Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Supplemental Information

Competitveness Case Studies

- *Photovoltaics*
- *Wind Turbine Blades*
- *Lithium Ion Batteries*
- *Light Emitting Diodes*
- *Carbon Fibers*

Public-Private Consortia and Technology Transition Case Studies

- *Carbon Capture Simulation Initiative (CCSI)*
- *Combustion Research Facility (CRF)*
- *Consortium for Advanced Simulation of Light Water Reactors (CASL)*
- *Critical Materials Institute (CMI)*
- *Joint BioEnergy Institute (JBEI)*
- *Joint Center for Energy Storage Research (JCESR)*
- *Trustworthy Cyber Infrastructure for the Power Grid (TCIPG)*
- *United States Advanced Battery Consortium (USABC)*

U.S. DEPARTMENT OF
ENERGY

Quadrennial Technology Review 2015

Public-Private Consortia and Technology Transition Case Studies

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

This Supplemental Information appendix begins with an examination of some essential practices for effective technology transfer and other technology transition activities at the Department of Energy (DOE) and its national laboratories and facilities. This examination is followed by a discussion on industrial consortia as effective models for DOE-supported public-private partnerships for advancing energy innovation and commercializing new energy technologies. Next, a brief summary of cases studies on several DOE supported industrial consortia are provided (Table 1). The appendix concludes with more detail on each of the case studies, each of which is also separately broken out in a standalone paper, based on the work to date and plans of each individual consortium as of late 2015. These case studies were developed by the respective consortia, activities were presented and reviewed at workshops, and the materials below were reviewed by DOE and external experts. These are just a few of the many DOE-supported public-private partnerships.

Table 1 Case Studies

Case Study	Page
Carbon Capture Simulation Initiative (CCSI)	16
Combustion Research Facility (CRF)	25
Consortium for the Advanced Simulation of Light Water Reactors (CASL)	34
Critical Materials Institute (CMI)	45
Joint BioEnergy Institute (JBEI)	53
Joint Center for Energy Storage Research (JCESR)	64
Trustworthy Cyber Infrastructure for the Power Grid (TCIPG)	67
United States Advanced Battery Consortium (USABC)	72

DOE National Laboratory Technology Transfer/Transition Practices

A key part of publicly funded research, development, demonstration, and deployment (RDD&D) is the effective transition of technology to the private sector. Cost-shared competitive solicitations between government and industry effectively build such transitions into the work itself, as the investing industrial partner is usually committed to obtaining a return on investment by commercializing the technology. The long history of successful technology transfer/transition to industry for commercial markets, with large public benefits, has been detailed in reports by the National Academy of Sciences, and many others.[1] A number of statutes, such as Stevenson-Wydler and Bayh-Dole,[2] support these and other similar efforts.

The following discussion focuses on the transition of the scientific and technical outputs of DOE's 17 national laboratories and other research and production facilities to private sector partners, an effort that has been an integral part of DOE's mission and an important contributor to national energy-linked economic, environmental, and security challenges.[3] In support of technology transfer (TT), the DOE Secretary created the Office of Technology Transitions (OTT) in February 2015, to "expand the commercial impact of the national laboratories by coordinating the technology transfer activities carried out at the national laboratories and facilities, by actively supporting private sector commercialization activities, and by serving as a partner to the Department's research and development program offices."[4]

The creation of OTT recognizes that technology transition from the national laboratories is undertaken with a different set considerations from that of purely private sector-driven technology development and market implementation. Several activities, including those below, are needed to understand and improve national lab technology transition:

- Determine what data can be collected to both track the effectiveness and efficiency of TT and provide insights on how TT can be done better
- Identify how DOE could systematically test, evaluate, and identify best approaches for TT within the constraints of the many uncontrollable variables that impact TT
- Evaluate how experimental design frameworks could be developed for TT activities to test for the factors that are most important for effective TT

To help move these and other critical actions forward, OTT is working with the DOE Technology Transfer Working Group to identify essential practices for effective TT, including the following:

- **Provide support for the TT mission,** including a top-to-bottom emphasis on technology deployment as an essential component of the nation's investment in national laboratory research and development (R&D) and tracking of mission-appropriate commercialization and deployment goals in strategic plans,[5] program reviews, annual laboratory evaluations, and local commercialization and deployment goals.[6, 7] The RDD&D and TT missions should be fully aligned and coordinated.
- **Set clear goals and objectives for TT,** including establishing metrics and conducting analyses and impact evaluations to measure the performance and effectiveness of mechanisms.[8] Both qualitative and quantitative metrics are essential, as are different metrics over the life of an RDD&D project, given the long-term nature of technology commercialization. As extensive data collection can create burdens that detract from the mission, streamlining, consolidating, and automating data collection is needed, where possible, to minimize impacts on laboratory resources.
- **Set clear and consistent priorities and practices,** including ensuring that all TT activities conform to Federal Regulations[9] while clarifying policies, streamlining approvals, and ensuring consistency across such issues as fairness of opportunity, managing perceived and actual conflicts of interest, enabling and encouraging (i.e., career incentives) scientific staff participation in the commercialization of technologies, adhering to U.S. competitiveness and U.S. preference policies, and appropriately managing risk on a consistent basis.[10]

- **Conduct outreach to industry**, including communicating with potential industrial partners about the programmatic and laboratory activities in DOE, supporting connections between industrial partners and relevant DOE partners, and identifying industry needs and challenges for incorporation in the RDD&D process, as appropriate. Where mission-appropriate, DOE's research agenda should be informed by the energy science and technology needs of the private sector, recognizing the importance of focusing public support on areas with substantial public benefits that would not be realized by the private sector acting alone. In this way, new innovations from the national laboratories can provide foundational science and technological advances to support industry. Conversely, insights from the private sector can drive new areas of science and exploration in the laboratories, and both the federal government and industry potentially leverage investments of the other, achieving much greater impact. To this end, it's important to link RDD&D expectations to industry operational and strategic needs and requirements; to areas that can potentially leverage strategic industry partner resources (e.g., financing; technology development, including manufacturing, market development, marketing, and supply chain management); and to the perspective of the industry partner (e.g., whether the partner considers itself to be an RDD&D investment partner or a strategic partner). Mechanisms such as web portals can contribute to achieving these links,[11] as can focused events, such as workshops, annual summits, targeted industry trade shows and technology fairs, and national laboratory-hosted industry showcases. Further, a human contact, such as a customer relationship manager can facilitate effective communication with potential industrial partners. Metrics are needed to track these outreach and assurance processes to determine their value.
- **Offer TT support for commercial uptake**, including addressing possible barriers that may impede the progression of national laboratory innovations to commercial adoption.[12] These barriers may include, for example, insufficient data, hand-off of the research before it is ready for commercial adoption,[13] failure of R&D to adequately address the needs and challenges of potential commercial partners and end users (likely due to lack of early input from stakeholders), delays in processes and procedures for licensing/approval, and lack of business acumen on the part of the researchers. The following and other approaches, which all rely on active engagement of the Laboratory Technology Transfer Offices with the laboratory R&D teams and the potential external partners—may provide helpful guidance in addressing barriers:
    - The Oak Ridge National Laboratory (ORNL) Technology Innovation Program (TIP), a competitive technology commercialization acceleration program that simultaneously invests in scientific R&D and in aggressive commercial outreach[14]
    - Energy Efficiency and Renewable Energy (EERE) Small Business Vouchers (SBV) Pilot, which provides national laboratory expertise to a group of competitively selected small businesses[15]
    - The Energy Technology Commercialization Fund, a $20 million funding opportunity created by statute to leverages the R&D funding in the applied energy programs to mature promising energy technologies with the potential for high impact[16]
    - Lawrence Berkeley National Laboratory's (LBNL's) internal entrepreneurship expertise, as well as new and more flexible options to partner with the laboratories, such as the Agreement for Commercializing Technology Pilot
    - External peer reviews of internal lab initiatives by advisory groups made up of academic, government, and industry experts from outside the laboratories to help ensure that projects are not just scientifically rigorous and that transition possibilities to external projects or industry are well-defined in advance
    - External partnerships with groups such as regional economic development agencies, incubators, the investment community, industrial consortia, or others
- **Ensure professional development of staff,** including professional training such as those offered by the Federal Laboratory Consortium, the Association of University Technology Managers, and the

Licensing Executive Society. Efforts to prepare laboratory scientific staff members for engaging with commercialization efforts and the associated industry cultures and needs are less well developed and would benefit from focused attention.[17] Many of the laboratories also offer their staff members varying opportunities to support ventures through entrepreneurial leave and consulting programs. There is, however, inconsistency in the guidance and implementation of these programs from lab to lab—variations due to specific policies and priorities at the different laboratories, such as approaches to mitigating potential conflicts-of-interest.

- **Impact regional economic development,** by promoting and enhancing the positive impact of national laboratories upon their local regions[18] through a variety of approaches:[19]
  - The New Mexico Small Business Assistance Program (Sandia National Laboratories (SNL) and Los Alamos National Laboratory (LANL))[20]
  - The Revv! Tennessee Manufacturing Innovation Program (ORNL)
  - Technology Assistance Programs (National Renewable Energy Laboratory (NREL), Idaho National Laboratory (INL), ORNL, Pacific Northwest National Laboratory (PNNL))
  - Public-private consortia, which often involve a multitude of medium and large companies and universities in cross-cutting research areas

  Many of the laboratories also engage directly with their regional entrepreneurial communities.[21]

These practices provide a framework for increasing the impact of national laboratory RDD&D on the nation's energy challenges. Many of these activities also create opportunities to conduct experiments to determine which approaches provide particular value for TT and why.

DOE Public-Private Consortia

Public-private consortia play important roles in commercializing new energy technologies. As defined here, a consortium entails engaging in precompetitive research activities under a formal agreement that covers the work to be performed and how information will be shared. Thus, consortia enable joint research on platform technologies and early-stage research in a technical field and leave participants free to build on the shared information to create proprietary outcomes of commercial utility. DOE proactively manages consortia to maximize their impact and benefits to the overall goals of those projects—and assesses their success in terms of their contributions to the success of those projects or transitions or in refocusing the consortia to more relevant trajectories.

DOE launched the DOE Industrial Consortia Initiative in 2014 to solicit the input from the leadership of many consortia, some of whom have already participated in workshops with follow-on discussions, and provided written case studies—detailed below—summarizing their charters, operations, membership, successes, and lessons learned, as well as other information. These workshops and reviews identified key considerations for consortia to be effective, including the following:

- **Purpose:** Each consortium is built around a specific vision and goal, often focused on a technology family or industry sector, and conducts defined activities with aggressive project planning and a well-defined set of milestones. The consortia emphasize strong risk management, value management, and contingency planning, toward achieving that vision and goal. Formally documenting the purpose and intended work of a consortium, such as through a program or implementation plan and updating the documentation to capture its evolution can help clarify technology goals and member roles and responsibilities as well as provide a basis for tracking progress. The purpose also helps define the life-cycle of a consortium.
- **Governance model:** The consortium management plan defines leadership and decision-making structures, methods for communicating among members, and a sustainability model. It thus allows

members to share progress and discoveries, work through roadblocks and operational challenges, fine-tune R&D activities, and evolve the roadmap to address current needs. It also defines roles, responsibilities, authorities, and accountabilities of key personnel.

- **Intellectual property (IP) strategy:** An IP management plan (IPMP) facilitates the efficient transition of innovation to the marketplace. The plan should define and assign protection to background IP (BIP), which is generated before the collaboration by each party, as well as foreground IP, which is generated by parties in the performance of the consortium. It should also protect proprietary information and outline a process for licensing of shared IP and public dissemination.
- **Funding strategy:** A funding plan that defines the allocation of resources needed to achieve the implementation plan scope and schedule can drive collaborative efforts and leverage partner infrastructure. Many consortia models leverage both public (e.g., DOE) and private funding sources into an effective portfolio with appropriate partitioning of their roles; for example, with public support focused on earlier science and technology R&D.

These workshops and reviews also found that consortium success is determined by a variety of factors, many of which are intangible. These factors including the following:

- **Leadership:** As with all high-impact endeavors, strong empowered leadership and a clear structure with a conflict resolution and mitigation strategy for prompt decision-making are essential. Consortia can manage the complexities of working with different organizations with varying cultures and goals by crafting a clear statement of governance and decision-making processes and by taking deliberate steps to empower the appropriate leaders. These efforts will lay the groundwork for the focused and dedicated leadership needed—and help ensure member support for decisions rendered.
- **Membership:** Having an engaged and diverse membership is as important as establishing the right leadership. The membership should be sufficiently diverse to cover the range of expertise needed to achieve consortium goals and represent, where possible, prospective customers, clients, and stakeholders. Members should also share mutual objectives and be willing to collaborate at the appropriate level.
- **Clear objectives and expectations:** Consortia objectives often reside at the intersection of members' varied business models. Achieving individual member objectives outside that intersection but through the consortia allow each partner to effectively integrate the consortium work into their home institutional plans and technology roadmaps. Similarly, a clear articulation of the participation required from all members—including a definition of roles and responsibilities—is needed for the consortium to succeed.
- **Commitment:** Commitment from all members is essential to keep work moving in the right direction and achieve the planned outcomes and benefits. Several mechanisms can help ensure that commitment, such as building the right team and scope of work, requiring a fee (even if nominal) for annual or flexible multiyear membership, ensuring open and ongoing two-way communication, and including all members in decision-making. Especially committed champions can also be helpful.
- **Communication:** The consortium governance structure should include a communication plan that outlines processes for ongoing communication on progress, developments, issues, and decisions, best practices, and lessons learned. Effective communication will help the consortium track progress, troubleshoot issues, and allocate resources toward ensuring overall success. Note also that strong leadership is central to effective communication.
- **Agility:** As the consortium progresses, evolution of the business and technology environment inevitably necessitates tuning activities and perhaps even objectives—pointing to a need for operational agility, contingency management, and flexibility. Likewise, financial, human, facilities, and other resources may require adjustment, and membership may need to be modified to bring additional expertise to the team. The governance plan for a consortium should be adaptable to address management of such changes.

- **Trust,** that essential yet elusive quality, is especially important to public-private enterprises, where built-in differences in organizational roles and goals can lead to misunderstandings. Deliberate and open attention to the factors outlined above can help build that trust, facilitating the ready collaboration and cooperation of all members in the critical activities of the consortium. Key to trust is the ability of consortium leadership to build lasting relationships across the consortium.

To determine its performance and outcomes, the consortium needs agreed-upon metrics, along with detailed data collection, analysis and evaluation. The following considerations, developed from the workshops and case studies, may help consortia select and apply the most appropriate means of tracking their progress:

- **Focus on goals:** Each goal should be tied to a specific outcome quantified by metrics. Operational metrics should also be established to clarify the links between goals and the day-to-day management of the consortium.
- **Metrics:** Quantifiable metrics are essential to understand, track, and communicate results and issues. Different types of metrics can provide valuable information on progress. Integrated and time-dependent metrics that focus on operations (such as milestones) should be balanced with metrics centered on results and impacts (outcomes). More qualitative information—which might be obtained from member feedback and regular partner reviews—may provide a perspective on more intangible aspects.
- **Sustainability:** A sustainability plan with metrics that track the ability to sustain operations after an eventual discontinuation of federal support is an important component of a consortium's charter if it is to provide RDD&D support over time.
- **Outside review:** For unbiased analysis of operations and effectiveness, consortia must actively seek independent science, technology, and management reviews as part of portfolio assessment, in-progress peer review, and stage-gate review activities.

DOE and its national laboratories and facilities currently engage in a number of consortia with industry aimed at different targets for different technologies. To illustrate how different consortia organize to achieve their given targets, short summaries of eight case studies depicting real-world models are provided in the next section.

This brief section is intended to underscore the most important considerations and operational elements of consortia that bring together DOE, its national laboratories, universities, and the private sector to accelerate energy technology transfer and innovation. The factors developed from these eight consortia and workshop reviews are overarching, rather than comprehensive, and may not apply to other types of consortia that exist or can be envisioned. Establishing a framework to collect key data and extract important lessons learned is an important aspect of moving these activities forward as rapidly and effectively as possible.

Summary of Case Studies: Real-World Models

DOE and its national laboratories currently engage in a number of consortia with industry aimed at key targets for important technologies. To illustrate how different consortia organize to achieve consortia specific targets, Tables 2 through 10 outline the essential components and characteristics of several of these consortia.

