# DOE Industrial Consortia Initiative Case Study:
# The Joint Center for Energy Storage Research (JCESR)

This case study is an overview and description of the Joint Center for Energy Storage Research (JCESR), a DOE-sponsored Energy Innovation Hub with public and private components. JCESR's program, structure, industrial engagement, intellectual property management, timeline, metrics of success, and best practices are outlined. The information presented here allows comparison with other public-private partnerships, distillation of common and contrasting features and identification of best practices that may be refined and applied to future public-private partnerships.

## 1. Program Overview

JCESR is a public-private research partnership that integrates government, academic, and industrial researchers from many disciplines to overcome critical scientific and technical barriers and create breakthrough energy storage technology.

Led by the U.S. Department of Energy's Argonne National Laboratory, our partners include national leaders in science and engineering from academia, industry, and national laboratories. Their combined expertise spans the full range of the technology-development pipeline from basic research to prototype development to product engineering to market delivery. JCESR is making rapid progress and meaningful advances by strengthening the links among these functions. Our academic partners are contributing world-leading expertise in energy policy, economics, and market analysis.

**JCESR Program Goals**

JCESR's vision addresses the two largest energy sectors in the U.S.: transportation and the electricity grid, which together account for two-thirds of our energy use. Our vision is aggressively transformative: to enable widespread penetration of electric vehicles that replace foreign oil with domestic electricity, reduce carbon emissions, and lower energy use; and to modernize the electricity grid by breaking the century-old constraint of matching instantaneous generation with instantaneous demand, enabling widespread deployment of variable wind and solar electricity and increasing resilience, reliability and versatility. Both transformations can be achieved with a single disruptive breakthrough: high-performance, low-cost electricity storage. This is JCESR's vision.

Achieving this storage breakthrough requires a new paradigm for battery R&D: integrating discovery science, battery design, research prototyping, and manufacturing collaboration in a single, highly interactive organization, illustrated in Figure 1 below. In the conventional battery R&D community,

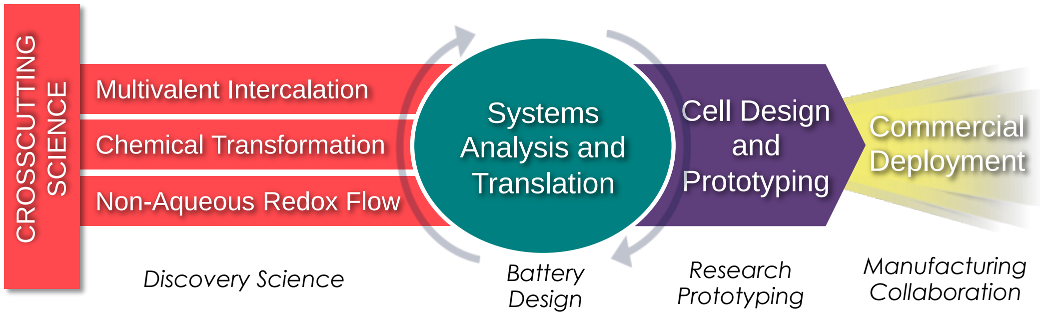


Figure 1. JCESR's new paradigm for battery R&D, integrating discovery science, battery design, research prototyping and manufacturing collaboration in a single highly interactive organization.

Prepared in response to formal guidance and a request by Sam Baldwin, Ellen Williams and Charles Russomanno of the U.S. Department of Energy (DOE) for input into the DOE Industrial Consortia Initiative and the 2015 DOE Quadrennial Technology Review.

these functions are separate, communication among them is slow, and they operate with independent visions, missions and approaches. JCESR's consortium tightly closes this loop, significantly accelerating the pace of discovery and innovation. In addition to strong integration and interaction, JCESR's new paradigm brings innovative new tools to battery R&D, including extensive computer simulations of tens of thousands of crystalline electrode materials and liquid organic electrolytes to identify the most promising candidates before they are synthesized in the laboratory, a state-of-the-art electrochemical discovery laboratory for designing, synthesizing, characterizing and refining the electrochemical interfaces that govern battery performance, and techno-economic modeling of integrated battery systems to evaluate performance and cost to select the most promising candidates for prototyping.

