enhance the performance, cost, and rate of adoption of energy storage systems. Additionally, ARPA-E wishes to explore whether new tools and methodologies can enable quantum leaps in the speed and robustness of validating battery models and degradation mechanisms for practical management of commercial battery systems.

Managing individual storage devices is clearly a challenge, but now consider the case of fully integrated battery systems, where hundreds or thousands of electrochemical cells are electrically coupled to meet energy and power requirements. The problem of battery management is significantly compounded[8]. Presently, monitoring and control of individual cells is not practical. Series and parallel cell configurations couple the states of groups of cells, and the cost of highly parallelized wiring or sensing is prohibitive. Cells subject to different environments, a natural consequence of variations in cell positioning, experience different degradation, a problem that is then accelerated by inter-cell interactions. This mandates active management of the environment and elucidates the need for highly engineered and expensive thermal management in applications such as electric vehicles. Even harder to manage is cell-to-cell variability, which despite efforts to bin cells for consistency, can cause cells to be driven into different states even when subjected to identical loads and environments. ARPA-E sees opportunity for innovation in design and control of battery systems to manage the difficulties of maintaining the state of health and safety of batteries. Higher fidelity, more robust, or lower cost sensing and control of environment across a battery pack would clearly be beneficial. Other approaches focus on optimizing dispatch via power electronics, either to achieve performance gains in existing systems or to enable new systems employing hybrid or flexible cell configurations. It is possible that a breakthrough is achievable through these or other creative approaches; however, no such solution will be transformational unless it can provide system level benefits (e.g. increased battery utilization, lifetime, safety, and/or applicability), which far exceed the cost of implementation.

It is unlikely that any one particular innovation will completely solve the challenges of battery management. However, comprehensive system-level solutions combining data from novel sensors with advanced models, system designs, and control paradigms may allow us to drastically enhance the utilization and rate capabilities of battery systems within safe limits, while extending their life and meeting operational requirements. Such an energy management system would be a game changer – significantly accelerating the adoption and value of energy storage for primary applications in all sectors, and opening the door to dual- and secondary-use application. Better still, energy storage management breakthroughs will not only improve the capabilities of today's state-of-the-art technologies, but will also be applicable to new battery chemistries, thus providing a multiplier to the benefit of research and development focused on next generation battery materials and designs. ARPA-E seeks to understand whether transformational new approaches can be developed to render such solutions feasible and cost-effective, and seeks to better quantify the potential benefit of innovation in this space.

Purpose and Need for Information: The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future energy storage management systems programs. Information obtained may be used by ARPA-E on a non-attribution basis. This RFI provides the broad research community with an opportunity to contribute views and opinions regarding novel sensing, modeling, and management strategies to maximize the performance of an ESS. Based on the result of this RFI and other considerations, ARPA-E may decide to issue a formal FOA for this area. If a formal FOA is issued, it will be issued under a new FOA number. No FOA exists at this time. ARPA-E reserves the right to never issue a FOA in this area.

REQUEST FOR INFORMATION GUIDELINES: Comments in response to this RFI should be submitted in PDF format to the email address ARPA-E-RFI-SMART@hq.doe.gov by **8:00 PM Eastern Time on March 9, 2012.** ARPA-E will not review or consider comments submitted by other means. Emails should conform to the following guidelines:

- Please insert "Responses for RFI for FOA DE-FOA-0000673" in the subject line of your email, and include your name, organization, email address, and telephone number in the body of your email.
- Respondents are requested to include the following information as part of the response to this RFI:
  - Company/Institution name;
  - Individual contact name and title;
  - Mailing address;
  - Phone number;
  - Email address;
  - Type of company/institution (e.g.. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO)); and
  - Area of expertise.
- Responses to this RFI are limited to no more than 10 pages in length (12 point font size).
- **Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential methodologies.**
- Respondents should not include any information in the response to this RFI that might be considered proprietary or confidential.

ARPA-E will not pay for information provided under this RFI, and there is no guarantee that a project will be supported as a result of this RFI. This RFI is not a FOA, and ARPA-E is not accepting applications for financial assistance under this RFI. Responses to the RFI will not be viewed as any commitment for the respondent to develop or pursue the project or ideas discussed. ARPA-E may decide at a later date to issue a FOA based on consideration of the input received from this RFI.

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E reserves the right to contact a respondent to request clarification or other information relevant to this request. All feedback provided will be taken into consideration, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses.

QUESTIONS: ARPA-E encourages responses that address any subset of the following questions of relevance to the respondent.

1. Transformational technologies for next generation energy storage management

A. Sensing

1. Most of today's battery management systems rely on measurements of current, voltage, and temperature for state estimation. What approaches could dramatically enhance current battery sensor systems? Examples include sensor technologies that improve fidelity of state-estimation over the life of the battery and reduce the cost of sensor integration.

2. What novel online sensing or probing mechanisms could be employed to improve energy storage management? Examples include but are not limited to:

    a. Cost-effective approaches to probe various parameters such as internal cell temperature, physical structure within a cell, chemical composition within a cell, specific electrode potentials, or other state parameters.

    b. Sensors based on a variety of probing mechanisms such as chemical, acoustic, impedance-based, optical, magnetic, biological, or other probes.

    c. Sensors that rely on probes embedded within a battery cell, either as a new component or as an existing component with enhanced functionality. However, these probes must not adversely affect the performance of the battery.

    d. Sensing technologies that derive new information from existing cell designs.

B. Modeling

3. Most of today's battery management systems rely on simple equivalent-circuit models coupled to rule-based control algorithms. What approaches could be employed to dramatically enhance the state-of-the-art modeling of batteries?

4. Are there novel characterization tools or other approaches that would allow for dramatic improvements in the robustness of physical-based battery cell models, or in the ability to rapidly validate such models for diagnostic and prognostic use?

5. Are there novel characterization tools or other approaches that would allow for dramatic improvements in ability or speed of determining degradation and failure mechanisms in batteries?

C. Design and Control of Battery Systems

6. What novel approaches to energy storage system design or control could be employed to dramatically improve performance, lifetime, and safety of energy storage systems given state of the art sensing and modeling capabilities?

7. What integrated system level approaches could combine innovations in sensing, modeling, design, and/or controls to dramatically enhance energy storage management?

2. Detailed description of suggested approaches

For approaches described in (1) above, please address:

1. What would constitute a breakthrough in this technology area?

2. What evidence exists (if any) that a breakthrough is possible, and what are the key challenges?

3. How would successful implementation of the new capability and the impacts/benefits of the solution be validated at the end of the program?

4. If a breakthrough was made, what would be the impact on performance, cost, safety, and widespread adoption of energy storage systems relative to the state-of-the-art? Please provide quantitative estimates.

5. Would the applicability of this breakthrough be limited to a specific energy storage system or would it provide benefits to a range of current and future chemistries and architectures?

6. At what cost would such a technology be viable for practical implementation?

References

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4. Newman, J.; Thomas-Alyea, K.E., *Electrochemical Systems 3rd Edition*, Wiley-Interscience 2004

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7. Broussely M; Biensan P; Bonhomme F; et al., Main aging mechanisms in Li ion batteries *J. Power Sources*, vol. 146(1-2), 2005

8. Lukic, SM; Cao, J et al, Energy storage systems for automotive applications, *IEEE Transactions on Industrial Electronics*, vol. 55(6), 2008.