Table 2 Carbon Capture Simulation Initiative

Carbon Capture Simulation Initiative (CCSI)	
Lead Organization	Membership
National Energy Technology Laboratory (NETL)	■ National laboratories: LBNL, Lawrence Livermore National Laboratory (LLNL), LANL, NETL, and PNNL ■ Universities: Carnegie Mellon University, West Virginia University, Princeton University, Boston University, University of Texas at Austin ■ Approximately 20 companies are currently active via a no-fee advisory board. Members over the 5 years have included GE, B&W, Chevron, ADA-ES, Phillips 66*[22], Alstom/GE, Southern Company, Southern California Edison, Eastman Chemical, Fluor, Air Products, American Electric Power*, Process Systems Enterprise, AspenTech, ANSYS, Schneider Electric, Linde, URS/AECOM, ExxonMobil, EPRI, SRI International, RTI International, ESI*, Clean Energy Systems*, GSE Systems*, UKY Center for Applied Energy Research, Babcock Power*, DuPont*, Boeing*, Worley Parsons*, Duke Energy*, Ramgen*,and Burns & McDonnell*.
Essential Components and Characteristics Simulation of Light Water Reactors (CASL)	
Purpose	To help overcome the barriers to widespread, cost-effective deployment of carbon capture technology by developing, demonstrating, and deploying computational tools and models ***to be used by industry*** to reduce the time required to move new energy technologies from discovery to commercialization
Technology Readiness Level (TRL)[23]	Low TRL
Life cycle	Five-year project initiated Feb. 1, 2011 and completed Sep 6, 2016.
Governance model	Technical Director leads overall effort with support from Technical Leadership Team and Executive Committee (high level representatives from each lab and two senior university professors). A Board of Directors (BoD)—Chief Research Officers at each laboratory—reviews the initiative annually. An Industry Advisory Board (IAB) provides regular input to ensure program is on track to impact industry. Roles are detailed in CCSI Project Plan.
Funding sources	DOE Office of Fossil Energy (FE) provided approximately $50 million over 5 years. Industry provided in-kind cost share only for proprietary work conducted under specific cooperative research and development agreements (CRADA).
IP strategy	Intellectual Property Management Plan signed by laboratories and universities provides co-ownership of all IP developed under initiative. Any royalties are divided equally among national laboratories. Central management of IP provides a single point of contact for licensing. CCSI Toolset initially provided under a Test and Evaluation license.
Metrics	■ Industry uptake and licensing of CCSI Toolset ■ Reduced time/cost to scale up technology (long-term metric) ■ Measurable progress and regular release of CCSI Toolset to industry licensees ■ Proactive response to recommendations from bi-annual reviews by IAB, BoD, FE ■ Significant scientific contributions as evidenced by high-quality, peer-reviewed publications and invited presentations
Impacts on U.S. economy	New methods and computational tools to accelerate the development and scale-up of new carbon capture and related technologies, which could save approximately $500 million during the scale-up per technology taken to commercial scale.[24] Direct assistance to ensure the success of carbon capture scale up projects via Cooperative Research and Development Agreements (CRADAs).

Table 3 Combustion Research Facility's Advanced Engine Consortium

Advanced Engine Combustion Consortium (AEC): An example consortium of the Combustion Research Facility (CRF)	
Lead Organization	Membership
Combustion Research Facility of Sandia National Laboratories	■ Auto industry: Caterpillar, Chrysler, Cummins, Detroit Diesel, Ford, ElectroMotive, GM, John Deere, Mack Trucks, PACCAR, Volvo ■ Energy companies: BP, Chevron, ExxonMobil, GE Global Research, Shell Global Solutions ■ National laboratories: Argonne National Laboratory (ANL) LLNL, NREL, LANL, NREL, ORNL, SNL ■ Universities (participants, but not voting MOU signatories): Clemson University, Massachusetts Institute of Technology (MIT), Michigan State University, Michigan Technological University, New Hampshire University, Pennsylvania State University, Stanford University, University of California, Berkeley, University of Connecticut, University of Michigan (UM), University of Vermont, University of Wisconsin, Wayne State University, Yale University
Essential Components and Characteristics	
Purpose	Support U.S. engine manufacturers by increasing scientific understanding of internal combustion engine processes affecting efficiency and emissions
Technology Readiness Level	Low TRL
Life cycle	Enduring - Initiated in 2003
Governance model	■ MOU, signed by membership, who each receive one vote ■ Biannual technical review and business meetings
Funding sources	DOE and targeted CRADAs between industry and laboratory/university partners
IP strategy	Precompetitive R&D – IP owned by industry partners
Metrics	Adoption of combustion models and tools by industry
Impacts on U.S. economy	Over $70B of energy and health care savings over last decade.[25]

Table 4 Consortium for the Advanced Simulation of Light Water Reactors

Consortium for the Advanced Simulation of Light Water Reactors (CASL)	
Lead Organization	Membership
Oak Ridge National Laboratory	■ Industry stakeholders: Westinghouse, Electric Power Research Institute (EPRI), Tennessee Valley Authority (TVA) ■ Universities: North Carolina State, MIT, University of Michigan (UM) ■ National laboratories: ORNL, INL, LANL, SNL, PNNL ■ Numerous associate members
Essential Components and Characteristics	
Purpose	Develop and deploy advanced modeling and simulation (M&S) tools that interoperate so as to create Virtual Environment for Reactor Applications (VERA), a "virtual" version of an operating light water nuclear reactor
Technology Readiness Level	Medium TRL
Life cycle	Two 5-year phases
Governance model	■ Consortium agreement signed by all members. ■ Governed by a director with advice/guidance provided by a Board of Directors consisting of high level representatives from each partner and 3 outside directors ■ Technically reviewed by science and industry councils.
Funding sources	$25M per year provided by DOE Office of Nuclear Energy (NE) with 50% matching by industry
IP strategy	Initial master IP agreement signed by all partners. Implementation of a team-level IP management plan (IPMP)
Metrics	■ Measurable progress and delivery of milestones (541 to date) and the commensurate ability of VERA to demonstrably address nuclear reactor phenomena ■ Proactive response to findings and recommendations provided by annual DOE NE reviews of CASL ■ Substantial scientific productivity, measured in part by high-quality peer-reviewed publications, technical and milestone reports, invited presentations (over 1300 and counting) ■ Early and aggressive deployment of its M&S technology (VERA) to the nuclear energy and broader science and technology communities.
Impacts on U.S. economy	Development of M&S tools that will be used by the nuclear energy industry and utilities to address reactor performance and safety issues, thus enabling the increased generation of low-carbon electricity

Table 5 Critical Materials Institute

Critical Materials Institute (CMI)	
Lead Organization	Membership
The Ames Laboratory	■ Industry: Advanced Recovery, Cytec, Eck Industries Inc., General Electric, Molycorp, OLI Systems, Simbol Materials, United Technologies Research Center ■ National laboratories: The Ames Laboratory, INL, LLNL, ORNL ■ Universities: Brown, Colorado School of Mines, University of California, Davis (UC Davis), Florida Industrial and Phosphate Research Institute (FIPR, at Florida Polytechnic University), Iowa State University, Purdue, Rutgers ■ Affiliate Members: - Industry: ABB, Barr Engineering, Electron Energy Corp., Etrema Products, Infinium, Mosaic, Native American Mining Solutions (NAMS), National Aeronautics and Space Administration (NASA), Niron Magnetics, Phinix, PRINTSPACE, Rare Element Resources, REEcycle, Rio Tinto, Simplot, Tasman Metals, Urban Mining - University: Montana Tech of the University of Montana - Other: ASTM International
Essential Components and Characteristics	
Purpose	■ Mission: Assure supply chains of materials critical to clean energy technologies to enable innovation in U.S. manufacturing and enhance U.S. energy security ■ Strategies: Coordinate basic and applied pre-competitive research to bring technologies to the marketplace to strengthen the supply chains of critical materials in three ways: - Diversifying the sources of critical materials - Finding alternative materials - Enabling more efficient use of existing resources ■ Current Goals: One technology in each of three focus areas adopted by U.S. industry: Source diversification, materials substitution, and materials re-use and recycling. With technology licensed in November 2015, have met goal for industry use of a CMI-developed technology in materials re-use and recycling.
Technology Readiness Level	TRL 1–TRL 6
Life cycle	Five-year term ending on June 30, 2018; renewable for an additional five years
Governance model	Advisory Board, Industry Council and Commercialization Council advise the Director
Funding sources	DOE and cost-share from corporate partners
IP strategy	IPMP signed by all members
Metrics	Invention disclosures, patents, and licenses; Has achieved 41 invention disclosures, one licensed technology, and 17 patent applications in two and a half years of operation
Impacts on U.S. economy	Secure supply chains for clean energy OEMs. Will generate at least one technology adopted by industry in each of three areas noted above.

Table 6 Joint Bioenergy Institute

Joint BioEnergy Institute (JBEI)	
Lead Organization	Membership
Lawrence Berkeley National Laboratory	■ National laboratories: LBNL, SNL, LLNL, PNNL ■ University of California, Berkeley (UC Berkeley) and UC Davis ■ Carnegie Institution for Science
Essential Components and Characteristics	
Purpose	To advance the development of cellulosic biofuels to replace petroleum-based gasoline, diesel, and jet fuels
Technology Readiness Level	TRL 1–TRL 3
Life cycle	Funding in five-year increments, beginning in 2007 and renewed in 2012
Governance model	Executive body is a committee composed of the vice presidents of the four JBEI research divisions, the JBEI Chief Executive Officer (CEO), Chief Science and Technology Officer, and Chief Operating Officer (COO). A Board of Directors provides high-level oversight of management and operations.
Funding sources	$25 M/year DOE funding; funding from nearly two dozen CRADAs and Strategic Partnership Projects (SPPs) with industry
IP strategy	An inter-institutional agreement (IIA) among all member institutions establishes that each member owns its own IP and that LBNL manages and has rights to license all JBEI IP on behalf of the members
Metrics	■ Achievement of scientific milestones reported to DOE monthly ■ Publications and presentations – 508, from FY2008, JBEI inception, to end of FY2015 ■ Records of Invention/software – 208, from FY2008 to end of FY2015* ■ Patent applications/patents - 114, including foreign applications, from FY2008 to end of FY2015* ■ Technologies licensed – 68, from FY2008 to end of FY2015* ■ Industry visits to JBEI – 326, from FY2008 to end of FY2015** ■ General visits/tours – 574, from FY2008 to end of FY2015** *data compiled from LBNL's Sophia Technology Transfer database **data compiled from JBEI monthly DOE reports
Impacts on U.S. economy	■ Reduced U.S. dependence on foreign oil through scientific breakthroughs that will enable advanced biofuels to be cost-competitive with petroleum-based fuels ■ Invigorated economies in some U.S. rural areas through cellulosic feedstock production on non-food producing lands ■ Decreased greenhouse gas emissions in the transportation sector ■ Jobs created through startups and licensing to industry ■ Development of future generations of scientists who will innovate and create U.S. jobs

Table 7 Joint Center for Energy Storage Research

Joint Center for Energy Storage Research (JCESR)	
Lead Organization	Membership
Argonne National Laboratory	■ Partners: ANL, LBNL, PNNL, SNL, SLAC National Laboratory, University of Illinois at Chicago, Northwestern University, University of Chicago, University of Illinois at Urbana-Champaign, UM, Johnson Controls, Dow Chemical, Applied Materials, Clean Energy Trust ■ Funded collaborators: MIT, Harvard University, Notre Dame University, Northern Illinois University, United Technology Research Centers
Essential Components and Characteristics	
Purpose	Discovery, development, and demonstration at laboratory scale of next-generation, beyond lithium-ion electricity storage technology
Technology Readiness Level	Discovery science, battery design, research prototyping, and manufacturing collaboration
Life cycle	Five-year initial term with the possibility of renewal for a second Five-year term
Governance model	Director, management team, research leaders and research team; oversight by Governance Committee, advised by External Advisory Committee (EAC)
Funding sources	DOE, State of Illinois, State of Michigan
IP strategy	Maximize value through pooling, *no a priori* exclusive licensing for partners or external entities, single licensing agent acting in consultation with all partners
Metrics	Published papers, patents, prototypes, milestones completed, webinars, in-person interactions, collaborations, regional events
Impacts on U.S. economy	Lithium-ion batteries are a \$10B–\$15B market today, next-generation beyond-lithium-ion electricity storage estimated to become equally large over the next decade

Table 8 Trustworthy Cyber Infrastructure for the Power Grid

Trustworthy Cyber Infrastructure for the Power Grid (TCIPG)	
Lead Organization	Membership
University of Illinois at Urbana-Champaign	■ Arizona State University ■ Dartmouth College ■ Washington State University
Essential Components and Characteristics	
Purpose	R&D to advance cyber security and resiliency of energy delivery systems
Technology Readiness Level	Research activities spanning cyber security and resiliency for generation, transmission, distribution, and customer premise. Pilot deployment of developed technologies in utility environments.
Life cycle	Funded through 08/30/2015.
Governance model	PI from Illinois, leadership team with site leads from all member institutions, external advisory board (EAB). Weekly leadership meetings (telecom). Quarterly reviews with funding agencies and EAB.
Funding sources	DOE, Department of Homeland Security, university cost-share
IP strategy	Multiple: Startup, licenses, pilot technology deployment, and open-source
Metrics	Technology adoption by the sector; graduates in the field.
Impacts on U.S. economy	Two cybersecurity startups. Adoption of a solution to secure embedded systems (typical of electric substation devices) by a leading utility equipment vendor. Pilot deployment of security for advanced metering infrastructure (AMI) at a major utility. Outreach to K–12 students and the general public on smart grid awareness. Workforce development in the form of training modules.

Table 9 U.S. Advanced Battery Consortium

U.S. Advanced Battery Consortium (USABC)	
Lead Organization	Membership
EERE Vehicle Technologies Office (VTO)	■ Fiat-Chrysler Automobiles ■ Ford Motor Company ■ General Motors Company
Essential Components and Characteristics	
Purpose	Conduct pre-competitive automotive battery R&D
Technology Readiness Level	Fund competitively awarded R&D contracts to develop lower cost and higher performance advanced automotive batteries for hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEV), and full electric vehicles (EVs). To a lesser extent, USABC also funds competitively awarded R&D contracts to develop lower cost battery materials, such as separators or electrolytes.
Life cycle	Partnership conducted through a five-year CRADA. However, DOE has been working closely with USABC through a series of cooperative agreements that span more than 20 years.
Governance model	The CRADA calls for substantial involvement by DOE regarding program direction, funding, proposal review and selection, and project review. The USABC Management Committee (MC) comprises one management employee from each of the auto companies, FCA, Ford, and GM, and one member from DOE; one of the original equipment manufacturer (OEM) individuals serves as Chair. The MC makes both personnel and funding level decisions for the USABC: they allocate staff to various USABC functions and decide if a given proposal will ultimately be funded. A technical advisory committee (TAC), made up of 20–30 technical experts in the battery development field, drawn from each of the automotive OEMs, DOE, and the national laboratories, provides technical guidance and recommendations to the MC.
Funding sources	Department of Energy EERE Vehicle Technologies Office (VTO) provides 50% of contract costs, battery developers cost share their contracts at a minimum of 50%. Automotive OEMs provide in-kind contributions through their MC and TAC members.
IP strategy	IP developed under USABC contracts is held by the technology developer, who cost shares the development effort at 50%. DOE retains march-in rights to that IP. Developers are given wide latitude to develop and commercialize their technology as none of the USABC members directly compete with battery or ultracapacitor developers; rather, the member organizations are users and purchasers of that technology.
Metrics	■ Quantitative battery performance requirements developed and used for all electric drive vehicle applications ■ Use of a "gap chart" for each energy storage technology (EV, PHEV, HEV batteries) that specifies performance metrics, mass, volume, and cost to evaluate hardware from developers ■ Use of standard test procedures and a standard cost model to ensure use of consistent methods to quantify a developer's progress towards those goals each quarter.
Impacts on U.S. economy	Agreements with DOE have resulted in many successes, including the development of the battery currently powering the GM Volt; nickel metal hydride (NiMH) batteries used in nearly all HEVs; and Maxwell ultracapacitors currently in use in millions of vehicles. An analysis by RTI International, "Benefit-Cost Evaluation of U.S. DOE Investment in Energy Storage Technologies for Hybrid and Electric Cars and Trucks" determined that the DOE's $971 million R&D investment (including $315M funds to USABC) in advanced battery technology for electric drive vehicles (EDVs) from 1991–2012 directly led to the commercialization of the 2.4 million EDVs sold between 1999–2012 that incorporate nickel metal hydride and lithium ion batteries, which are projected to reduce U.S. fuel consumption by $16.7 billion through 2020.[26]

Details on Technology Transition Case Studies

The sections below describe the case studies presented in the tables above in greater detail. The intent is to provide both information on the formation, operation, and value to the nation of the case study organizations and lessons learned that could be applied to similar DOE TT programs.

Public-Private Consortia and Technology Transition Case Studies:

Carbon Capture Simulation Initiative

The Carbon Capture Simulation Initiative develops, demonstrates, and deploys advanced computational tools and models to accelerate the development of the next generation of cost-effective carbon capture technologies. CCSI grew out of a series of planning meetings conducted in early 2010 in response to a Presidential memorandum, which charged a Carbon Capture and Storage (CCS) Task Force to overcome the barriers to widespread, cost-effective deployment of CCS technology. At these meetings, representatives from DOE, industry (including energy companies and technology providers), and technical leaders from the national laboratories and universities examined the use of computational modeling to reduce the long timeframes (historically two to three decades) required to move new energy technologies from discovery to broad commercial deployment. Industry representatives explained the barriers to technology development they face and provided information on the capabilities and limitations of modeling and simulation (M&S) within an industry context. In turn, laboratory and university leaders discussed new advances in modeling, optimization, and uncertainty quantification that could address the barriers. The resulting CCSI project plan focused on developing computational tools and models *for use by industry* to accelerate the development and scale-up of carbon capture technologies.

Technical Scope

The Toolset developed through CCSI will offer numerous benefits:

- More rapid evaluation of promising concepts based on an optimized process
- Reduced time for design and troubleshooting by integrating process and device-scale simulations to better predict performance and more effectively resolve scale-up issues
- More focused scale-up activities through quantification of technical risk
- Stabilized costs during commercial deployment through a more comprehensive understanding of the process and underlying behavior of the system

CCSI is organized around tasks that correspond to the activities involved with the development of a new chemical process, such as a carbon capture system, including the following:

- Development of submodels for basic data, such as thermodynamics and kinetics
- Use of those submodels within process models to synthesize and optimize a process design
- Identification of promising device configurations to serve as the basis for more detailed computational fluid dynamics (CFD) simulations
- Consolidation of information to assess project risk and determine whether or how to proceed
- Integration of uncertainty quantification (UQ) among the simulation scales

Each of these tasks is important to effectively design a new process with new technology, and each must interact to achieve an efficient, cost-effective system. The CCSI Toolset consists of several product categories: basic data submodels, high resolution filtered submodels, validated high-fidelity CFD models and UQ, steady-state and dynamic process models, process optimization and UQ, dynamics and control, and crosscutting integration tools.