Based on this new paradigm, we have defined an aggressive mission that captures the opportunity, the excitement, and the urgency of our vision: five times the energy density, one-fifth the cost, within the five-year term of our initial contract with DOE. With strategic intent, this aggressive mission goes well beyond today's lithium-ion battery technology. It requires JCESR and the community to develop disruptive beyond lithium-ion electricity storage technology that will create jobs, drive economic growth, and maintain our competitive position in the global marketplace. Consistent with its vision, JCESR focuses exclusively on next-generation, beyond lithium-ion battery technologies.

JCESR's vision and mission are expressed in three legacies or outcomes that we intend to achieve: a library of fundamental knowledge of the materials and phenomena of electrical energy storage at atomic and molecular levels; two prototypes - one for the car and one for the grid - that, when scaled to commercial production, are capable of delivering five times the energy density at one-fifth the cost of today's commercial batteries; and implementation of the new paradigm for battery R&D described above, integrating discovery science, battery design, research prototyping, and manufacturing collaboration in a single highly interactive organization.

The first legacy is a new approach for battery R&D, which typically operates by Edisonian trial-and-error methods, never developing the library of fundamental understanding of energy storage materials and phenomena that would eliminate many trial-and-error dead-ends and more directly point to the most promising materials and directions. JCESR's library of fundamental knowledge will be created with the tools of nanoscience and nanotechnology developed over the last fifteen years. This knowledge, made freely available in the open literature and open access databases, will lift efforts across the entire battery R&D community. JCESR has already implemented its third legacy, a new paradigm of battery R&D, and is continuously evaluating, refining and improving it. JCESR's third legacy significantly accelerates the pace of discovery and innovation and is critical to achieving its other two legacies. The second legacy, demonstrations of next-generation battery technologies, is the tangible outcome of JCESR's vision.

JCESR has defined three beyond-lithium-ion electricity storage concepts shown in red in Figure 1, all capable of contributing to our aggressive mission: multivalent intercalation, chemical transformation, and non-aqueous redox flow. These thrusts, pursued simultaneously across the spectrum of discovery science, battery design, research prototyping, and manufacturing collaboration, are at the core of JCESR's vision and mission. We pursue these concepts agnostically to expose their inner workings at the atomic and molecular level, fully expecting that the ultimate batteries we produce will incorporate threads from all three concepts.

**DOE's Role**

JCESR is funded through and managed by the Office of Basic Energy Sciences (BES), within the Office of Science in the Department of Energy. DOE BES takes an appropriately active role in managing JCESR, both formally and informally. BES monitors and advises regarding progress against agreed-upon goals, a detailed work breakdown structure, and budget. Careful change control processes have been developed and are used, and DOE has oversight of higher-level project, budgetary, and partnership changes. DOE requires quarterly written reports, and formal annual reviews by outside experts through site visits.

Importantly, although the JCESR program resides in the Office of BES, BES incorporates EERE and ARPA-E into the management of the program. Likewise, especially when industrial participation is involved, BES regularly engages the DOE Office of General Counsel, to ensure best practices for issues from the terms for collaborative research with industry to licensing practices.

JCESR management believes that DOE's active engagement in managing the program is vital both to the technical success of the program, as well as its integration into the broader landscape of science and technology development.

**Philosophy of Industrial Engagement**

JCESR research is engaged directly with industry, through core partnerships and through affiliate programs (described below). JCESR has four industrial partners who function as part of the R&D enterprise, as well as serve on the Governance Committee for the consortium. JCESR also has over 80 affiliates, who participate in research as appropriate, but have no role in governance.

JCESR's philosophy regarding industrial engagement has three facets:

- *Bring industrial vision and pressing market needs directly into our early research*. Industrial involvement results in a team focus on research that can enable breakthrough technologies to be fabricated.
- *Ensure rapid transition from discovery science to innovation and technology development*. By working directly with industry even in early-stage research, we increase the probability of successfully transitioning scientific discoveries into technological products that impact society.
- *Engage partners who can perform the product development and deployment*. The consortium can maximize its impact by having partners whose role includes commercializing technology that benefits to U.S. citizens.