Leadership

CCSI is led by NETL and leverages core and complementary strengths in M&S at NETL, LLBL, LLNL, LANL, and PNNL. CCSI's academic participants (Carnegie Mellon University, West Virginia University, Princeton University, Boston University, and University of Texas) bring expertise in process synthesis and optimization, process control techniques for energy processes, multiphase flow reactors, and amine scrubbing. University participants serve as subcontractors to the national laboratories, providing specialized expertise. Overall, the project's technical team provides an excellent example of the significant accomplishments possible when uniting the talent that exists across DOE to work collaboratively on an issue of national importance.

A BoD, consisting of the Chief Research Officer of each laboratory, meets annually to review the program and offer guidance. An executive committee—consisting of senior leadership from each lab (i.e., Focus Area Leader, Division Director, Department Head, Program Manager, etc.), who report to their lab's representative on the BoD, as well as two distinguished university researchers—provides high-level management of the program.

Representatives from key industry partners participated in the initial planning. Their participation was essential to ensuring that the initial plan both met industry needs (i.e., addressed current industrial barriers to accelerated development) and would be readily usable by industry within the constraints of their computational resources and expertise. In addition, because industry involvement is vital to the success of CCSI, an IAB was immediately formed and met with the CCSI Technical Team in February 2011, following the formal kickoff of the project earlier that month.[27]

The most significant contributors to the success of CCSI include the early and ongoing involvement of industry partners and the development of an innovative approach to managing IP that fosters creativity, maximizes the contributions of all individuals, and promotes unity of the overall technical team. As testament to this unity, an industry representative remarked at an early IAB meeting that until he learned that the team represented five national laboratories and five universities, he had thought that everyone was from single institution based on how well everyone worked together.

CCSI Industry Partnership

CCSI developed a no-fee industry partnership program founded on prior industry-government research experience and several innovative approaches. The CCSI IAB includes energy technology providers, design and construction companies, power companies, oil and gas companies, chemical companies, software companies and others. Members over the 5 years have included GE, B&W, Chevron, ADA-ES, Phillips 66*, Alstom/GE, Southern Company, Southern California Edison, Eastman Chemical, Fluor, Air Products, American Electric Power*, Process Systems Enterprise, AspenTech, ANSYS, Schneider Electric, Linde, URS/AECOM, ExxonMobil, EPRI, SRI International, RTI International, ESI*, Clean Energy Systems*, GSE Systems*, UKY Center for Applied Energy Research, Babcock Power*, DuPont*, Boeing*, Worley Parsons*, Duke Energy*, Ramgen*, and Burns & McDonnell*.

An initial suite of partners, identified by CCSI and laboratory leadership, participated in the design of the overall program. These partners and program leadership then identified other suitable partners involved in carbon capture technology development who were subsequently recruited into the partnership. Membership generally included high-level technical management of the partner companies (Vice-President of Technology level and direct reports) as well as technical leaders more familiar with the working level development of CCSI products.

CCSI developed an outline describing the role of the IAB at the beginning of the program, which served to inform potential partners of their expected role and function. Specifically, CCSI depended on industry partners to provide substantial inputs on program relevance, content, progress, and directions. Where strong matches of technical interests occurred between partner companies and the program, collaborators from industry partner organizations were expected to contribute directly by working closely with specific technical teams

In addition to the factors discussed above—early involvement of key partners, targeted partner recruitment, and participation of staff from different levels within partner organizations—following are some of the essential features of the CCSI industry engagement program:

- **Continual interaction:** A monthly conference call process was implemented to give all industry partners an opportunity to gain regular exposure to detailed updates of individual program components, provide regular direction and feedback, and support planning and execution of the bi-annual program reviews.
- **Regular program reviews and product demonstrations:** Bi-annual face-to-face programmatic reviews provided industry partners with a view of progress in all areas, as well as opportunities to test new product releases, interact with the tool developers, and recommend shifts in program direction and emphasis.
- **Direct input to the initiative's directions and priorities:** Industry participants are integral at both the overall program planning level and the individual technical task level, providing feedback and recommendations to CCSI leadership and the technical teams. For example, industry helps select technology focus areas, such as the initial decision to focus demonstration of the CCSI Toolset on solid sorbents and the subsequent decision to expand into conventional and advanced solvents. In addition, they provided input on the computer and software platforms that would maximize industry uptake and impact. (To ensure compliance with the Federal Advisory Committee Act, IAB input occurs through LBNL since NETL is a federally operated laboratory.)
- **IP flexibility:** An innovative approach to IP management, described below, considerably improved the transfer of CCSI products to industry.
- **Creation of pathways to deeper partnerships:** CCSI worked closely with industry partners to identify the specific technology development programs that could be accelerated by the application of CCSI tools and developed cooperative relationships to further apply CCSI tools to these programs. Only some companies have elected to pursue the opportunity for deeper partnerships available to all of CCSI's industry partners. Such partnerships are established through CRADAs and nondisclosure agreements (NDAs) between individual companies and the required subset of the CCSI Technical Team needed to pursue the work. These mechanisms provided opportunities for partners to engage at a deeper level and better protect data and IP while continuing to utilize program talent, products, and relationships. Specific results from these deeper partnerships benefit the companies involved and remain protected. However, the broader results, such as models validated at large scale, bring benefits to all members of the consortium by improving the overall CCSI Toolset.

CCSI IP and Licensing

CCSI operates under a unique IPMP that is one of the primary reasons for the success of the development of the CCSI Toolset and its ongoing transfer to industry partners. The IPMP is designed to facilitate a cohesive, collaborative technical team and enable a single point of contact for industry to license the toolset. The IPMP was created with the goal of enabling collaboration and mitigating the barriers based upon eventual conflict over IP rights. By agreeing up-front to share any royalties equally among laboratories and giving each laboratory equal IP rights to everything developed under the project, the technical team could easily function as a single, unified team.

Additionally, the licensing terms state that any works derived from using the Toolset that contain a company's proprietary information will be owned by the company, clearly allowing industry to have rights to IP generated from their usage or modification of the Toolset. This element was essential to enable evaluation and use of the Toolset without concern of contamination of a company's IP, as often occurs with software made available via certain open-source licenses.

Two mechanisms facilitate industry adoption of the tools:

- Establishment of a single lead laboratory as the primary licensing and the project's IP lead, creating a single point of contact for industry and other potential licensees obviates the need to negotiate separate agreements with each laboratory
- Provision to each laboratory of the right to use and modify all of the components of the CCSI Toolset for subsequent projects, license subsets of the Toolset and, if the IP lead does not secure commercial licenses within five years after the conclusion of the project, license the entire Toolset

The primary licensing agent leads an IP Council, which includes representatives from all the labs' technology transfer offices. Together, they coordinate software disclosures and joint copyright assertion. The lab serving as primary licensing agent can be changed if necessary. This approach helps ensure that the technology developed through this effort will continue to be used, adapted, and expanded upon in the future.

The IP Management and Licensing Principles are summarized in Table CCSI-1 below, based on planning as of late 2015.

Table CCSI-1 CCSI IP Management and Licensing Principles

#	Description	Value
1	All CCSI-developed source code is available under a **common CCSI license** to enable laboratories equal access to all of the source code of CCSI Toolset during and after the project and give all laboratories the right to modify and use the source code and the compiled components of CCSI Toolset, including the right to distribute it (as described in #2).	■ Essential to removing barriers to cooperation and collaboration during the development of the CCSI Toolset ■ Enables each lab to contribute and accept assistance from any member of the CCSI Technical Team, regardless of lab affiliation, as necessary
2	**The IP lead is responsible for licensing the CCSI Toolset** for usage and distribution. The royalties from licenses minus an administration fee will be equally divided among the five laboratories. Five years after the completion of the project, if distribution licensing of the CCSI Toolset has not yet occurred, the individual laboratories may negotiate non-exclusive distribution and end-user licenses for the CCSI Toolset or its components.	■ Maximizes the potential for the CCSI Toolset to be licensed and utilized by industry following the end of the project ■ Allows all laboratories to license the toolset and/or components if no distribution licensing occurs in the five-year timeframe
3	Any **IP generated from the usage and modification of the CCSI Toolset by an IAB member** (or other licensee) is owned by that IAB member and need not be contributed to the Toolset. If the company chooses to contribute the IP, then the IP will fall under CCSI license.	■ Enables industry to use the tools without concern of 'contaminating' their own IP ■ Enables rapid evaluation and use of the tools by IAB members
4	The CCSI Toolset—simulation and experimental data, verification & validation hierarchies, models, software, application programming interfaces, and best practices documentation—will be **available for download from one official CCSI location**. Code review and release management is coordinated by a product deployment team that is an integral part of the project. Additional review occurs through software disclosures prior to copyright assertion. During the project period, the technical team can respond to requests from licensees to help install and use the Toolset.	■ Ensures that users know where and how to obtain the software ■ Enables the technical team to manage the release process (project-level source code management, version control, and rigorous beta testing) ■ Enables tracking of bug reports and feature requests from licensees and the technical team

Table CCSI-1 CCSI IP Management and Licensing Principles, continued

#	Description	Value
5	Any required complementary software (e.g., FLUENT, Aspen Plus, gPROMS, etc.) that is licensed under separate commercial licenses is not part of the Toolset and will continue to be licensed by their respective owners.	Clearly indicates content that is not part of the CCSI Toolset
6	Non-commercial complementary software (e.g., MFIX, PSUADE) will be separately available from their developers and is not necessarily part of the Toolset. However, such software may be available via a link from CCSI website or directly from the CCSI website (if such redistribution is compatible with the license terms).	Clearly delineates relationships between CCSI Toolset and complementary software
7	Enhancements made to complementary software with CCSI funding can, at the discretion of the developer, be contributed to the complementary software for distribution under that software's license.	Clearly delineates management of enhancements to complementary software through CCSI
8	Existing software packages (libraries) can only be included in components of the CCSI Toolset if their license permits redistribution. Otherwise they will be termed complementary software.	Clearly delineates relationships between CCSI Toolset and complementary software components
9	The CCSI Toolset will be classified at the lowest level of export control (EAR99). If content that needs to be export controlled is disclosed by a developer, the export controlled component will be distributed separately under a special license for export controlled content.	Defines processes to facilitate export control

Funding

CCSI is funded through DOE FE. An initial $10M of funding was provided in 2010 via the American Reinvestment and Recovery Act. The remaining $40M is from FE's Crosscutting Research Program. NETL's Office of Research and Development leads the program and initially funded the university collaborators. Funding to the other four national laboratories was initially agreed to be split evenly to enhance collaboration among the organizations. This was achieved by matching the breadth of CCSI's technical needs with the diversity of cutting-edge technical capabilities that the participating laboratories offered and helped to ensure a unified, integrated development team.

Two potential funding mechanisms are being planned to enable ongoing support of the Toolset beyond the CCSI project. A planned subsequent project, Carbon Capture Simulation for Industry Impact (CCSI2), includes proposed funding for Toolset maintenance. In addition, In FY15, FE's Crosscutting Research Program has issued a Funding Opportunity Announcement (FOA) (DE-FOA0001238) to enable the Toolset to be commercially supported, integrated with the existing modeling and simulation tools, offered as a commercial product, and demonstrated on multiple advanced energy systems. As a result, In August 2015, the U.S. Department of Energy's National Energy Technology Laboratory (NETL) selected Process Systems Enterprise, Ltd. (Cedar Lakes, NJ) to receive Phase 1 funding through its Crosscutting Research Program's Technology Development to Enable Highly Efficient Power Systems with Carbon Management initiative. PSE partnered with Carnegie Mellon University and West Virginia University to identify market opportunities and develop commercialization plans for state-of-the-art computation modeling and simulation tools created by CCSI within gPROMS (general PROcess Modeling System), software that provides a modeling environment.

Unfortunately, the Phase 2 proposal submitted in 2016 was not selected. Alternative approaches for ongoing support of the CCSI Toolset are currently being investigated.

The IAB is strictly advisory in nature and has no membership fee. Membership is based on interest and a willingness to commit 10–20 working days per year, participate in monthly teleconferences, two annual program review meetings, and otherwise interact with the CCSI Technical Team as appropriate. The no-fee membership was deemed appropriate for the early stage of development of CCSI at its inception. This membership structure is evolving toward more participatory and cost-sharing approaches as the technology matures and draws greater application interest with specific partners for specific purposes.

Partnership Governance

The integrated technical structure of CCSI includes a technical leadership team reporting to a Technical Director, with overall technical leadership provided by NETL. As described previously, an executive committee provides high-level management of the program and a BoD meets annually to review the program and offer guidance. Leadership of particular tasks is shared among laboratories and universities. Membership in each technical team crosses institutional boundaries, as the IPMP removes many of the barriers to such cross-institutional teams. Industry stakeholders interact with the leadership and technical team through the IAB as described above.

The CCSI Technical Leadership Team meets weekly via teleconference/web capabilities to review progress, update milestones, and revise plans. Each technical task team meets regularly, usually weekly, via teleconference/web meeting. Prior to each IAB program review meeting, the technical teams meet in-person to review activities across the entire project. In spring 2014, the regular IAB program review meeting was replaced by a two-day technical team meeting to allow a more focused engagement among team members at separate institutions. In addition, each technical task team regularly reviews ongoing work internally, gaining additional value from the diverse perspectives possible with researchers from multiple institutions.

Every six months, the IAB, the executive committee, and representatives from DOE review the program's progress over a two-day period that includes presentations, software demonstrations, and posters by nearly all the members of the CCSI technical team. The IAB provides written and verbal feedback and suggestions. The BoD formally reviewed the program in early 2012. Since then, the BoD review has primarily occurred in conjunction with IAB meetings. In addition, CCSI has participated in merit reviews conducted by the Strategic Center for Coal.

An initial program review was conducted by DOE with a panel of reviewers that included members of the National Academy of Engineering. Over the course of the project, focusing project review efforts on the two annual meetings with the IAB has alleviated the time burden of providing effective oversight. An ongoing challenge has been reconciling the project-level reviews with the review requirements associated with each organization involved in the program to avoid duplicative review activities.

The program is continually adjusted based on feedback from the IAB, DOE, and other stakeholders to ensure that it achieves its goals and has significant impact. The leadership team meets annually to review feedback from the previous year and develop the detailed plans and milestones for the following year. This schedule enables the detailed plans to adjust to actual funding available.

Partnership Results

Due to positive feedback from the IAB members, and an expressed desire to use the software as soon as feasible, the first version of the CCSI Toolset was released in 2012, a year ahead of the originally scheduled release date. A second-generation Toolset was released in 2013, followed by a third-generation release in 2014.

Many of the improvements were the result of feedback from IAB members. The final major release occurred in November 2015.

The Toolset has been offered to the partnering companies under a Test and Evaluation License since 2012. Under this license, the industrial partner is granted use of the software for 18 months without charge, provided the partner offers thorough feedback on the use of the Toolset, including information on what works and what doesn't and recommends improvements. After 18 months, if the company provides detailed feedback, they are able to renew the license for a subsequent 18 months, an arrangement that incentivizes further interaction with the development teams. Currently twelve companies have active licensing agreements: GE, B&W, Chevron, SRI International, RIT International, Arizona State University, EPRI, Process Systems Enterprise, ESI, WS Corporation and Clean Energy Systems, and GSE Systems.

The fourth release of the CCSI Toolset is organized around nine major products, each with multiple modules:

1. CCSI Basic Data Fitting Tools, a suite of routines that fit combined thermodynamic and kinetic models from laboratory-scale data;
2. CCSI Computational Fluid Dynamics (CFD) Models, which includes validation and uncertainty quantification hierarchies for device-scale models for sorbent and solvent contacting equipment;
3. CCSI Process Models, which can be used to simulate complete carbon capture systems for using solvents, sorbents, and membranes including CO2 compression;
4. Framework for Optimization, Quantification of Uncertainty, and Surrogates (FOQUS), which serves as the primary computational platform enabling advanced Process Systems Engineering (PSE) capabilities to be integrated with commercial process simulation software;
5. Automated Learning of Algebraic Models using Optimization (ALAMO) tool, which generate algebraic surrogate models of more complex systems to support large scale optimization;
6. CCSI Superstructure Formulation, which uses surrogate models from ALAMO to optimize the configuration of carbon capture systems;
7. CCSI Oxy-Combustion Models, which consists of a detailed, validated boiler model and a suite of equation-based models to enable optimization of complete oxy-combustion power generation systems;
8. CCSI Advanced Process Control (APC) Framework, which enables more rapid and effective control of integrated capture systems; and
9. CCSI Special Solvent Blend Models, which provide a framework for estimating the properties of blends of aqueous amines.

Three companies (ADA-ES, GE, and Babcock &Wilcox) are currently involved with the technical team through CRADAs or information-sharing arrangements to increase the success of their carbon capture development projects. Such opportunities are available to all the industry partners. These projects illustrate use of CCSI technology by industry to accelerate carbon capture technology development, and their successful completion will result in the early direct impact of CCSI on carbon capture technology development. Thus, while these partnerships assist the companies, they also assist the whole consortium by providing real opportunities to validate the CCSI Toolset. In addition, Southern Company, through the National Carbon Capture Center, has provided valuable data to use for model validation.

To promote Toolset use, educational sessions are training current and future engineers in the use of the CCSI Toolset. Members of the CCSI development team have visited industry sites to instruct their employees on the capabilities of the Toolset and have conducted web meetings to demonstrate how to use the technology. Through these methods, the Toolset will continue to be developed with a heightened awareness of industry needs, based upon regular dialogue between the research teams and the ultimate end users of the technology.