## 2. Structure of JCESR

JCESR's leadership group is comprised of technical, project management, safety, budgetary, and legal personnel from across the partner set, including industrial members. Importantly, governance and multiple committees and advisory groups are constituted primarily of personnel from partner institutions. As such, the enterprise is managed by consensus, with strong leadership by Argonne personnel.

**Structure**

JCESR's organizational structure, shown in Figure 2 below, expresses strong integration and communication, the fundamental principles of its new paradigm. Research and management leaders are drawn from across the partner set and communicate often to make strategic and tactical decisions on research directions and management implementation.

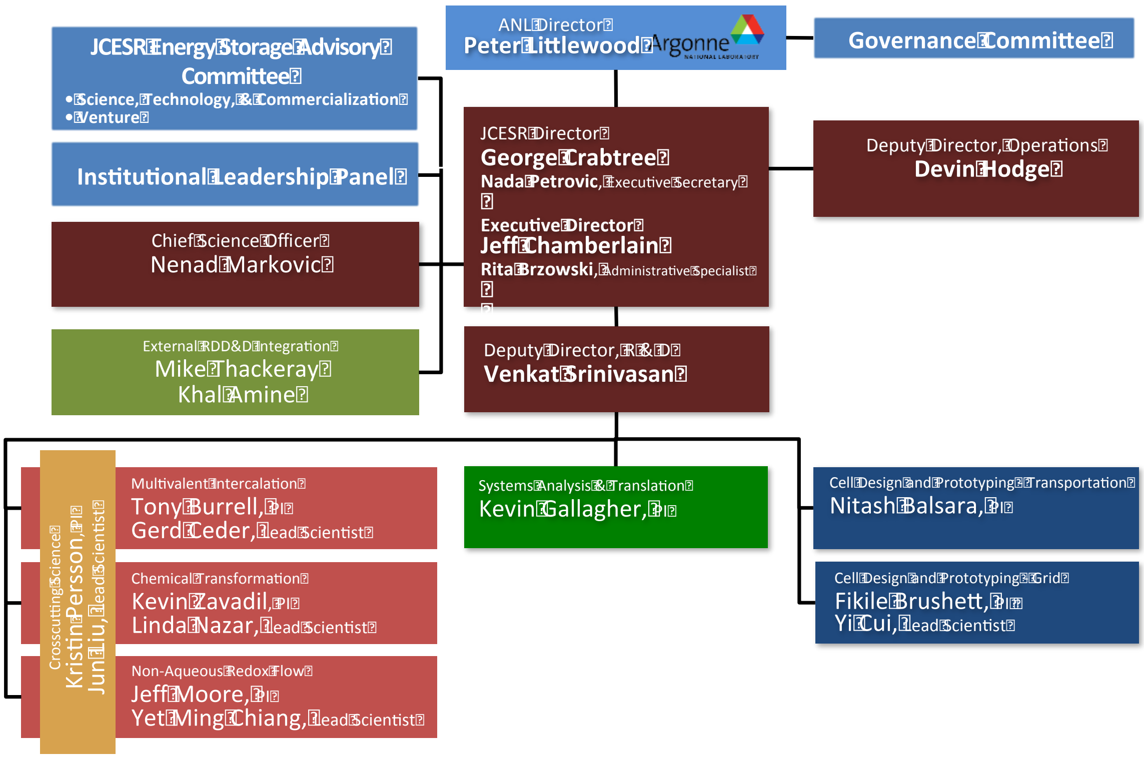


Figure 2. JCESR's organizational structure.

The Director of Argonne National Laboratory (ANL) chairs the Governance Committee (GC), composed of the CEOs of JCESR's partner institutions. The members of the Governance Committee have decision authority for their home organizations in JCESR and ensure alignment of JCESR's strategic goals with those of its partners. Reporting to the ANL Director is the JCESR Director who, together with the JCESR Deputies, comprise the Executive Leadership Team of the Office of the Director.

The Executive Leadership Team has full responsibility for all management and operational decisions for the Hub. Reporting to the Director is the Operations, Safety, and Assurance Manager, who manages daily Hub operations.

The Deputies for Research, Integration, and Development and Demonstration have full responsibility and authority for developing and executing the Annual Research Plan in their area of assignment. The three Deputies balance discovery science and development of pre-commercial prototypes and focus on the systems-level requirements that define the metrics of success of the transportation and grid prototypes to be developed.