Commercialization of the technologies available in the toolset is expected to provide significant economic impacts because the implementation of these tools holds the potential to reduce development time by 25% and costs by $500 million for each carbon capture technology scaled-up utilizing the CCSI Toolset.[28] Industry has enthusiastically embraced the releases of the CCSI Toolset; as noted above, nine companies hold test and evaluation licenses for the technologies. Even though many of these companies do not have immediate plans for carbon capture, they recognize the value of these new computational tools to revolutionize their process optimization and modeling capabilities across multiple technology areas. To help track the impact of the CCSI Toolset on industry, a licensing term requires users to report on the impact of the CCSI Toolset on their development activities. While not quantitative, such information will help measure the extent to which the CCSI Tools have changed current practice.

In addition, CCSI enables training of PhD students at regional universities. These students become part of innovative project teams and then join the workforce with industry-specific skills, which will ensure continued expertise in carbon capture technology.

CCSI is scheduled to conclude at the end of January 2016. At that point, the IAB has expressed a desire for the Toolset to be licensed and supported by independent software vendors. Discussions on the potential licensing and commercialization of CCSI technology have been held with Process System Enterprise, Chemstations (makers of ChemCAD), GAMS Development Corporation (makers of optimization software), and AspenTech. Process System Enterprise is currently receiving funding under DE-FOA0001238 to identify market opportunities and develop commercialization plans to incorporate the CCSI Toolset with its own modeling and simulation software. Licensing and commercialization discussions are expected to intensify in 2016 as the CCSI effort draws to a close.

The CCSI Toolset is expected to be utilized by industry and industry/lab partnerships to advance the development and scale-up of new carbon capture and related technologies. For example, a planned follow-on project, the planned CCSI^2 should help maximize the learning obtained from large-scale industry pilot programs to enable more cost effective scale-up to demonstration scale. Data collected during this project will enable quantitative estimates of actual cost savings and return on investment.

Lessons Learned

The following are specific lessons learned from CCSI that could apply to new programs:

- CCSI's model for industry engagement yielded excellent participation and strong interest in product uptake and application.
- New initiatives placing greater emphasis on developing early joint development programs to utilize the products for specific technology development applications might be considered.
- Tiered industry engagement, regular involvement and reviews, and the IPMP are components that should be propagated forward into any new program.
- Two innovative systems and policies fostered creativity and maximized the contributions of individuals:
    - A plan for effectively managing IP among multiple organizations
    - Incorporation of potential users of the tools from the very beginning of the initiative to ensure a successful technology transfer pathway
- The IPMP represents an innovative, integrated approach specifically designed to facilitate licensing of technology developed by a partnership of multiple laboratories and universities.
- The use of a common CCSI license, a single point of contact, and the availability of the CCSI Toolset download from a single website created a straightforward path for industry to utilize and reap the benefits of the Toolset.

For future partnerships, CCSI plans the following:

- Further engage industry partners during early program planning.
- Use these laboratory-industry relationships to identify shared goals, targeted implementation plans, and other cooperative R&D arrangements as an integral part of program planning and execution.
- Early in the program, articulate a clearer, shared understanding of the potential value to be delivered to industry partners by program success.
- To develop more specific collaborations with industry, create a streamlined process for developing, approving, and executing multi-lab/university CRADAs with industry at the same time as the IPMP and other project documents are established.

Conclusion

United in the goal of developing computational tools that meet industry needs, members of the CCSI Technical Team have worked closely with each other and industry partners to deliver a Toolset that successfully addresses challenges related to the scale-up of new technologies and can accelerate the development of carbon capture systems. Industry stakeholders are rapidly adopting the CCSI Toolset and clearly recognize its value, as demonstrated by the following quotes:

> *The development of this CCSI Toolset is a major innovation, which will have a significant impact on the way industry develops new technology. We are excited to be among the first to adopt these computational tools. We believe they will ultimately give us a competitive advantage as we incorporate them into our work processes.*
>
> - Terry K. Leib, Technology Director, GE Global Research
>
> *The CCSI Toolset provides a unique set of capabilities not currently available from any other source. We consider these capabilities of great value to our process development activities.*
>
> - Arnold Smith, Executive Director, Fluor Enterprises, Inc.
>
> *Users will license CCSI's advanced simulation Toolset because the Toolset has capabilities that were not previously accessible to industry, and various parts of the tool set can be integrated as stand-alone capabilities within existing evaluation, design, and scale-up processes. Additionally, the tool set will be broadly applicable to the development and scale-up of advanced energy conversion and emissions control systems.*
>
> - Chris E. Latham, Director, Babcock & Wilcox Research Center

Public-Private Consortia and Technology Transition Case Studies:

Combustion Research Facility

Established as the first Department of Energy (DOE) user facility in the 1970s and designated as a DOE collaborative research facility in 2008, the Combustion Research Facility (CRF) at SNL has served as a national and international leader in combustion science and technology for more than 30 years. Within the CRF, staff and visiting researchers have greatly expanded fundamental knowledge of combustion processes, pioneering research into new science and applied concepts—while at the same time helping the automotive industry to produce cleaner, more efficient vehicles.

To establish this improved understanding of combustion science, the CRF develops advanced, laser-based diagnostics and other techniques that are applied to both studies of combustion fundamentals and investigations of engine-combustion processes through the use of optically accessible engines and other specialized experimental hardware that simulate realistic engine conditions. As new engine data emerge, the understanding gained by basic-science researchers on combustion fundamentals or laser spectroscopy in flames is often used by the more-applied researchers in their data analysis and interpretation to create new conceptual frameworks of the physics underlying engine-combustion processes.

Findings and frameworks are shared and transitioned to other applied researchers and industry stakeholders in many ways, including in-depth discussions, influential papers in academic and applied journals, and presentations at widely attended events. In some cases, the work can be distilled into freely available models that accurately reflect combustion phenomena—and yet are sufficiently condensed for practical use by industry in creating proprietary innovations that enhance transportation engines.

Foundational DOE Sponsorship

The flow of knowledge and ideas between scientific and applied researchers reflects the two missions of the CRF, which in turn stem from the two major sources of CRF funding. Specifically, BES within the Office of Science (SC) directs the CRF to do excellent science, while the Vehicle Technologies Office within EERE directs the CRF to create results that can be more immediately useful to industry.

The core of the CRF's success is founded in the synergy created by these two missions. Focusing on the much-needed science fundamentals from the perspective of delivering applicable results has been central to the continued value of the CRF. Thus, the CRF has approached its science undertakings with an eye to meeting industry's needs and pioneered methods for bridging the transfer of knowledge and technologies across the spectrum of activities required to generate innovation. Learning from its experiences, the CRF has created and continues to enhance principles for collaborations—which can take many forms, such as consortia like the Advanced Engine Combustion Consortium; close collaborations with researchers within and external to the CRF, including visiting researchers who come to the CRF for weeks, months, or years; and Strategic Partnership Projects (SPPs) formerly known as Work for Other (WFO) Agreements and CRADAs that enable the CRF to conduct focused research to meet DOE and partner needs.

Creating an effective program that produces results also requires strong relationships with DOE program managers. Through ongoing communication, the CRF is able to listen to and share perspectives on how building and applying scientific knowledge can fulfill the needs and goals of both DOE and industry. With this understanding, CRF and DOE managers are well prepared to engage in strategic planning that advances science and technology in ways that allow industry to achieve the critical national goal of progressing toward a clean, efficient, and low-carbon transportation system.

To focus more specifically on how the CRF ensures its continued impact on industry, it is helpful to understand some of the forms that impact can have, the principles that the CRF follows for engaging with industry, the different engagement models the CRF has employed, and the best practices developed at the facility.

Impact

The success of the CRF may have been best summarized by a top U.S. automotive industry executive, who maintained that every vehicle being built today is cleaner and more efficient due to work done at the CRF. A quantitative perspective on the benefits of the CRF's work is available from a 2010 report[29]—prepared by Albert N. Link at the University of North Carolina at Greensboro with funding from EERE—that estimated the benefits of DOE investments in vehicle technologies.

Examining just two CRF research areas—laser and optical diagnostics and combustion modeling for heavy-duty vehicles—the study found that the DOE investment achieved total economic and health benefits of $70.2 billion (in 2008 dollars) from 1995–2007 by reducing the diesel fuel consumption of heavy-duty trucks by 17.6 billion gallons over this period. In addition, the study credited the DOE investment in the CRF with reducing U.S. crude oil imports by 1% during the study period and creating a knowledge base supporting more than a dozen important technologies, including fuel injection, homogenous charge compression ignition combustion processes, exhaust gas recirculation, and low-emissions diesel fuel formulations.

Evidence of impact is embodied in the knowledge and models the CRF has transferred to industry, as well as in the influence of CRF publications. In addition, awards demonstrate the value that peers have placed on the CRF's work. Each of these areas is discussed below.

New Knowledge and Models

Science-based Understanding of Key Diesel-Engine Combustion Processes

Realizing that a more detailed understanding of the physics underlying combustion and emissions formation in heavy-duty vehicle diesel engines was a prerequisite to meeting stringent standards for nitrogen oxides (NO_X) and soot, industry leader Cummins entered into a CRADA with the CRF, LLNL, and LANL in late 1993. Under this CRADA, which later grew to include General Motors (GM), Caterpillar, and Detroit Diesel, the CRF conducted in-depth measurements over several years using advanced laser diagnostics applied in a new-generation optically accessible engine.

This effort yielded highly significant results. Specifically, a series of increasingly refined measurements—augmented by close collaborations with scientists supported under DOE's BES program—allowed CRF researchers to revolutionize the existing physical understanding of fuel/air mixing and NO_X and soot formation in diesel engines and to reduce this information to a tractable physical description.[30]

Guided by this new understanding, researchers at LANL and the University of Wisconsin improved CFD models and developed new submodels that enabled the numerical simulations to match the CRF's experimental data. Armed with these new models, quantitative experimental data, and a much more accurate understanding of combustion, engine manufacturers, refined, and validated their proprietary computational models for engine design to produce cleaner and better performing engines.[31]

As an additional testament to the long-term value of this work and the methods used to obtain the experimental data, the optical engine built by the CRF researchers for this work has remained in use for 22 years, providing measurements and data that continue to enhance understanding of combustion physics today.

Understanding Supercritical Fuel Mixing

Under the high temperature and pressure (supercritical) conditions present within the cylinder of a diesel engine, liquid and gas molecules behave in unconventional ways. The CRF's computational experts have developed a theoretical model that captures the physics of fuel/air mixing processes under supercritical conditions, and images from CRF experiments have verified the mixing behavior predicted by the models. These findings can help engine makers redesign fuel-injection and fuel-air mixing strategies to achieve better engine emissions and efficiency.

In-cylinder Carbon Monoxide Emissions Control

Controlling emissions within the engine cylinder is more effective and cost-efficient than mitigating emissions with after-treatment in the exhaust system. In addition, emissions of some species, and particularly of carbon monoxide (CO), occur because of incomplete combustion and can therefore signify a substantial efficiency loss. To help industry understand the in-cylinder sources of CO emissions, CRF researchers performed time-resolved laser-sheet imaging that showed the evolution of the in-cylinder CO distribution. Using quantitative spectroscopic information developed under the CRF's BES program, they were able to provide accurate measurements of the in-cylinder CO concentration. Comparison to tailpipe CO measurements taken using well-established methods verified the optical measurements and gave the industry confidence to use the optical measurements to validate their proprietary models and ultimately to decrease engine emissions.

In 2007, Cummins produced the world's first all-computationally designed diesel engine, eliminating the traditional test-and-build approach. The new design approach—developed by Cummins based on knowledge from a multi-institution collaboration led by the CRF—reduced by about 10% the time and cost of producing a new more robust, fuel-efficient engine that met all expectations for performance and emissions. First marketed in 2007, the Cummins ISB series 6.7-liter diesel engine now powers more than 200,000 Dodge Ram heavy-duty pickup trucks. Further, all new U.S. engines today are designed in large part with computer simulation, a development that is helping U.S. industry reduce product development cycles and costs.

Presentations and Publications

CRF researchers publish extensively every year, targeting academic and scientific researchers via the scientific press and more-applied researchers and industry stakeholders in relevant industry association journals. These articles—along with presentations offered at such conferences as the International Combustion Symposium (the largest event for combustion science in the world, held biannually), the SAE International Congress (the largest event in the world for engine-combustion research, held annually), and many other events for both fundamental and applied research—allow the CRF to disseminate its findings to others in like-minded research and applied pursuits.

One indication of the quality of the CRF research is the high rate of citations of its papers. The nearly 600 papers published by CRF researchers between 2009 and 2014 are referenced in thousands of citations.

Awards

CRF scientists have been recognized with the highest awards in their fields, including the Gold Medal of the Combustion Institute and the Broida Prize of the American Physical Society. Since the CRF's inception, one CRF researchers has been elected a Fellow of the American Physical Society's (APS) Division of Chemical Physics, six CRF researchers have been designated as SAE Fellows, and CRF researchers have won the SAE's prestigious Horning Memorial Award seven times—honors that are unmatched by any other institution.

Principles for Industry Impact

To create such impact, the CRF follows specific principles:

- **Build foundational scientific understanding:** As noted, the CRF has been focused on generating basic knowledge about combustion for more than three decades. Although much has been learned, several interrelated factors—including the complexity of modeling combustion processes, ever-more stringent regulation of vehicle efficiency and emissions, and the need to understand the interaction of engines with future fuels—strengthen the mandate to continue the search for increasingly in-depth understanding of combustion and engine science.
- **Focus on industry needs, including emerging challenges:** Through deliberate and ongoing partnerships with industry, the CRF seeks to focus its research toward helping industry face its toughest challenges and develop technological solutions to enable each new generation of clean engines. Thanks to trust earned through decades of effective working relationships and a track record of meeting objectives, the communications include a solid feedback loop from industrial partners, which allows the CRF—working with DOE program managers—to adjust goals, programs, and deliverables as needed to maintain their relevance.
- **Deliver valued results:** Beyond delivering new knowledge, CRF researchers seek to package that knowledge into forms that industry can use to further their own development processes by creating proprietary solutions and IP. Whenever possible, the knowledge is delivered as computational models, considered the most succinct form of encapsulating the most relevant knowledge of a process. Key models delivered by the CRF, in addition to the supercritical mixing models discussed above, include better turbulence models, soot and NO_X formation and oxidation models, and models for spray flame entrainment, mixing, and combustion under conventional sub-critical conditions.
- **Deliver pre-competitive results:** Industry has consistently expected the CRF to deliver results at the pre-competitive stage by providing the science base of fundamental understanding, leaving industry free to compete by drawing upon this understanding to develop propriety products. Thus, while the CRF has been a source of often unique breakthroughs, it has created relatively fewer patents than similar organizations, opting instead to meet DOE goals and industry needs by delivering knowledge and tools at an upstream development phase. This strategy has in fact proven extremely successful.

  This said, some evidence suggests that when the CRF does create patents, they can be highly influential. The May 2010 cost benefit report cited earlier [Link 2010] noted that, based on citation averages and patent families filed since 1999, each of the combustion patent families associated with DOE investments is linked to an average of 2.35 subsequent patent families owned by a set of leading companies. As such, DOE places second in patent influence only to Nissan, whose combustion patent families filed since 1999 are each linked to an average of 2.67 later patent families of the leading companies.
- **Work collaboratively on projects with mission importance:** Much of the benefit delivered from the CRF can be traced directly to an intense pursuit of collaboration—a strategy that dates back to the CRF's inception as a DOE user research facility. However, the CRF operates differently from typical user facilities, which provide staff scientist support and access to major equipment and facilities for users with research proposals judged sound by their peers. Instead, the CRF accepts collaboration only on research topics of interest to the CRF mission, as well as to the partner. In recognition of this unique operating model, DOE changed the CRF's designation from user facility to collaborative research facility in 2008. The section below on engagement approaches discusses the different avenues that the CRF has taken to maximize the value of its collaborations.

Approaches to Engagement

To maximize its ability to collaborate effectively and deliver on its objectives, the CRF engages with others in several ways, as described below.

Consortia

The CRF has initiated and leads several consortia with industry stakeholders and other research centers. The focus of these consortia is to accelerate research and obtain more accurate results by coordinating either DOE-funded research with U.S. industry or research being carried out across the globe. Table CRF-1, Table CRF-2, and Table CRF-3 summarize the goals, types of partners, and working arrangements of three current consortia.