The Office of the Director leads a team of Thrust Principal Investigators to deliver the groundbreaking research required to understand the materials and phenomena of electrical energy storage and apply that transformational knowledge to the design and development of next-generation batteries. The Office of the Director and the Thrust Principal Investigators comprise the JCESR Directorate.

JCESR benefits enormously from its advisory and operational committees (see Role of the Consortium below), including the Governance Committee composed of the CEOs of our partner institutions, the Energy Storage Advisory Committee (ESAC) composed of the Science, Technology and

Commercialization subcommittee and the Venture Capital subcommittee, and the Institutional Leadership Panel (ILP) composed of the line manager at each institution with administrative responsibility for all JCESR members at that institution. These advisory and operational committees evaluate JCESR's vision and strategic directions, ensure JCESR's alignment with national trends and partner institution aspirations, and address operational challenges at partner institutions.

**Institutional Partners**

JCESR chose its institutional partners to provide the knowledge and capability in discovery science, battery design, research prototyping and manufacturing collaboration to implement its new paradigm.

- Partner national laboratories:
  - Argonne and Lawrence Berkeley Laboratories provide leading battery expertise for transportation applications and access to the Midwest and California battery ecosystems
  - Sandia and Pacific Northwest Laboratories provide battery expertise for the electricity grid
  - SLAC provides leading materials science expertise and access to the California battery ecosystem
  - DOE scientific user facilities at partner national laboratories leverage JCESR's research capability. These facilities include the Advanced Photon Source, Center for Nanoscale Materials, Argonne Leadership Computing Facility, Advanced Light Source, Molecular Foundry, National Energy Research Scientific Computing, Environmental Molecular Sciences Laboratory, and Center for Integrated Nanotechnologies. DOE facilities at non-partner laboratories are also available for use.
- Partner universities: University of Illinois at Chicago, Northwestern University, University of Chicago, University of Illinois at Urbana-Champaign, and University of Michigan provide leading expertise in electrochemistry, battery R&D and materials science, and access to the Midwest battery industry
- Funded collaborators from non-partner institutions: MIT, Harvard University, University of Waterloo, Notre Dame University, Northern Illinois University and United Technologies Research Corporation (UTRC) provide battery leadership and start-up mentality.
- Partner private firms: Dow provides battery materials development and manufacturing, Applied Materials provides advanced manufacturing processes and equipment design, and Johnson Controls provides leading battery prototyping and manufacturing. Clean Energy Trust (non-profit) coordinates JCESR's outreach to the broad entrepreneurial/venture capital community interested in next-generation transformative energy storage technologies.

## 3. Timeline for JCESR Program

The scope and complexity of the beyond-lithium-ion space dramatically exceeds that of the lithium-ion space as illustrated in Fig. 3. Mixing and matching JCESR's three energy storage concepts and including the options of liquid or solid electrolytes (illustrated on the vertical axis of Fig. 3) yields a rich variety of at least 18 different conceptual designs for beyond lithium-ion battery systems. Add to this the 20-30 candidate materials (illustrated on the horizontal axis of Fig. 3) that could implement these battery design concepts and there are at least 50-100 beyond lithium-ion battery combinations whose feasibility and performance remain to be explored. In contrast, the lithium-ion space has a single conceptual design, lithium intercalation at anode and cathode, and fewer than ten materials in play to implement this concept.

JCESR approaches the vast, rich and largely unexplored beyond lithium-ion space with its new paradigm of strong integration and interaction across discovery science, battery design, research prototyping and manufacturing collaboration, innovative new tools to explore potential battery materials and systems, a broad and distinguished team that embraces the knowledge and expertise needed to explore this space, and a focus exclusively on beyond lithium-ion battery opportunities.

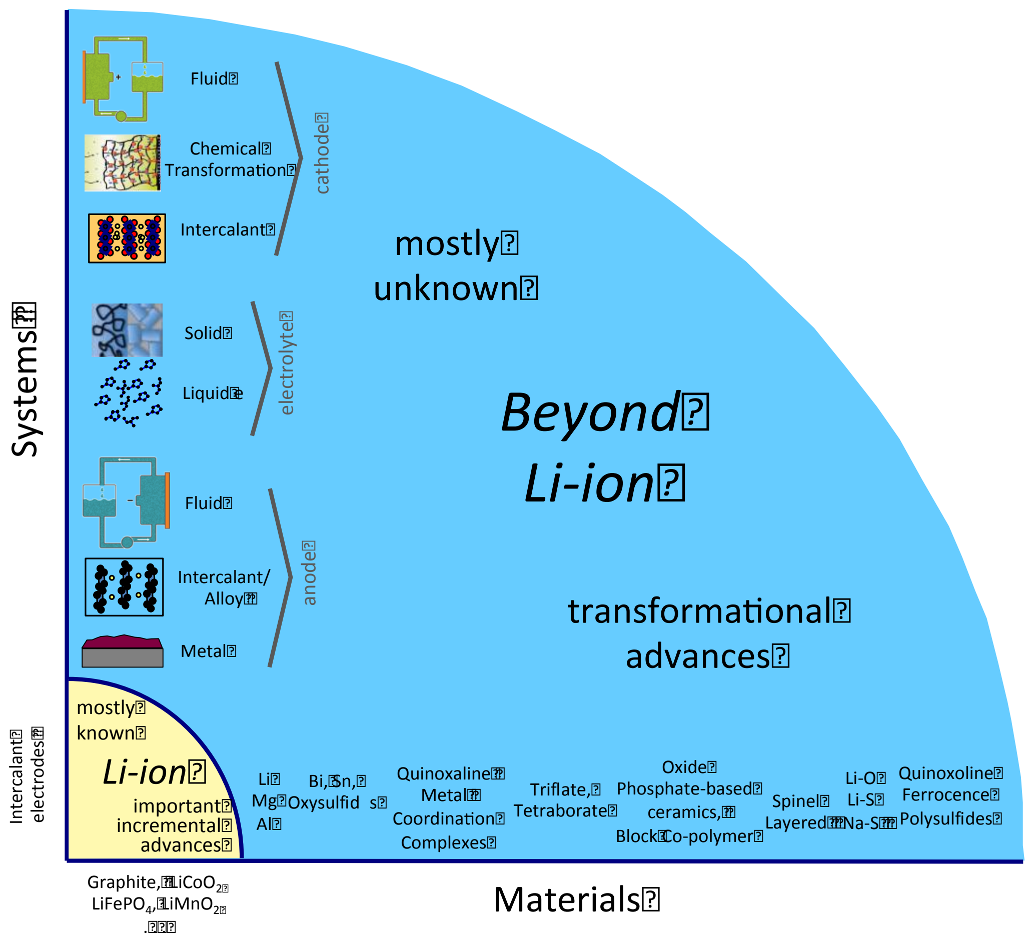


Figure 3. The vast, rich and largely unexplored beyond lithium-ion space compared to the mostly known and much smaller commercial lithium-ion space. With at least 18 different battery concepts and 20-30 different materials to implement these concepts, there are at least 50-100 battery systems to be explored in the beyond lithium-ion space.

JCESR divides its research into two categories: exploratory "divergent" research that surveys the diverse materials, phenomena and systems of beyond lithium-ion batteries to identify those most likely to meet our aggressive performance and cost thresholds, and directed "convergent" research to develop the promising prototypes we select as efficiently and quickly as possible. In JCESR's first two years we completed foundational exploratory research in all four of our functional areas including discovery, synthesis and testing of electrochemical materials and interfaces; analysis of engineering battery designs incorporating multivalent working ions, chemical transformations such as lithium-air and lithium-sulfur, aqueous and non-aqueous flow batteries, metal anodes, and advanced lithium intercalation cathodes; building and testing preliminary prototypes to reveal system integration challenges; and defining target prototype attributes such as size and performance levels in collaboration with industrial partners to anticipate and smooth the eventual transition to manufacturing. Towards the end of our second year we selected four promising prototype directions panning cars and the grid and introduced convergent research to rapidly develop these directions. Our industrial partners, advisory committees and affiliates are key players in defining our target prototype attributes and in converging promising prototype directions.