Table CRF-1 Advanced Engine Combustion Consortium

Dates of Operation	Initiated by the CRF in 2003 and renewed until 2018 through a memorandum of understanding (MOU) agreed upon by all partners
Goals	**Current goals:** ■ Working at the pre-competitive stage, coordinate DOE-funded engine-combustion research with U.S. industry to provide the science and knowledge basis for the next generation of clean, high-efficiency light- and heavy-duty engines running on conventional and future fuels ■ Advance models for engine design to support further proprietary work conducted outside of the AEC **Target combustion strategies:** ■ Advanced dilute-burn gasoline engines (e.g. boosted, spray-guided gasoline direct injection) ■ Advanced clean diesel combustion (e.g., multiple injections, high exhaust gas recirculation) ■ Low-temperature combustion (e.g., homogeneous charge compression ignition, partially pre-mixed charge compression ignition) ■ Alternative liquid hydrocarbon, natural gas, renewable fuels, and hydrogen
Membership	■ **Auto Industry:** Caterpillar, Chrysler, Cummins, Detroit Diesel, Ford, ElectroMotive, GM, John Deere, Mack Trucks, PACCAR, Volvo ■ **Energy Companies:** BP, Chevron, ExxonMobil, GE Global Research, Shell Global Solutions, ■ **National laboratories:** ANL, LANL, LLNL, NREL, ORNL, SNL ■ **Universities (participants, MOU signatories):** Clemson University, MIT, Michigan State University, Michigan Technological University, New Hampshire University, Pennsylvania State University, Stanford University, UC Berkeley, University of Connecticut, UM, University of Vermont, University of Wisconsin, Wayne State University, Yale University
Significant Achievement	Maintains the relevancy of DOE research by providing a forum for communicating research results to members in a timely manner and gaining feedback from industry
Organizational Structure	■ MOU, led by the CRF; each MOU member has a single vote ■ Biannual review meetings to share latest research results and partner needs ■ Maintain AEC efforts at the precompetitive stage; IP based on this work is performed by members outside the scope of the MOU ■ Additional work through SPPs and CRADAs between specific partners is handled by those partners, and IP management is determined in those agreements ■ Governance and planning conducted via a business meeting held with the biannual review meeting. DOE investment decisions ultimately reside with DOE program managers. ■ Consideration of new members determined by existing partners, and new partners require the unanimous approval of the existing MOU membership

Table CRF-1 Advanced Engine Combustion Consortium, continued

Dates of Operation	**Initiated by the CRF in 2003 and renewed until 2018 through a memorandum of understanding (MOU) agreed upon by all partners**
Member Roles	**Industry:** ■ Actively participate in biannual program review meetings ■ Provide constructive feedback on research progress and direction ■ Make presentations on industry needs and non-proprietary in-house research ■ At their discretion, provide technical assistance and hardware to facilitate research **National laboratory and university researchers:** ■ Actively participate in the biannual program review meetings ■ Present latest research ■ Listen to and respond to industry feedback

Table CRF-2 ºEngine Combustion Network (ECN)

Dates of Operation	**Initiated by the CRF in 2011**
Goals	**Goals:** ■ Coordinate international research to provide the science and knowledge basis for the next generation of clean, high-efficiency light- and heavy-duty engines running on conventional and future fuels ■ Advance models for engine design **Current Focus:** ■ Establish an internet library of well-documented experiments that are appropriate for model validation and the advancement of scientific understanding of combustion at conditions specific to engines ■ Provide a framework for collaborative comparisons of measured and modeled results ■ Identify priorities for further experimental and computational research
Membership	Multiple partners, including automotive companies, research laboratories, and universities from specialized facilities around the world; current participants follow: **Experimental Participants:** ■ *United States:* ANL, Caterpillar, GM, Michigan Technological University, Pennsylvania State University, Purdue University, SNL, University of Massachusetts ■ *International:* Aachen University, Germany; Chalmers University of Technology, Sweden; CMT, Spain; Eindhoven University, Netherlands; IFP Energies Nouvelles, France; Meiji University, Japan; Seoul University, South Korea **Modeling Participants:** ■ *United States:* ANL, SNL, University of Wisconsin ■ *International:* CMT, Spain; Eindhoven University, Netherlands; Politecnico Di Milano, Italy; University of Cambridge, U.K.; University of New South Wales, Australia
Significant Achievement	Generates collective results far beyond what any single institution could achieve by linking and coordinating research efforts from multiple partners with different capabilities
Organizational Structure	■ Voluntary participation ■ Led by the CRF

Table CRF-2 Engine Combustion Network (ECN), continued

Dates of Operation	Initiated by the CRF in 2011
Member Roles	**Experimental participants:** ■ Conduct experiments on a set of identical fuel injectors to improve the understanding of injector-produced fuel sprays, spray mixing and spray-combustion processes in engines, and to provide a database for modeling these sprays. **Modeling participants:** ■ Use the experimental data to validate and improve models to predict the behavior of fuel sprays and spray-combustion in engines.

Table CRF-3 Turbulent Non-premixed Flame Workshop (TNF)

Dates of Operation	Initiated by the CRF in 2003 and renewed until 2018 through a memorandum of understanding (MOU) agreed upon by all partners
Goals	**Goals:** ■ Understand fundamental issues of turbulence-chemistry interactions in gaseous flames **Objectives:** ■ Provide an effective framework for comparison of measured and modeled results ■ Establish a series of benchmark experiments and calculations that cover a progression in geometric and chemical kinetic complexity across a range of combustion modes and regimes ■ Understand the capabilities and limitations of various combustion models and submodels ■ Identify priorities for further collaborative research
Dates of Operation	■ Since July 1996, 12 international workshops with invited session coordinators presenting collaboratively generated information on selected topics
Participants	■ Each workshop typically attracts 80–100 experimental and computational researchers in turbulent combustion from 13 countries with expertise in a variety of areas, including velocity measurements, scalar measurements, computational methods, turbulence modeling, chemical kinetics, reduced mechanisms, mixing models, direct and large-eddy simulation, radiation, and combustion theory ■ *Main participating institutions:* Cambridge University, Cornell University, Delft University of Technology, DLR-Stuttgart, Ecole Centrale Paris, Hanyang University, Imperial College of London, Aachen University, Ohio State University, Princeton University, Purdue University, SNL, SINTEF, Stanford University, Stuttgart University, Sydney University, Technical University of Darmstadt, University of Adelaide, UC Berkeley, University of California-San Diego, University of Duisburg-Essen, University of Melbourne, University of New South Wales, University of Southern Queensland, University of Texas-Austin, University of Toronto
Significant Achievements	Pursues collective research strategies that generate basic science knowledge far beyond the scope of any single organization. Tangible results include a TNF library that includes: ■ Multi-scalar and velocity data from several flows and flames that carry through a progression in complexity of the chemistry and the flow field ■ Research on flames of simple hydrocarbon fuels (methane, natural gas, and methanol), that include modeling challenges, such as local extinction and re-ignition, detached or lifted reaction zones, auto-ignition, flow recirculation, and swirl ■ Workshop proceedings available via the Internet[32]
Organizational Structure	Voluntary collaboration with participants
Participant Roles	■ Contribute to development of a collective research strategy ■ Present and share results

Co-location of Researchers

A major asset of the CRF is co-location of applied and fundamental researchers, a strategy that encourages collaboration and creates strong synergies between basic science and applied efforts. The CRF expands on the benefits of proximity by hosting more than 100 visiting researchers every year from around the world. These visitors, who work at the CRF from periods of weeks to years, include industrial collaborators, postdocs, university faculty and graduate students, high school teachers, and national laboratory and government researchers. Flexibility of the period and longevity of visits fosters relationships that maximize the value of the CRF. For example, some CRF visitors have returned to the CRF multiple times over 20 years to pursue ongoing projects, while a researcher from Cummins worked at the CRF for a continuous three-year period.

Working side-by-side with CRF staff, visiting researchers help develop new research methods and approaches and conduct experiments that benefit from the unique facilities and techniques available at the CRF. In turn, the visitors boost CRF capabilities by sharing developments and unique knowledge from their home institutions that stimulate progress and new approaches to CRF projects.

Industry-Sponsored Research

CRADAs and SPPs allow the CRF to conduct focused research on proprietary projects in areas important to a DOE mission with funding or significant in-kind support from partners outside of government. Such partners share in project strategy development and receive regular, in-depth information on their respective projects to enable them to stay current on the research and continue to play a role in project strategy. Agreement terms may protect proprietary information and can protect designated project-generated information for up to five years before public disclosure.

CRF has worked under sponsored research agreements with many in the engine industry, including General Motors, Ford, Chrysler, Toyota, Caterpillar, Cummins, Detroit Diesel, International, and John Deere. In addition, Chevron has funded an ongoing project for many years, and other energy companies, such as ExxonMobil, Shell, ConocoPhillips, and BP, are exploring options for working with the CRF on various combustion experiments of interest.

As discussed above, one of the most significant CRF CRADAs, formed with Cummins, laid the foundation for a new understanding of diesel combustion that has changed the way engineers think about and model the combustion process and led to the first entirely computer-designed engine.

Engagement Best Practices

From lessons learned through years of working with industry partners, the CRF has developed the following best practices for engaging in ways that produce impact:

- **Deliver precompetitive results:** On numerous occasions in different types of collaborative forums, industry has expressly stated that the CRF should focus on creating fundamental knowledge that industry can then carry forward to create IP and proprietary designs. This approach allows deep and open information-sharing that results in trusted relationships between the CRF and its partners.
- **Engage in impactful research topics:** Strong communication with industry allows CRF researchers to gain intimate understanding of their needs and identify important research topics that impact the industry. For example, from Ford, the CRF has understood the importance of accounting for not only engine emissions and efficiency, but also for factors, most notably noise, that drive consumer acceptance. Further, the OEMs have helped direct research towards emerging concepts, such as low-temperature combustion and the mega-knock phenomena that arises in modern boosted, down-sized engine designs. The CRF is also responding to an industry-expressed need for research on advanced ignition systems.

- **Develop strong connections:** The deep level of discussions and information-sharing possible with close relationships steer the CRF's research toward highly valued and relevant results and—perhaps more important—generate mutual trust that facilitates further information-sharing. The benefits of close connections can accrue to individual companies, as well as to the CRF and the industry as a whole. For example, by taking the step of donating fuel injectors to the ECN experimental partners for their studies, Bosch gained detailed information on their product from research facilities around the world.
- **Share information:** The CRF makes a concerted effort to share its information and results. During projects, CRF researchers schedule regular meetings with partners to discuss progress, data, developments, and issues. Partners thus have access to findings before they can be published in public journals. As noted above, the CRF publishes extensively and presents at meetings that are well attended by industry. Further, because of the importance it places on information sharing, the CRF often organizes sessions at industry-attended events, such as the SAE Congress, the SAE Powertrain, Fuels, and Lubricants Meeting, and the International Combustion Symposium.

Moving Forward

As pressures for cleaner, more efficient, and low-carbon transportation intensify, so does the need to direct research in areas that can accelerate development of vehicles that contribute to a sustainable energy future. The CRF therefore plans to continue to examine, expand, and enhance its collaboration processes to maintain its relevance to industry. This strong engagement with industry will be balanced with an equally focused partnership with DOE program managers and others who are helping to shape national research agendas toward the achievement of critical overarching goals.

Public-Private Consortia and Technology Transition Case Studies:

Consortium for the Advanced Simulation of Light Water Reactors (CASL)

The Consortium for the Advanced Simulation of Light-Water-Reactors is a relatively new type of DOE R&D entity, the Energy Innovation Hub. The concept of Energy Innovation Hubs was first brought to DOE in 2009, and the first such hubs, including CASL, were established in 2010. Hubs bring together teams of top scientists and engineers from academia, industry, and government to collaborate and overcome critical technical barriers in energy technologies. Hubs focus on a single topic, with the objective of rapidly bridging the gaps between basic research, engineering development, and commercialization through a close partnership with industry. To achieve this goal, the Hubs consist of large, highly integrated, and collaborative creative teams working to solve priority technology challenges.

CASL Background

In 2010, the DOE Office of Nuclear Energy (NE) issued a FOA to solicit a team that would operate an Energy Innovation Hub focused on modeling and simulation (M&S). The FOA requested that teams provide their plans for developing a virtual version of an operating light water reactor (LWR), approach for addressing the mission of hubs to improve U.S. energy security, and the qualifications of the team slated to execute the plans. After an extensive evaluation that included site visits, CASL was selected to receive $24M annually over a five-year Phase 1. CASL was also offered the opportunity to apply for a second five-year phase if the Hub was able to significantly impact nuclear energy modeling and simulation.

CASL is an integrated partnership composed of national laboratory, academia, and industry organizations that are leaders in nuclear power research and development. The 10 CASL founding partners, listed below self-selected one another in late 2009 to form the consortium (as founding members) that formulated the original CASL plan and proposal for Phase 1:

- Westinghouse Electric Corporation
- Tennessee Valley Authority (TVA)
- Electric Power Research Institute (EPRI)
- North Carolina State University
- Massachusetts Institute of Technology (MIT)
- University of Michigan (UM)
- Idaho National Laboratory (INL)
- Los Alamos National Laboratory (LANL)
- Oak Ridge National Laboratory (ORNL)
- Sandia National Laboratory (SNL)

CASL partner organizations, which include a wide range of nuclear equipment vendors, nuclear power utilities, modeling and simulation software vendors, engineering design organizations, and universities, have contributed to the consortium's R&D activities during Phase 1. The consortium's objective is to continue expanding its partnerships during Phase 2 to maximize the number of users who gain experience with the CASL tools and the ability to access the tools to analyze problems of interest.

CASL aims to develop coupled, high fidelity, usable capabilities needed to address LWR operational and safety performance-defining phenomena. The capabilities, embodied within CASL's Virtual Environment for Reactor

Applications, are being designed to run efficiently on modern high performance computing platforms and deliver insights based on the integrated effects of all the physical processes that impact reactor operations. CASL's four strategic goals help focus the consortium on completing its mission:

- Develop and effectively apply modern virtual reactor technology
- Address light-water reactor (LWR) design, operational, and safety challenges
- Engage the nuclear energy community through modeling and simulation (M&S)
- Deploy new partnership and collaboration paradigms

CASL, run by ORNL, is funded by NE as one of its programmatic R&D activities. CASL is a consortium arrangement, with each member signing an agreement with ORNL. Funding is provided to each CASL partner through subcontracts managed by ORNL. The subcontracts are typically established at the beginning of each fiscal year and modified or renewed annually, as appropriate.

At its conclusion, if successful, CASL will have developed, assessed, applied, and broadly deployed a comprehensive collection of M&S technologies capable of addressing many of the current challenges, emerging issues, and evolving opportunities for the nuclear industry. Proactive extensions of Virtual Environment for Reactor Applications (VERA) to pressurized water reactors, boiling water reactors, and integral pressurized water reactors will have been realized and deployments to nuclear vendors and utilities as well as the modeling and simulation and high performance computing communities will have taken place. Through these applications and deployments, if successful, the CASL technology will demonstrate its capability to improve the cost-effectiveness of nuclear energy generation via design efficiencies, decreased design-iteration cycle time, and enhanced engineering creativity.

Partnership Formation and Governance

The industry's role and influence in CASL is inherent due to the structure and management of the consortium. First, among the 10 founding partners are 3 entities that represent the pillars of the community:

- Westinghouse, representing vendors, who design and sell nuclear fuel and reactor designs
- TVA, representing reactor owners and operators
- EPRI, representing the collaborative R&D arm of the industry

These founding partners originally self-selected one another, based on a match of CASL strategic goals with partner institutional interest and expertise, to form the consortium that formulated the original CASL execution plan during the Aug 2009 – Mar 2010 timeframe. Additional members subsequently joining CASL across these three pillars are identified below.

CASL does not require membership fees, but industry participants are required to share at least 50% of the cost of CASL operations by providing technical experts at reduced labor rates, codes or model validation data, and/or other tools or services that have commercial value. CASL is not managed and operated with any kind of formal voting process for its partner (funded) and affiliate (participating) institutions. Details of CASL's leadership, management, and operations structure and processes are outlined in the CASL Management Plan, an internal document not publicly available, and briefly summarized in later sections of this document. DOE NE is the sole federal agency responsible for CASL's execution and outcomes.

Resource allocation decisions ultimately reside with the CASL Director, who consults with the Senior Leadership Team (SLT) while arriving at final decisions. An open planning process, driven top-down by CASL strategic goals as supported by milestone schedules and scope, informs the allocation decisions. A stepwise and iterative process is used in arriving at resource allocations on an annual fiscal year (FY) basis.

CASL Organization

Following a hierarchical management structure, CASL is led by a Director, who is joined by a Deputy Director and Chief Scientist to make up the Senior Leadership Team (SLT). The SLT is supported by six Focus Areas: four organized by the types of physics needed for LWR M&S; one to manage the integration of the products from the four physics-based Focus Areas; and one to manage the application of the CASL virtual reactor and the verification, validation, and uncertainty quantification (UQ) of those tools as they are applied to particular problems.

Focus Area leaders are selected from across CASL based primarily on their proven ability to lead a technical team to produce M&S tools. To keep CASL focused on solving the industry-defined challenge problems, the Hub assigned a number of challenge problem integrators who have an in-depth understanding of the challenge problem and can assess the ability of CASL-developed tools to address those problems. CASL is also supported by a number of organizations that provide important program, financial, and contract services.

Major features of CASL's organization follow:

- Central, integrated management working predominately from a single location at ORNL:
  - Director with full line authority and accountability for all aspects of CASL
  - Deputy Director to drive program planning, performance, and assessment
  - Chief Scientist to drive science-based elements
  - Computational Chief Scientist to oversee and drive cross-cutting computer and computational science assets
  - Focus Area Leads and Deputies with responsibility for the core science and engineering elements
- Strong science, engineering, applications, and design leadership
- A virtual one-roof approach and widespread implementation of state-of-the-art collaboration technology via a Collaboration and Ideation Officer responsible for Virtual Office, Community, and Computing (VOCC) Project execution and integration across the core elements
- Well-informed and timely decision-making and program integration
- Independent oversight and review via an external BoD advising on annual performance goals, tactical and strategic plans, and performance metrics, and science and industry councils for external oversight, review, and advisory functions
- Integrated project management for scope, schedule, and budget planning and tracking, and an integrated Operations and Management Support team providing clear leadership for environment, safety, and health; partnerships and IP management; finance and procurement; quality; and security
- Robust TT and partnerships with a Technology Deployment and Outreach element to ensure efficient, widespread industrial engagement and coordinated management of intellectual property, ensuring that CASL discoveries and VERA will be translated rapidly to commercial applications

NE conducts annual reviews that involve federal employees and teams of independent experts. To date, four of these reviews were conducted in accordance with the NE Hub Oversight Plan and focused on addressing key questions about CASL's management, execution, and performance. CASL has instituted a formal process to analyze and develop actions for findings and comments resulting from assessments and annual reviews. As needed, responses to the findings are delivered at the next annual review.

The CASL BoD serves as both an advisory and oversight body for the ORNL Laboratory Director and the CASL SLT on issues related to management, performance, strategic direction, and institutional interfaces within CASL. The CASL Director reports to the BoD on all matters related to CASL strategic program plans and decisions. The advice and oversight by the BoD is consistent with commitments made by UT-Battelle, LLC, which is the management contractor for ORNL. The BoD works to ensure the execution of CASL operational and R&D plans provide maximum benefit to key stakeholders, such as DOE and the CASL Industry Council.