We structure our convergent research with a new concept called "sprints," small teams of researches assembled to answer a single high priority question central to prototype development on a time scale of one to six months. Sprint questions are simple and fundamental, such as "do magnesium working ions intercalate into manganese oxide cathodes?" or "what membrane materials and performance are required to make a given flow battery work?" The outcomes of these sprints may lead to a go-no go decision on a prototype, they may enable asking and answering the next high priority sprint question on the road to prototyping, or they may reveal additional challenges that are referred to divergent research teams for more comprehensive analysis.

Using parallel lines of divergent and convergent research spanning discovery science, battery design, research prototyping and manufacturing collaboration, JCESR expects to significantly advance or complete its three legacies at the end of its initial five-year term. We have made and continue to make significant contributions to the library of fundamental knowledge of electricity storage at atomic and molecular levels through papers published in the open literature, through conference presentations, through collaborations within the battery R&D community, and through open source databases and computer codes. We have built and continue to build preliminary research prototypes, for the car and the grid, that test the performance and compatibility of promising beyond lithium-ion battery materials and systems. We have implemented and continue to refine our new paradigm for battery R&D integrating discovery science, battery design, research prototyping and manufacturing collaboration in a single highly interacting organization.

Our contract with DOE allows renewal for a second five-year term subject to rigorous review of our first term accomplishments and renewal vision. We are considering the challenges and opportunities that may be appropriate for a second five-year term, depending on the still-developing outcomes of our first five-year term.

## 4. JCESR IP Management Plan

JCESR operates under an Intellectual Property Management Plan that was fully executed prior to submission of our proposal to DOE. The benefits of the executed plan are that it enables open collaboration, and that it enables more rapid dissemination of technology to the market.

The advanced battery market is expanding dramatically in the United States and around the world – from $5 billion in 2010 to nearly $50 billion in 2020, an average annual growth rate of roughly 25 percent. Four years ago, virtually all advanced vehicle batteries were built overseas, and it looked like the United States might miss out on this enormously important, rapidly expanding market. (http://energy.gov/articles/update-advanced- battery-manufacturing). The maturity and competitive nature of the advanced battery industry necessitated that JCESR employ a proactive approach to intellectual property management that would effectively manage the creation, protection, and dissemination of JCESR=generated IP.

**Creation:** The JCESR IP management plan contains all the necessary and standard title vesting language, so that before any intellectual property is even created, it is understood who will own the intellectual property once created. However, it is also important that JCESR create the right intellectual property in the first place. Thus, JCESR assembled a distinguished and energetic team and developed an innovative research plan to quickly deliver high value intellectual property. JCESR is structured to continuously evaluate and adjust its plan based on results. One of JCESR's management tools is a progressive IP strategy, providing continual feedback, enabling alignment of resources, talent and tasks to manage and deliver successful JCESR research. This recursive process supports the movement of projects toward technology enablement. Specifically, when research begins, the JCESR IP Office focuses on corresponding or complementary technology areas as directed by JCESR leaders. The IP Office maps the technology areas against (1) JCESR capabilities, (2) a market analysis to determine what areas of research may be desired by the commercial sector, and (3) potential funding opportunities to leverage with existing funding in JCESR to perform additional research. The resulting technology map is a tool that provides quantifiable opportunities that the Directorate prioritizes for further analysis.

**Protection:** The JCESR partner institutions have a proven track record in appropriately protecting intellectual property. The JCESR members have succeeded because they have (1) an understanding of the laws and regulations governing the creation and protection of intellectual property and (2) an intellectual property management plan in place that reflects this knowledge in order to anticipate and prevent distracting side issues. JCESR members have rolled our collective experience into the JCESR IP Management Plan; for example, the plan includes sections on compliance with federal laws and regulations.

**Dissemination:** JCESR pools IP developed with federal funds and IP developed through sponsored research agreements and available for broad license. It is important to note that the JCESR IP Management Plan does not grant *a priori* exclusivity to the JCESR industrial members. A novel feature of the JCESR IP plan is the pooling of background IP contributions from JCESR members. The JCESR IP pool, along with centralized licensing authority at Argonne for JCESR IP, creates a one-stop shop for industry (members and non-members) to license battery- and energy storage-related IP. JCESR's inclusion of industrial members brings the right expertise to the process immediately, thereby allowing the Hub to strategically expedite the development and transfer of IP.

JCESR actively collaborates in the management in IP. Specifically, every member institution has a representative on the Intellectual Property Management Council, which is led by JCESR's IP and Business Development Manager. Collectively, the IPMC proactively addresses IP issues to ensure any barriers to collaboration are removed. Additionally, the IPMC assists in determining commercialization strategy for JCESR developed IP.

## 5. Role of the Consortium

The consortium is fundamental to JCESR's new operational paradigm. As illustrated in Figure 1, JCESR integrates four functional areas, discovery science, battery design, research prototyping and manufacturing collaboration, in a single highly interactive organization. Fully embracing these four functions of the RDD&D enterprise requires team members with diverse expertise and capability spanning universities, national laboratories and the private sector. The breadth and depth of the consortium is its strength, enabling it to formulate integrated strategic approaches, implement a spectrum of multi-modal experimental and simulation tools, critically evaluate research accomplishments and adjust strategic directions accordingly, and rapidly identify challenges and work collaboratively across functional area to resolve them. Frequent communication and exchange of information and ideas among these experts is the power of our new paradigm.

In addition to our diverse set of partners, we rely on our advisory and operational committees. JCESR's Energy Science Advisory Committee (ESAC) composed of distinguished experts in science, technology and commercialization and of leading venture capitalists provides critical advice on strategy and vision integrating fundamental and applied research with prototyping and scale-up to manufacturing. ESAC advised us, for example, on the importance of in-person communication (see Best Practices below), on the central role of techno-economic modeling to link discovery science with research prototyping, and on measuring progress of prototyping toward transition to manufacturing. JCESR's Governance

Committee, composed of the CEOs of the partner institutions, provided invaluable advice on challenges in managing a diverse team located at multiple institutions, and continually ensures alignment of JCESR programs with the vision and strategy of each partner institution. This close alignment of institutional aspirations with JCESR's trajectory brings critical strength to JCESR's program. Finally, JCESR's Institutional Leadership Panel (ILP), composed of a line manager at each institution with administrative authority over all JCESR members at that institution, coordinates JCESR's operational programs and manages operational challenges at each institution. The ILP is among JCESR's most central, important and effective operational committees (see Best Practices below).

The integration and communication central to our new paradigm, the diversity of expertise and capability that fully embraces our four functional areas, and the advisory and operational committees that continuously monitor and critically evaluate our strategic and tactical directions make the JCESR consortium significantly greater than the sum of its parts. JCESR's transformative vision, mission and legacies cannot be achieved without integrating these fundamental elements into a living whole.

## 6. Program Status and Metrics

In the first two years of its initial five-year term, JCESR has made foundational advances in all four of its functional areas. Many of these advances are documented on our web page (http://www.jcesr.org) and in a review paper posted on our web site and on arXiv (https://anl.app.box.com/s/wixxv7f3mg9ev3t926rc and http://arxiv.org/abs/1411.7042). Beyond these technical accomplishments, we have refined our new paradigm in several ways, for example by adding the Institutional Leadership Panel, strategically de-emphasizing research on lithium-air batteries and emphasizing research on metal anodes, introducing divergent and convergent research approaches, and structuring our convergent research with sprints.

In addition to its research program, JCESR reaches out to the larger battery R&D community. We do so through our Affiliates program for private corporations, startup companies, venture capitalists, trade associations, research universities, Energy Frontier Research Centers and other organizations with a research and development interest in JCESR's program, progress and outlook. The Affiliates include potential science and technology collaborators, strategic planners for the use and impact of beyond lithium ion batteries in transportation and the grid, policy analysts for the implications of next generation storage for the broader energy system and society, and large and small companies who may wish to license JCESR's intellectual property. At its launch in January 2013 JCESR counted 45 Affiliates; that number has grown to 80+ at present. As part of our affiliates program, JCESR organizes regional events to identify and analyze key challenges, opportunities and outcomes of commercialization of next generation high performance, low cost electricity storage. We have organized two regional events, in Urbana IL and Buffalo NY, and have plans for seven additional events in Seattle, the San Francisco Bay area, Chicago, Mississippi, and the Southwest, among others.