The BoD consists of representatives of the executive leadership of CASL founding partner institutions plus a group of up to four at-large internationally recognized leaders in R&D programs or organizations of relevance to CASL. The CASL BoD, which makes decisions by consensus, meets for three full-day meetings annually, with one of those meetings conducted “virtually” via video teleconference.

CASL formed an Industry Council in its first year of operation (2010). Comprising representatives from nuclear power utilities, nuclear technology vendors, engineering services companies, the Council is charged with facilitating interaction between CASL and eventual industry users of CASL technology and products. Industry Council members can, for example, identify opportunities for access to experimental data, technical information, or initial testing.

The Industry Council was formalized with a documented charter, or term of reference, that is updated annually. The charter was significantly modified in 2014 to align with plans that were established for the second five years of CASL operations (2015–2019). The charter specifies the scope for the Council, membership, management, meetings, and expenses. Council meeting information (agendas, minutes, actions, supplementary reference material) is provided to the public on the CASL website.[33]

While CASL is careful to ensure that all information discussed and disseminated outside CASL Industry Council meetings and discussions is open public information, members are nevertheless required to sign an NDA to ensure appropriate protection of CASL information.

Current Industry Council membership includes these companies:

- Vendors of nuclear fuel and nuclear steam supply system: TVA, Duke, Dominion, EDF, Exelon
- Owner/operators of nuclear plants: Westinghouse Electric Corporation, NuScale, B&W Power Generation, GNF, AREVA
- Providers of engineering design, services, and R&D: EPRI, Battelle, BMPC, Rolls Royce, Studsvik Scandpower
- Independent software vendors: ANSYS, CD-adapco, Dassault Systems, GSE Systems
- Computer technology vendors: Cray, IBM, NVIDIA
- Ex-officio: DOE NE, CASL BoD

Technical Execution

The CASL founding industrial partners (Westinghouse, EPRI, and TVA) are deeply involved in technical development of the CASL software. For example, the consortium’s industry partners have supplied several challenge problem integrators who guide the CASL code development teams during creation of the consortium’s models and software. These challenge problems are focused on complex physical processes, such as Chalk River Unidentified Deposits (CRUD)–induced power shifts, Chalk River Unidentified Deposits–induced localized corrosion, and departure from nucleate boiling that cause operational and safety issues in light water reactors. Creation of integrated M&S software that addresses the challenge problems is at the heart of the CASL code development strategy.

The challenge problem integrators are tasked with developing charters and implementation plans that lay out technical strategies for achieving progress on each of the challenge problems, and the integrators work closely with the code development teams to guide development of codes that meet the implementation plan objectives. Meetings between the integrators and the code development teams are typically held at least once per month. The integrators also participate in weekly CASL management meetings; monthly CASL co-location meetings that bring the entire CASL team together for a week to coordinate code development planning and implementation, and annual DOE reviews of CASL operations. As needed, they also contribute to reviews of CASL milestone reports that detail technical accomplishments. In addition, the integrators work with their home organization management teams to identify and access experimental data that can be released to CASL for use in code validation. This data is extremely valuable to CASL because it allows testing of codes to ensure they produce results that match reality with an acceptable level of uncertainty.

CASL technical work is identified, deconstructed, planned, and executed using a milestone-based approach. These milestones are recorded and communicated to all elements of the CASL team via a six-month Plan of Record that document details milestones, tasks, and risks for each six-month horizon. All milestone information (owner, scope, plan, completion criteria, etc.) is entered into the CASL milestone project management system, which is CASL's project management document of record for quality purposes. CASL documents each Plan of Record, which allows for managed change. That is, the plan is dynamic and responsive to approved change while enabling the meeting or exceeding of commitments made at the onset of the Plan of Record.

CASL implements a *virtual one-roof* to allow engagement of its researchers without the requirement for permanent physical relocation. The VOCC[34] delivers a unified collaboration platform and creative work environment to support CASL's mission by bringing staff together under one virtual roof to successfully operate a state-of-the-art scientific collaboration space (the VOCC Laboratory) that supports all CASL R&D use cases.

Co-location is defined as a significant collection of CASL participants in a single physical location to execute CASL scope. Often this physical location is on the ORNL campus at the anchor CASL facility, but any single physical location where a significant collection of CASL staff gather is considered co-location. CASL currently conducts one formal week of co-location every month, alternating each month between physical and virtual co-location. "Co-location weeks" replace the regular information-exchange of weekly meetings and huddle sessions with deep dive reviews, planning sessions, and working meetings targeting specific technical activities associated with key milestone deliverables.

Setting the annual 100+ CASL milestones is intrinsically intertwined with the resource allocation process, as discussed previously. Once primary milestones are defined, supporting milestones are defined jointly with appropriate risks and mitigation strategies and with the Focus Area budget targets required to meet those milestones. Scope, schedule, and budget milestones are set for every project, along with the personnel needed to achieve those milestones. Finally, the senior leadership analyzes the ability of proposed collective Focus Area plans to meet the defined primary milestones and retain appropriate interdependency and linkages.

CASL tracks milestones delivery throughout the Plan of Record. Recurring project team meetings, programmatic meetings, and meetings with DOE NE are designed to quickly identify and address key issues and risks. Quality review of work delivered occurs throughout this phase and in closeout. Monthly program status updates are produced and sent to leadership covering recent activities, milestones (delivered, due near-term, and late), and issues. Change control is necessary as unplanned, unforeseen, and non-managed change can upset schedules, costs, and resource allocation. CASL's change control process for milestones is managed via a formal Baseline Change Control process that defines and constrains the type, occurrence, and potential impact a given change request may have. All requests submitted are not necessarily approved.

CASL industrial partners have been instrumental during the planning and execution of "test stand" projects. Test stands involve releasing a portion of the CASL codes to an independent host organization that uses the codes to analyze one or more technical problems of interest to CASL and the host. After using the codes, with only limited support from CASL, to complete analyses of the selected problems the host organization writes a report that describes the analyses and details any code issues or limitations that were identified during the testing. This invaluable process supports early identification of issues that would, if not addressed, limit the usefulness of the CASL codes.

Three test stands were deployed with partners during the first five years of CASL operations:

- A test stand hosted by Westinghouse to predict startup neutronics response of the company's AP1000 reactors
- A test stand hosted by EPRI to compare CASL fuel performance modeling capabilities against EPRI's industry standard code
- A test stand hosted by TVA to perform analysis of a lower plenum flow anomaly that has impacted a number of domestic nuclear reactors

In all three cases, CASL and the host organization gained important information on making the CASL tools user friendly, incorporating CASL tools into existing nuclear power analysis processes, and providing support that encourages industrial use of the VERA M&S package.

The first test stand to be deployed outside of the CASL founding partnership is expected to be hosted by Areva and deployed during FY 2015. The CASL management team is planning to deploy at least one new test stand per year to other internal and external hosts during the remaining period of CASL operations.

Partnership Results

CASL principal product, VERA, embodies many of CASL's R&D activities and provides a tangible route to deploy CASL's technology to industry users. CASL integrated many infrastructure toolkits and created others to achieve the necessary unique virtual environment to support multiple physics applications (termed components). Any pre-existing physics components have been integrated into the virtual environment, modified as necessary for the commercial reactor application, and configured for coupling and/or interface with the other physics components, as needed. VERA provides a versatile environment with coupled combinations and varying fidelity levels adaptable to available computational resources. VERA incorporates the required physics modeling tools, coupling technologies, and UQ methodologies to consider feedback effects from multiple simultaneous physics and allows for a common input to run the many applications within the environment. The tools are designed for implementation on both leadership-class and industry-class computing clusters.

The strategic vision for CASL is to evolve VERA into a standard M&S package used by industry to analyze nuclear reactor operations. To achieve this vision, CASL plans to continue supporting technology transfer of VERA through additional test stand deployments, initiation of an advanced M&S working group that encourages VERA users to share experiences and support further development of the software, and continuing broad releases of the software tools to the nuclear energy user community.

CASL has generated tangible products beginning with its first year of operation in 2010:

- Measurable progress and delivery of technical milestones and the commensurate ability of CASL software to model a wide range of nuclear reactor phenomena
- Substantial scientific productivity, measured in part by over 1300 high-quality, peer-reviewed publications, technical reports, and invited presentations
- Early and aggressive deployment of modeling and simulation technology to the nuclear energy community, including limited releases of the CASL software tools through the Radiation Safety Information Computational Center and deployment of the test stands described above

Intellectual Property

One of CASL's primary goals is to rapidly and successfully transfer nuclear reactor M&S technologies to the U.S. nuclear industry. However, this goal is tempered by the need to protect the IP of the consortium and the United

States. To ensure appropriate handling of CASL information, CASL has developed and implemented an IPMP that is updated annually or as appropriate. CASL has set the following as principal goals of the IPMP:

- Rapidly and successfully transferring new and previously developed nuclear reactor M&S technologies to the U.S. nuclear industry to facilitate the operational performance and longevity of today's operating reactors and the design and analysis of next-generation reactors and fuel technologies
- Openly disseminating scientific reports and results for public benefit
- Broadly and rapidly disseminating information among the CASL members to maximize productivity and progress
- Following the guiding principles for DOE TT of IP, licensing, and export control

The IPMP defines and establishes rules for management of different types of IP:

- **BIP**, or IP not created with CASL funding: Partners may incorporate, or modify BIP. When sharing such IP with other CASL partners, a CASL partner will identify the information as BIP and establish their own restrictions and licensing agreements. Surveys of all relevant BIP being made available to CASL have been conducted with all partners, and findings included in the IPMP are periodically reviewed and updated.
- **CASL IP**, or IP generated as part of the CASL program with CASL funding: Any CASL partner that receives CASL funding can create CASL IP, elect to retain title to inventions, and assert copyright in any copyrighted works. Each CASL partner is to report its CASL inventions to DOE Patent Counsel. Each CASL partner must also disclose all CASL inventions, copyrightable software, and tangible research products resulting from CASL funding. Each CASL partner must also disclose any executed fee and/or royalty-bearing licenses of CASL IP or BIP sought by CASL partners or third parties (or both) outside of the CASL Program.
- **Derivative works**, as specified in the IPMP, depending upon whether it is derived from CASL IP or BIP, can be the subject of separate license agreements for commercial rights in those derivative works. This includes the use of derivative works for providing a service to third parties who are not CASL members, as well as the creation of binary and/or executable codes created from CASL IP and BIP for commercial purposes. Rights to distribute any derivative works created from CASL IP and/or BIP will be in accordance with any restrictions on BIP that may impact future release of CASL IP or use of VERA (e.g., open source license requirements and/or proprietary license requirements).

Several classes of licenses are currently in use or under development to support distribution of CASL technology:

- Government license
- Test and evaluation license, which is used for the test stands
- Commercial license, which will be used for profit-based businesses
- The non-commercial license, which will allow the use of CASL software for R&D, education, and other non-profit purposes.

Both the commercial and non-commercial licenses will be made available during the second five years of CASL operations. The commercial license, as currently scoped, will not allow redistribution (for sale or otherwise) of the technology (i.e., VERA) outside of the licensee's organization; this allowance, if appropriate and approved by DOE, will occur in a separate product license.

As possible, ORNL will serve as the single point of contact for CASL licensing, subject to DOE approval and to conditions established by owners of software contained in the CASL tools. The objective of this strategy is to minimize the number of organizations that users of the CASL tools will have to negotiate with when establishing licenses to use VERA. An inter-institutional agreement (between the four organizations that have primary ownership of the CASL software tools (ORNL, INL, LANL, UM) is under development to establish sublicensing terms and conditions.

Performance Metrics

The four strategic goals identified during development of the original CASL proposal to focus CASL on completion of its mission have proven sound and remain intact since CASL began operations:

- Develop and effectively apply modern virtual reactor technology
- Address light water reactor design, operational, and safety challenges
- Engage the nuclear energy community through modeling and simulation
- Deploy new partnership and collaboration paradigms

Metrics developed by CASL management team help ensure CASL is making progress toward achieving these strategic goals. The CASL metrics have been divided into outcome metrics that are tied to strategic performance and operating metrics that evaluate short-term project performance. Quantitative measures are used to evaluate CASL performance against the metrics.

The metrics have been updated two times since CASL began operations in July 2010. The first update in FY 2012 reflected a shift in CASL priorities away from startup operations and toward code development. The second update, made in early FY 2015, reflects a shift in priority away from code development toward code deployment.

Metric performance is typically reviewed every six months to coincide with the CASL planning cycle. Data is generally collected by subject matter experts and recorded in a spreadsheet maintained by the CASL project manager. The review results are generally shared with the program's extended leadership team to support discussion of necessary corrective actions, and the results and corrective action plans are then summarized for presentation to the CASL BoD. Board input is collected and incorporated into response planning, and the metric results are presented to DOE as part of the CASL annual review.

Current measures of CASL performance and outcome metrics are documented in DOE annual review presentations, Management Plans, and six-month Plan-of-Record (PoR) documents.

CASL Enduring Value

CASL's strategic vision is to see its M&S technology evolving into the *nuclear enterprise community model* for nuclear reactor and power plant M&S technology. Early adoption and TT to the nuclear energy community in the form of test stands, a post-CASL entity, M&S working group, and broad release of VERA will demonstrate industry acceptance, integration, and adoption. Broad engagement of the nuclear community allows CASL to build interest, trust, confidence, and acceptance.

In the second phase now underway, CASL plans to expand its funded industry partnership (beyond its founding industry partnership) to include other nuclear fuel and design vendors and utilities as a required step in expanding the range of applicability of its M&S technology. CASL also plans to continue its Education Program and expand its reach to universities outside of the CASL partnership. CASL strives to build not just acceptance of its technology, but also an appreciation for the benefits to be derived from the use of and reliance upon predictive M&S capabilities.

Sustainability of CASL-developed technologies will be assured through a proactive plan to establish a stable and long-lived post-CASL entity—an innovation center for nuclear energy M&S and a vibrant M&S working group—to assume and carry on CASL's technology by bringing together and engaging leading experts from academia, federal agencies, and industry.

Lessons Learned

There are many lessons learned in executing a complex DOE program such as CASL; these lessons translate into a collection of programmatic strategies, implementations, and activities that would be undertaken differently or more efficiently within the context of a new program with similar constraints (e.g., public-private partnership, translational R&D, five-year term, etc.). Most of these lessons learned surfaced during the first 18 months of CASL startup but some did not manifest themselves until later. The lessons learned are itemized briefly below:

- Maintaining a focus on the efficient and timely execution of subcontracts for all partnering organizations is paramount for programs in which a lead institution manages funding. This is especially important in incremental funding scenarios, such as the U.S. government budget cycle, which often results in Continuing Resolution acts typified by monthly funding installments. A team of contracting authorities, procurement officials, and technical contract monitors must be available to address and execute contract modifications on a regular monthly basis.
- Formulate, document, and implement formal baseline change control policies and procedures for any required change scope, schedule, or budget of the baseline program plan. Critically, baseline change control management forces communication of risks (e.g., schedule slip or scope reduction) among the stakeholders before they become problems, and ensures an open, formal process for movement of funds across work breakdown structure elements.
- Formulate, document, and implement a technology control plan that articulates procedures for the processing, storage, and transmission of sensitive data (export controlled, proprietary) among partner organizations and staff. To minimize risk of loss of sensitive data, all staff should receive training on the technology control plan protocols.
- Actively track performance through formal reviews of staff- and team-delivered milestones and annual reviews of partner organizations.
- Balance the tension between development of capabilities and the development and application of products by appointing product integrators to drive critical applications, products, and outcomes that crosscut capability elements within the Hub.
- Actively pursue capabilities developed elsewhere (e.g., in other federal programs, universities) that can be leveraged to avoid duplication of effort.
- Impose project management processes (planning, execution, tracking, review) early in the lifetime of the Hub so that staff become quickly used to the constraints associated with working within a large integrated program. Expect and manage the widely-differing institutional views of the levels of project management required for successful execution.
- Aggressively embrace secure virtual collaboration technologies and solutions to optimize expensive and time-consuming travel required for physical co-location, which is not required for every task.
- Drive the process of metrics definition and collection early and often, otherwise others external to the Hub will "provide the answer." Devise performance metrics for regularly monitoring the vital signs of the Hub and outcome metrics that are directly tied to strategic goals. Utilize councils, committees, and boards to regularly and objectively assess the science, technology, and management performance of the Hub.
- Aggressively pursue formal partner organization agreements for managing and sharing proprietary data and IP. These agreements must include clauses for BIP, licensing of IP, inventions, and patents, and the creation and distribution of derivative works.
- Implement provisions and milestones for deployment of developed technology, even if the technology is in a beta state. This early deployment (or test stand) of developing technology yields invaluable feedback from prospective users and customers on whether the technology is useable and useful. This early feedback can influence the subsequent technology development activities and plans.

- Do not underestimate the importance of the required institutional infrastructure supporting the R&D activities. Directly support the infrastructure or, more optimally, leverage existing institutional infrastructure through aggressive in-kind and cost-share contributions as well as through integrating with the stakeholder public programs that are stewards of the infrastructure.
- Take great care to ensure that the end-use requirements driving R&D activities for the product technology are properly understood. Do not tacitly assume that the appropriate requirements always call for a fundamental and detailed understanding of all phenomena—but rather use existing products and technologies as a "baseline" for relative comparisons. Where possible devise progression problems for explicit measurement of if and how these requirements are being met.
- Maintain an open resource allocation and adjustment process that empowers the technical leadership team to make budget decisions based on requirements and priority R&D needs. Understand and appreciate the resource allocation expectations of partner organizations but do not commit to explicit levels; rely instead on the R&D needs for recommended allocations.
- Do not underestimate the importance of coordinated, clear, concise, and regular outreach and communication. Embrace all forms of communication (internet, social media, quarterly tech notes, brochures, one-pagers) and target a wide audience. Maintain a concerted effort to make available all scientific publications (internal technical reports, milestones, presentations) of relevance. Track if and how the external community is digesting this material.