Metrics for JCESR's progress towards its three legacies include traditional measures such as papers published, invited talks at conferences, patents pending and granted and milestones completed. These traditional metrics count the total number of contributions to our legacies but do not evaluate the integration, interaction and coordination of these contributions within JCESR, core principles of our new paradigm. To measure these features JCESR tracks the number of conference calls among research teams, number of sprints launched and completed, number of in-person sprint, Directorate, and thrust meetings, number of webinars, and number and type of prototypes completed. These activities by their nature require integration, collaboration and coordination. To measure outreach to the broader battery R&D community, JCESR tracks attendance at annual affiliate events, number, program and attendance at regional events, and collaboration and cooperation inspired by these events.

## 7. Best Practices

JCESR's experience in its first two years revealed several Best Practices that may be useful to other consortia. Among the most important are the value of in-person communication, sensitivity to organizational and management challenges and agility in addressing them. Continuous improvement of our new operational paradigm as we gain experience is a critical feature, as are balancing divergent and convergent research modes, and changing directions early when new opportunities arise or established directions begin to founder.

*In-person communication.* In our proposal we emphasized frequent conference calls and videoconferences as means to share information, evaluate ideas and innovate new research directions. At our first in-person Directorate meeting we realized that face-to-face interaction is much more powerful and effective than audio or video conference calls. The personal interaction is immediate and engaging, body language cues are evident, discussion moves faster, and hallway, dinner and coffee break conversations dramatically increase effectiveness, creativity, and vision. We resolved at that meeting to meet in-person at least monthly, a goal we have easily surpassed with many in-person meetings among thrust groups, sprints, and collaboration teams. Many of our partner institutions have recognized the value of in-person communications by placing most or all of their JCESR research activities in a common location.

*Organizational and management challenges.* In setting up our new paradigm, we overlooked an important function: managerial support at our partner institutions. This became clear, for example, after our initial definition of research directions, teams and budgets. These initial decisions triggered many questions, comments and reactions among JCESR members at partner institutions, where JCESR had no management representative to work locally with team members. We quickly established a new JCESR panel, the Institutional Leadership Panel (ILP), comprising a manager at each partner institution with managerial responsibility for all JCESR members at that institution. ILP members confer bi-weekly with JCESR's Executive Committee by conference call and are fully aware of emerging JCESR strategies, tactics and challenges. In addition they meet frequently with JCESR members at their home institutions, and often make valuable suggestions for dealing with strategic and practical challenges. The ILP has been one of JESR's most engaged, active and useful management teams.

*Continuous improvement of JESR's new paradigm.* Despite our best planning at and before JCESR's launch, we found and continue to find gaps in our new paradigm that must be addressed and new opportunities to organize and execute more effectively. Examples include supplementing some of our research teams by funding additional members outside the partner institutions, revising the motivation and execution of the Director's Fund for exploring new directions, establishing a robust, thorough, transparent and inclusive evaluation procedure for changing research directions, balancing our research between divergent and convergent modalities, and introducing sprints to structure and focus our convergent research. Had we not been attentive and agile, our new paradigm would not have matured as it has and we would be significantly less effective at pursuing our three legacies. Recognizing needs and opportunities in our operation and addressing them early has substantially improved our progress and our effectiveness.

*Balancing divergent and convergent research.* Divergent research discovers or identifies promising opportunities for prototypes; convergent research drives the development of specific prototypes. The vast, rich and largely unexplored beyond lithium-ion space can easily absorb all of our resources with either divergent or convergent modes of research. Our challenge is to balance divergent and convergent research to ensure that (a) we identify the most promising prototype opportunities and (b) we make rapid progress toward completing the prototypes we have identified. Given finite resources and an abundance of opportunities, striking an appropriate balance between divergent and convergent research modes is critical to success.

*Changing directions early*. Limited resources prevent following all the promising pathways to prototypes. Inertia and lack of continuous and critical evaluation may prolong research on an existing pathway even after the strategic value of the pathway is lost. Continuous critical evaluation of progress, challenges and opportunities for each pathway compared to alternatives is essential; early termination of pathways that are no longer strategically competitive is vital to achieving success without overspending resources.