Recommendations for Future Hubs

A detailed account of CASL procedures deemed effective can be found in the CASL Management Plan, Program Plan, and Renewal Application. These documents are not for public release; however, key procedures recommended for reuse are highlighted here.

- Have clear deliverables that solve industry issues and are driven by a well-defined yet dynamic plan. Commit to a hierarchical milestone plan with tangible deliverables and define products integrated across capabilities.
- Impose a strategy of delivering prototype products early and often. Early deployment of the Hub's technology into an industrial environment for rapid and enhanced testing and use to support real-world applications is crucial for ultimate adoption and commercialization.
- Define customers and users with industry pull ensured by an industry council that is chartered and engaged for early, continuous, and frequent interface and engagement of end users and technology providers. Use the industry council for critical review of plans and products to help drive the product from being the Hub's product to becoming the industry's product.
- Implement a true private-public partnership with parity where possible in management, leadership, and execution. Engage industry broadly and at all levels of execution. Involving the best and brightest technical personnel is crucial for success and credibility, using virtual collaboration technologies for daily interactions.
- Plan and execute with a minimum five-year horizon for completion and funding, acknowledging that a renewal option for a second five years may be useful and appropriate. A five-year period ensures the ability to attract and retain community leaders yet, upon execution, forces specific paths and decisions.
- Empower the Hub to be led by one institution with resource allocation authority and responsibility. This empowerment, while not a guarantee of success, enables risk-informed agility through assignment of clear authority and responsibility.
- Enable the lead Hub institution and Hub senior leadership to make annual scope, schedule, and within-Hub resource allocation decisions as long as execution and performance warrants (e.g., annual DOE Hub reviews are positive).

- Formulate and charter a BoD to provide regular (3–4 times annually) oversight and advice on management, plan, and science and technology strategy. The BoD is not a useful body unless the Hub senior leadership knows how to effectively utilize its assets. Hub senior leadership must be in a position to respond to BoD recommendations. If the Hub senior management is not empowered by DOE to implement BoD recommendations, then the BoD is not useful.
- Formulate and charter independent councils to review and advise on quality and relevance of science and technology. Utilize the Science Council for independent assessment of whether the scientific work planned and executed is of high quality and supports attaining the Hub's goals. This should motivate Hub senior leadership to more directly address problems with timely and needed decisions.

Public-Private Consortia and Technology Transition Case Studies:

Critical Materials Institute

The Critical Materials Institute is one of DOE's four Energy Innovation Hubs. Created in response to the "rare earth crisis" that emerged in 2010, CMI began operations in 2013 with the mission of ensuring supply chains of materials critical to clean energy technologies to enable innovation in U.S. manufacturing and enhance U.S. energy security. Although rare earth elements are high on every list of critical materials, not all rare earths are critical, and not all critical materials are rare earths. CMI addresses any material that is subject to supply risks and essential for an existing or emerging clean energy technology.[35]

One of the Grand Challenges in dealing with critical materials is the need for technological solutions on relevant timescales: while materials shortages can become crises in a period of just a few months, materials research and development typically takes more than a decade to deliver solutions to industry. Organized to significantly accelerate the delivery of solutions, CMI is beginning to demonstrate success in meeting this goal. The Hub adheres to the principle that the appropriate role of federally funded research is to develop technological options, leaving the marketplace to decide which ones are commercialized. However, it takes care to obtain input from the marketplace as it develops technologies to avoid pursuit of solutions that will be of no interest even if they meet the technological criteria. Early and frequent input from its industrial partners plays a key role in focusing CMI's resources to meet its goals, and is a primary benefit from adopting a consortium approach.

Foundations

The CMI partnership was initially forged during the preparation of a proposal in response to DOE's call for a Critical Materials Hub. Recognizing that the objective of the Hub was to provide secure supply chains, CMI gathered a team of corporations that spanned the entire materials lifecycle, from mining through processing to product manufacturing and recycling, to guide the development of its proposal. The partnership also engaged expertise across a spectrum from fundamental science to applied technology, leading to the inclusion of four national laboratories, seven universities, and half-a-dozen companies, many of which also offer applied research capabilities. Rounding out the team is an economic analysis group that helps to anticipate changes in the criticality landscape, identify key points of intervention, and quantify the contributions of CMI.

Once CMI was funded, the partnership was formalized under an IPMP and through subcontracts for research to several of the partners (also referred to as team members). Corporate membership has been expanded through the creation of a fee-based affiliates program and extensive outreach efforts that lead to the enrollment of new corporate members and affiliates.

The primary funding for CMI comes from the EERE's Advanced Manufacturing Office, and cost-sharing is provided by its corporate team members. The Affiliates Membership Program is funded through annual membership fees. It is anticipated that there will be both Cooperate Research and Development Agreements (CRADAs) and Strategic Partnership Projects (SPPs) as the program matures.

Impact

In many cases today, design choices for clean energy technologies are being affected by the availability of certain key materials. The location of manufacturing is also frequently determined by access to materials. These examples underscore these issues:

- When DOE sought to impose regulations to require the use of T5 fluorescent tubes in place of the older, less efficient T8 technology, lamp manufacturers protested that this change would require greater supplies of europium and terbium, which are in short supply. Lacking an immediate solution for this supply-chain challenge, the proposed regulation was tabled.
- Direct-drive wind turbines are more efficient, quieter, and more reliable than hybrid-drive systems that utilize large gearboxes. However, direct-drive units require high-strength magnets made of neodymium, iron, boron, and dysprosium. The vast majority of wind turbines in the United States and Europe, where supplies of neodymium and dysprosium are uncertain, are hybrid-drive systems, while China has a significant fraction of direct-drive wind turbines in its inventory.

CMI will be successful when supply constraints such as these are removed as a factor in the design and manufacturing locations of clean energy technologies.

Three fundamental technical approaches can be used to solve a shortage of any material or resource:

- Find more of that material
- Find something else that meets the need
- Live within the existing supplies by using less

To ensure maximum impact in minimum time, CMI addresses these three strategic approaches through three aligned R&D Focus Areas:

- **Focus Area 1 – Diversifying Supply:** Supply chains are especially fragile when only a few providers offer a given material. CMI seeks to develop technologies that make mining less costly and more efficient so that more mines can survive in the marketplace. It also develops technologies for accessing new, non-traditional sources for critical materials, such as co-production of rare earths from fertilizer processing.
- **Focus Area 2 – Developing Substitutes:** Reliance on a single source becomes significantly less burdensome when alternative materials are available to meet the same needs as a critical material. CMI is developing alternatives to rare earth elements in lamp phosphors and high-strength magnets.
- **Focus Area 3 – Improving Reuse, Recycling, and Manufacturing Efficiency:** Despite their value, many critical materials end up in landfills or distributed into the environment during manufacture or at the end of life of a product or device because the cost of recovery is too high. CMI is developing technologies to reduce waste and recapture waste materials more economically.

In many cases, the technologies under development in CMI are in direct competition with each other for market adoption. CMI fosters this healthy and invigorating feature as it strives, within its first five years of operation, to develop at least one technology adopted by U.S. companies from each of these three Focus Areas. As of November 2015, one technology developed by CMI has been adopted by a U.S. company. CMI partners ORNL and INL developed a membrane solvent extraction system, which aids in the recycling, recovery and extraction of rare earth minerals. This is licensed to U.S. Rare Earths, Inc.

CMI also has a fourth R&D thrust:

- **Focus Area 4 – Crosscutting Research:** The first three thrust areas serve the needs of industrial "clients." In contrast, the primary clients of this crosscutting research thrust are researchers in the first three Focus Areas who are engaged more broadly across disciplines. This thrust provides access to specialized tools and advanced expertise in relevant basic science disciplines and offers ecological assessments and economic analysis.

Principles for Industry Engagement

Conducting business as usual in this area of research tends to produce results that are adopted by industry in 10 to 20 years or more. CMI is seeking to reduce that timeframe to less than five years. To this end, CMI works to keep all efforts well targeted and closely on track and to focus resources on the most promising lines of research. CMI's leadership strives to maintain a clear line of sight from every research effort and activity to its potential industrial application. CMI seeks industrial input at every stage, through a number of formal and informal processes, facilitated by the following structures:

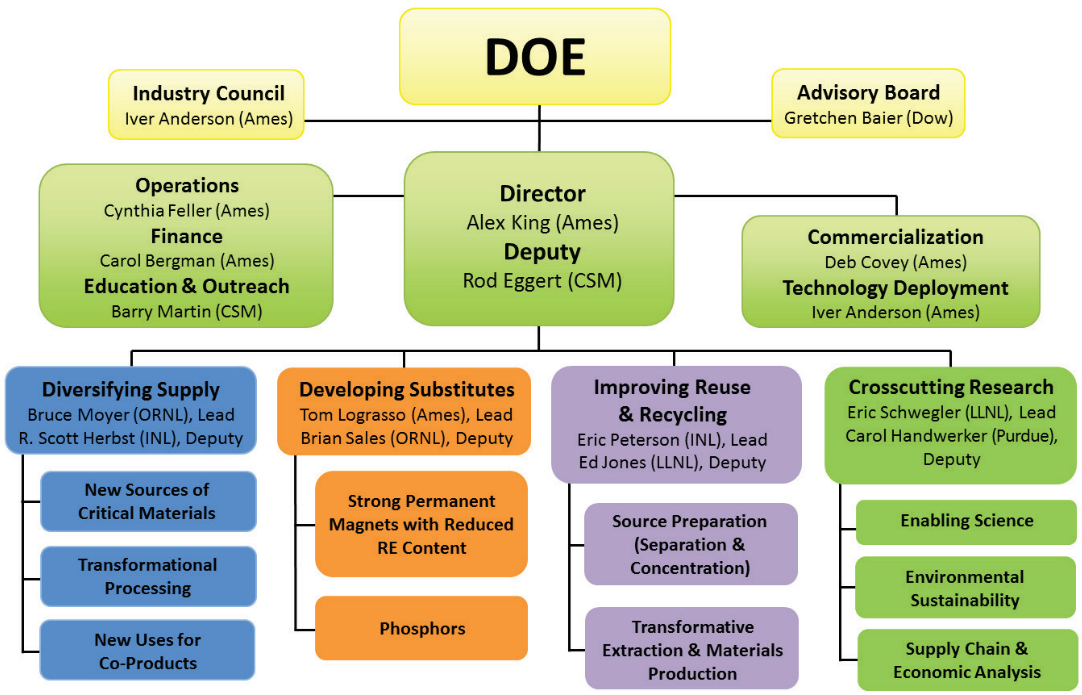
- **CMI team:** Team members help strategize and formulate the R&D priorities and projects listed within the successful CMI proposal. Team members also worked with the CMI Commercialization Manager to develop and execute the IPMP. Initial team members were chosen based on their ability to contribute, willingness to engage, diversity with respect to the supply chain, and the absence of conflicts of interest. Each team member has either a research subcontract from the CMI and/or provides cost sharing funds.

  Each Industry team member has representation on the Industry Council, which helps CMI management determine the research agenda and the commercialization strategies for discoveries and provides commercialization perspective and needs to the Focus Area Leads, Commercialization Manager, and Technology Deployment Manager.
- **CMI affiliates:** A reorganization of the affiliates program led to a streamlined fee structure rather than the original plan for each affiliate organization to pay an annual membership fee based on the organization size and type. The Industry Council includes two members elected from the affiliates.
- **Industry Council:** CMI's industrial partners contribute to the success of the CMI by participating in the research and becoming members of the Industry Council. As a major benefit, Industry Council members gain the opportunity to receive a non-exclusive license for R&D to one or more DOE-funded technologies arising from the research undertaken by CMI. The Industry Council also has a six-month option to negotiate a commercial license to DOE-funded CMI IP.
- **Technology workshops:** CMI holds several workshops each year, focusing either on a technology or an applicable research tool or method. Examples of recent workshop topics include magnets, thermodynamic tools, ionic liquids, and roadmapping. These workshops are usually open to non-member industrial representatives and always begin with a discussion of the needs and desires of the corporate sector as a precursor to dialog on how best to focus CMI's resources.
- **Roadmaps:** CMI has created detailed roadmaps for each of its research efforts, showing where, when, and how key decisions are expected and results handed off for further development. Industry partners, and particularly potential technology adopters, are engaged in the key decisions and in ensuring that the products to be transitioned continue to have value as circumstances change. The roadmap team is now linking individual project roadmaps together through shared hand-off points, and developing industry-level roadmaps to ensure that CMI products reach maturity in time to make an impact.
- **Mini-consortia:** All of CMI's projects are undertaken by subsets of the Hub's personnel and resources, collaborating with and drawing upon the resources of the rest of the Hub. These teams may be regarded as mini-consortia, and the most effective of these contain more than one industrial partner, with the ideal group including a materials producer and a potential industrial user, along with several key researchers. This strategy ensures that any material or materials technology invented by the team has both a potential user and a potential producer.

Oversight, Review and Response

CMI has an appropriated budget of $25M per year, and it receives about $1M per year in cost-matching support, primarily from its industrial partners. It supports work carried out by more than 300 individuals spread across the nation in industry, universities, and national labs. CMI has the structure needed for efficient management of these enterprise, while maintaining flexibility to respond to program needs and redirect resources as needed. CMI's current organizational chart is provided in Figure CMI-1, reflecting the Focus Areas described above. These Focus Areas are robust and applicable to any critical material that might arise. The details within each Focus Area, however, have been adjusted to meet emerging needs and opportunities as they have arisen.

Figure CMI-1 CMI Organization Chart



CMI maintains a clear focus on its goals through several layers of formal review:

- Annual reviews are conducted by an independent external expert panel, convened by DOE, on the basis of a written report and a site visit. These high-level reviews assess the extent to which the Hub is operating cohesively and meeting its highest-level goals.
- Annual project reviews are conducted by the Leadership Team, on the basis of accumulated quarterly reports and a short written summary of achievements submitted by the project leader. These reviews assess the extent to which each project is meeting its goals, and addressing market needs as they emerge. This review can result in a project being terminated, merged, restructured, or enhanced.
- The Advisory Board reviews overall Hub operations three times per year, providing advice to the Director.
- The Industry Council meets at least once a year and provides broad input on industry needs and directions.
- The Commercialization Council provides input on issues related to intellectual property generated by the Hub.
- Quarterly milestone reviews are conducted by the Hub Director and the program management in EERE's Advanced Manufacturing Office. These reviews provide assurance that each project is making headway at an appropriate rate.

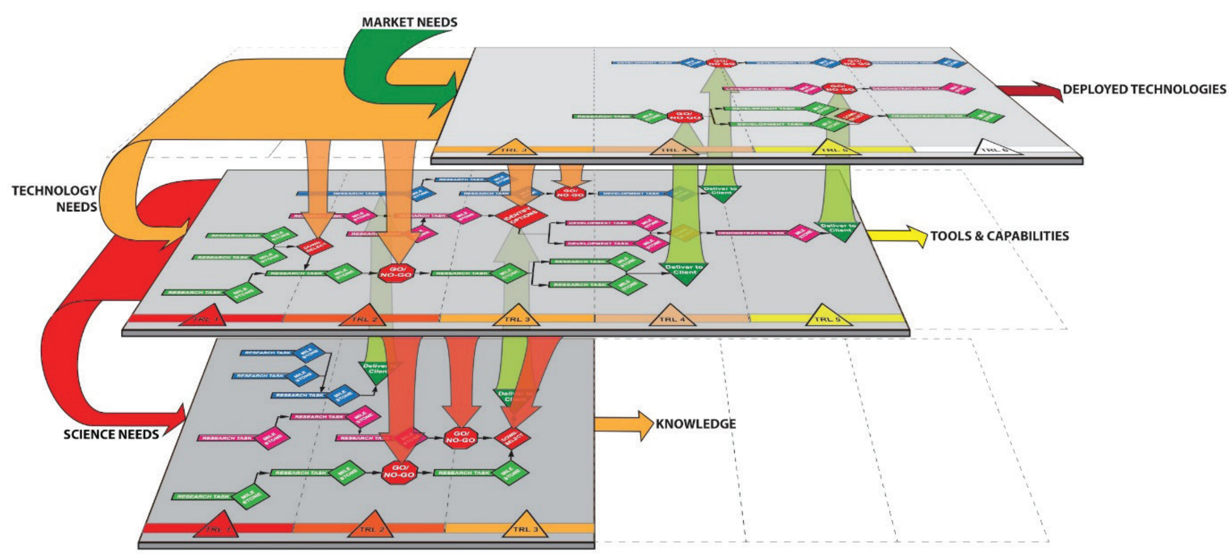
Several levels of informal review supplement these reviews:

- Project highlights are presented at the beginning of each weekly teleconference of the Leadership Team.
- CMI's Director attends Focus Area and Thrust Area conference calls.
- Hub leaders and AMO managers make visits to most of CMI's research locations once per year.
- An annual meeting provides a forum for all of our projects to see and be seen by every level of participant in the Hub, including industrial members of all kinds.

As CMI strives to solve problems that are important to its partners, on a schedule that matches their needs, the most important feedback provided to CMI comes from their industrial collaborators. Industrial partners provide input on the research programs at key decision points, particularly helping to identify lines of research that should not be pursued, enabling greater focus of available resources on the most fruitful avenues.

All CMI research projects have a commercialization plan, and a roadmap that identifies key timelines, decision points, and deliverables. Each project also has clients who anticipate making use of the work developed by the project. As noted earlier, the clients for R&D projects in Focus Areas 1, 2, and 3 are product or process development teams in industry, while clients for crosscutting research efforts in Focus Area 4 are typically R&D projects in Focus Areas 1, 2, and 3. The clients for economic analysis projects in Focus Area 4 may be in industry or in CMI R&D projects across the Hub.

Figure CMI-2 Knowledge and information flows within CMI



These relationships are illustrated schematically in Figure CMI-2, which represents the knowledge flows necessary for the deployment of new technologies. Each layer represents a generic project roadmap. The lowest layer would be a roadmap for a basic science project in Focus Area 4. The middle layer would be in Focus Areas 1, 2, or 3. The topmost layer represents the work of an industry partner. Information needs are fed downward from layer to layer. Information developed by the research projects is fed upward from layer to layer, and is intended to provide input that is both useful and timely with respect to the higher-level roadmaps. Assessments of progress toward meeting information needs flow downward, with broad input from higher layers, to inform specific decisions in lower layers.

Using this structure on a continuous basis, industry feedback guides the development of CMI projects, keeping them on track to deliver their results when and where it has the most impact, and avoiding devoting time and resources to unprofitable areas. This type of input is provided primarily in two modes:

- Regular project meetings and teleconferences, attended by industry partners and clients
- Dedicated workshops with groups of industry partners who are potential clients for CMI's work in a particular area

Impact

After nearly three years of work and carefully heeding the guidance of its industrial collaborators, CMI has announced 41 invention disclosures, across all three strategic thrusts. Seventeen of these have resulted in patent applications because of corporate interest in adopting them. Commercial use of CMI-developed technologies in all three areas is anticipated. So far, one technology has been licensed.

In addition, CMI is preparing to release an updated analysis of critical materials for clean energy technologies, looking 15–20 years into the future. This analysis will guide future research directions for the Hub and for others.

CMI's roadmapping efforts assess the impact of its R&D programs on materials supply chains for selected technologies. For example, in the wind power area, roadmapping has shown that if all of CMI's materials production and recycling R&D programs bear fruit, they can provide materials for enough high-strength magnets to allow direct-drive wind turbines to achieve about 39% market penetration (on the basis of certain assumptions). Other anticipated changes in the supply chain provide an additional 22% of the necessary capacity, giving a total potential for more than 60% market penetration. This compares very well with the current penetration of less than 1%, and represents a significant impact on technology choices and engineering options.

CMI has become a recognized force in the area of critical materials and is widely sought out for information, advice, and collaboration by other offices in DOE, other federal agencies, U.S. corporations, and international critical materials research teams. The formation of new external collaborations is anticipated in coming months.

Lessons Learned

Experience at CMI has led to the following set of lessons learned.

- IPMPs, partnership agreements, conflict of interest plans, antitrust waivers, and structures of auxiliary organizations, such as affiliates programs, are subject to many non-obvious federal and agency requirements and entail long approval times. It is essential to start these processes early and push hard to get them completed before the consortium starts work.
- Many industrial partner candidates are unable or unwilling to accept certain IP clauses or other provisions required to engage in the consortium. These barriers can be overcome if the value proposition is sufficient, but sometimes that cannot be achieved.
- An informal connection to an industrial concern is better than no connection, even if it creates management issues and IP control concerns.
- Technologies for promoting long-distance collaboration among different institutions (notably videoconferencing and shared fileservers) are often incompatible with local cybersecurity implementations.
- Even the most effective videoconference is not as good as a face-to-face meeting. Budget for plenty of travel.
- All organizational structures promote the tendency for "silos" at some level. Leadership needs to be creative in promoting collaboration, by, for example, holding events that deliberately cross the organizational lines.

- With industrial collaborators: listen first, talk later. An hour of listening to an industrial partner can save a thousand hours of research.
- Industrial partners talk more freely when their competitors are not in the room, irrespective of the existence of an NDA.
- Understand the drivers of your industrial collaborators; they are not always obvious.
- Be rigorous in assessing your progress and flexible in adapting to changing market conditions.
- Focus on the smallest number of high-level performance metrics possible. The ideal is one, and two is acceptable. Beyond three, the metrics start to lose value.

Table CMI-1 CMI Basic Facts

Dates of Operation	An Energy Innovation Hub initiated by AMO in June 2013. Continued funding anticipated through June 2018. (Renewable for one additional 5-year term).
Goals	**Mission:** ■ Assure supply chains of materials critical to clean energy technologies—enabling innovation in U.S. manufacturing and enhancing U.S. energy security. **Strategies:** ■ Coordinate basic and applied pre-competitive research to bring technologies to the marketplace to strengthen the supply chains of critical materials in three ways: - Diversifying the sources of critical materials - Finding alternative materials - Enabling more efficient use of existing resources **Current Goals:** ■ One technology adopted by US industry in each of the areas named above. As of November 2015, one technology developed by CMI has been adopted by industry in the area of reuse and recycling.
Current Membership	■ **Industry:** Advanced Recovery, Cytec, Eck Industries, General Electric, Molycorp, OLI Systems, Simbol Materials, and United Technologies Research Center ■ **National laboratories:** The Ames Laboratory, INL, LLNL, ORNL ■ **Universities:** Brown, Colorado School of Mines, UC Davis, Florida Polytechnic University, Iowa State University, Purdue, Rutgers ■ **Affiliate Members:** ***(Companies)***— ABB, Barr Engineering, Electron Energy Corp., Etrema Products, Infinium, Mosaic, Native American Mining Solutions (NAMS), National Aeronautics and Space Administration (NASA), Niron Magnetics, Phinix, PRINTSPACE, Rare Element Resources, REEcycle, Rio Tinto, Tasman Metals, Urban Mining and Simplot; ***(Universities)***—Montana Tech; (Other)—ASTM International
Significant Achievement	■ 41 invention disclosures and 17 patent applications in the first two and a half years of operation.

Table CMI-1 CMI Basic Facts, continued

Dates of Operation	**An Energy Innovation Hub initiated by AMO in June 2013. Continued funding anticipated through June 2018. (Renewable for one additional 5-year term).**
Organizational Structure	■ Advisory Board has representatives from all national lab and university team members, plus elected representatives from the industry team members. The Board meets three times a year. ■ The Industry Council has members from all of the corporate Team Members of CMI who choose to send representatives, and elected members from the Affiliates Program. It meets at least once a year and provides broad input on industry needs and directions. ■ The Commercialization Council comprises the IP managers from each of the participating institutions. It advises on technology transfer policies and serves to resolve disputes. ■ Full-time Director provides scientific leadership and administrative oversight. ■ The Leadership Team works with the Director, and comprises the Deputy Director, Operations Manager, Finance Manager, Commercialization Manager, and the four Focus Area Leads. The Leadership Team meets weekly to coordinate CMI research, management and operations. ■ The Ames Laboratory is the recipient of DOE funds. ■ Additional work through SPPs and CRADAs between specific partners is handled by those partners, and IP management is determined in those agreements. ■ Research planning is independent of, but coordinated with the annual DOE review. ■ Consideration of new team members determined by existing partners, and new partners require the unanimous approval of the existing membership ■ Affiliate members pay an annual fee. Membership requests are approved by the Director
Member Roles and Benefits	**Team Members:** ■ Actively participate in R&D activities ■ “First look” at CMI-generated IP. Share in IP as specified by the IPMP **Affiliate Members:** ■ Participate in CMI meetings. Access to all CMI information streams. ■ Provide input and perspectives on CMI research ■ “Early look” at CMI-generated IP

Public-Private Consortia and Technology Transition Case Studies:

The Joint BioEnergy Institute (JBEI)

Overview

The Joint BioEnergy Institute is one of three Bioenergy Research Centers (BRC) funded by DOE for five years starting in September 2007; a second five-year phase began in 2012. The ultimate goal for the BRCs is to "provide the fundamental science to underpin a cost-effective, advanced cellulosic biofuels industry," according to DOE.[36] JBEI often refers to its research as "mission-driven science." The original JBEI member institutions were LBNL, SNL, LLNL, UC Berkeley and UC Davis, and the Carnegie Institution. PNNL joined JBEI during the 2012 funding renewal period.

JBEI's mission is unique among the BRCs in that it does not work on technologies to produce ethanol. Rather, its purpose is to advance the development of cellulosic, next-generation biofuels to replace petroleum-based gasoline, diesel, and jet fuels. From inception, it was designed to effectively partner with industry. To date, JBEI has brought in funding under nearly two-dozen CRADAs and SPP agreements with industry, including several multi-year strategic partnerships, to conduct research that both aligns with JBEI's mission and supports industry's market objectives.

The BRC FOA that led to JBEI was based on outcomes from the December 2005 Biomass-to-Biofuels Workshop convened by the Office of Biological and Environmental Research (BER), under DOE SC, and the Office of the Biomass Program (currently named the Bioenergy Technologies Office), under DOE EERE. The purpose was to "define barriers and challenges to a rapid expansion of cellulosic-ethanol production and determine ways to speed solutions through concerted application of modern biology tools as part of a joint research agenda."[37]

In the wake of the workshop, a few senior leaders at LBNL began to explore the opportunity to respond to the anticipated FOA and convened discussions with academics and other DOE laboratories. In June 2006, LBNL's Director and the LBNL lead PI for JBEI launched planning discussions with UC Berkeley and UC Davis, SNL, LLNL, the Carnegie Institution at Stanford University, and the local U.S. Department of Agriculture Agricultural Research Service, which was ultimately not included as a member of the consortium. SNL had already emerged as LBNL's principal partner.

The JBEI founders explored including industry partners in their proposal during the proposal preparation period, but determined that post-award engagement would open a larger range of possibilities and maintain flexibility as the nascent advanced biofuels industry took shape. Eight years later, JBEI believes it made the right decision. The JBEI founding team discussed at length how industry would be engaged post-award. They generated a tiered industry partnership program that was adopted during JBEI's first two years but eventually dropped the program. Discussions with companies working in biofuels and bio-based chemicals had led them to conclude that mutually beneficial scope-of-work-based partnerships between JBEI and individual companies would be a more fruitful approach. JBEI also established an Industry Advisory Committee (IAC) to ensure that JBEI researchers remained aware of challenges faced by the biofuels industry.

In July 2007, the LBNL–led consortium was selected for an award of $25 million annually for five years. After an extensive peer review, this funding was renewed in 2012 for an additional five years.

Organization

JBEI comprises four scientific divisions, each led by a vice president. These vice presidents, along with the CEO, Chief Science and Technology Officer (CSTO), and Chief Operations Officer (COO), serve on the JBEI Research Committee (RC), which is the executive body of the center. The responsibilities of the RC include:

- Recommending the annual JBEI research and management plan to the CEO, who then presents it to the BoD for approval
- Recommending the redirection or termination of funding of specific research programs within JBEI to the CEO and CSTO for approval by the BoD
- Reviewing and approving IP management decisions as set forth in the JBEI IPMP, including whether or not JBEI will financially support patent applications on JBEI-funded IP
- Meeting on a quarterly basis to assess overall research progress and ensure that specific milestones are accomplished
- Recommending members of the Science Advisory Committee (SAC) and the IAC for appointment by the CEO

Each division also has 3–5 division directors who lead specific scientific programs. Except for a feedstock research group located at UC Davis, JBEI researchers are co-located on a single floor of a building in Emeryville, California, which was designed specifically for and by JBEI. From the beginning of the JBEI effort, co-location of the majority of JBEI researchers was a priority to provide a heightened sense of teamwork and closer integration of the four JBEI research divisions.

JBEI divisional research spans the biofuels pipeline, from cellulosic feedstock development to feedstock deconstruction to synthesis of fuels from the resulting cellulosic sugars. It also includes a technology division that supports this research pipeline. Because industry faces challenges in integrating these steps, JBEI targeted those intersections through cross-divisional research. Co-location has enhanced integration through frequent and fluid communication among all JBEI researchers, regardless of home institution.

The JBEI BoD is composed of one executive-level representative from each of the partner institutions and meets annually (the JBEI CEO is an ex-officio member). The chair rotates and is elected by the members. The BoD holds final authority for budget and resource allocation and oversight; program review; researcher affiliation; resolution of major scientific, operational, and/or policy disputes; and appointment of the CEO. The BoD also reviews and approves the overall budget and research plan annually.

JBEI's BER funding is allocated by the JBEI RC (with BoD oversight) to the scientific divisions and driven by research goals established in the JBEI DOE proposals. Research directions are adjusted in response to scientific results, with an eye to industry and market needs and opportunities. While JBEI establishes yearly (and even monthly) research goals, major goal-setting occurs every five years in response to the funding cycle. JBEI chose from the beginning to take risky, rather than incremental, approaches to addressing industry challenges. As a result, the basic scientific approaches have not shifted significantly in response to immediate industry challenges. However, due to results from the JBEI technoeconomic model (TEM), the deconstruction division has allocated a greater portion of its funding to developing creative strategies to reduce the cost of its potentially game-changing approach to feedstock conversion. (The feedstock division has shifted focus based on early successes in the integration of novel synthetic biology techniques.)

JBEI researchers are encouraged to seek additional research funding and have been successful in garnering funding awards from sources such as the Advanced Research Projects Agency – Energy (ARPA-E), Bioenergy Technologies Office, and Defense Advanced Research Projects Agency (DARPA). The core DOE funding is also supported by complementary projects funded by industry through SPPs and CRADAs.

JBEI is reviewed by BER at an annual 1.5-day site visit. The reviewers are independent third parties selected by BER from universities and other national laboratories. The scientific and industry advisory committees provide feedback to the JBEI CEO, RC, and BoD, as well as DOE.

JBEI has an entrepreneurial culture. The Director had founded two companies before JBEI existed, and other members of the RC had been heavily engaged in industry collaborations and were familiar with the biofuels industry. Robust engagement and partnering with industry, diligent protection of IP, and accelerated transfer of JBEI inventions and expertise to the private sector were established as critical institutional goals. Implementation of these goals took the following forms:

- Execution of a JBEI IPMP that created a one-stop shop for industry engagement
- RC involvement in IP decisions and industry-facing activities
- Funding for 50% time of a business development staff member with an office in a central location at JBEI, a position that evolved into the Director of Commercialization (DOC), currently funded 100% by JBEI
- Establishment of an IAC
- Development of a commercialization and industry engagement program, including an emphasis on industry visits to JBEI
- Creation of a special startup track for IP that could form the basis of a spinoff company
- Development of a techno economic model (TEM) of a cellulosic biofuel refinery
- Internal entrepreneur-in-residence office hours and seminars

As noted above, JBEI took the unusual step of dedicating funding to hiring a 50% FTE for business development. This hire augmented the core IP and licensing team provided by the Technology Transfer Department at LBNL. The business development staff member, now the DOC, is located at JBEI, and the JBEI tech transfer staff members hold office hours on site. This sends a signal to the JBEI team that industry engagement is a core JBEI mission and invites routine interaction with JBEI researchers and has emphasized the crucial role of technology transfer in creating opportunities for growth and impact.

The JBEI staffing and responsibilities for IP and industry-related activities included the following:

2007–2012

- Manager of business development (50% Technology Transfer full-time equivalent (FTE), funded by JBEI): Conduct industry outreach and engagement (open houses, visits) and manage collaborations and IAC
- IP and licensing associate (50–75% FTE, funded by LBNL's Technology Transfer Department): Manage IP and licensing transactions
- In-house patent attorney (50% JBEI): File and prosecute JBEI patent applications
- NDA/Material Transfer Agreement (MTA) specialist (one FTE for all of Berkeley Lab)

2012–2015:

- Director of Commercialization (now 100% funded by JBEI): Oversee all business development and IP/licensing duties, so that one person was responsible for industry projects or licensing agreements from start to finish. Moving to a single position eliminated inefficient overlap between business development and licensing responsibilities. The Director of Commercialization is accountable for resolving bottlenecks in the entire partnership process, which helps prevent agreements and paperwork from falling through the cracks.
- In-house patent attorney (50% JBEI)
- NDA/MTA specialist (one FTE for all of LBNL)
- Entrepreneurial advisor (one FTE for all of LBNL)

JBEI Intellectual Property Management Plan (IPMP)

Overview

LBNL's licensing manager led negotiations among the JBEI partners and DOE IP counsel to develop IP management principles. The principles were codified in an IP Management Plan and appended as part of a side letter to the contractor's agreement to operate JBEI. This plan became the basis for a more detailed Inter-institutional Agreement (IIA) among the JBEI partner institutions.

The IPMP and IIA establish LBNL as the manager of all IP arising from JBEI funding and the single signatory authority for JBEI non-disclosure agreements, MTAs, licensing transactions, CRADAs, and SPPs. (Exceptions are made for mutual NDAs and NDAs-in, which require a SNL signature). This allows LBNL to serve as the single point of contact for all industry engagement and agreements, greatly streamlining the process. This structure has resulted in 23 CRADAs and SPPs between JBEI and industry collaborators.

The JBEI IIA includes the following additional principles:

- Each party takes title to the inventions of its employees; joint inventions are jointly owned.
- Each party discloses its inventions to LBNL, which reports those to the owning institutions.
- LBNL is responsible for filing, prosecuting, and maintaining all patent applications covering JBEI inventions, providing owning parties with all necessary records and copies of patenting activities.
- JBEI has the option to pay for the following to receive royalties from JBEI-funded inventions in pre-defined "core" areas of research (60% of royalties accrue to JBEI once they exceed $200,000 net per license):
    - Up to 50% of JBEI patent applications/patents, including 50% of filing fees, maintenance fees, and a $6,500 patent application preparation fee that covers in-house patent attorney time for filing provisional, utility, and Patent Cooperation Treaty patent applications.
    - A second $6,500 fee that covers patent attorney time from the first office action through issuance.
    - 50% of fees for outside attorneys, if used
- JBEI institutional members have the right to finance patent applications from their inventors and receive corresponding royalties. Participation rights are based on inventor share and whether or not JBEI is participating.
- LBNL can negotiate for equity as partial consideration in a licensing agreement and will have any equity shares issued in the name of the JBEI institutional owner.
- LBNL retains 15% of licensing income, including royalties, up-front fees, maintenance fees, milestone payments, to help offset the cost of administration.
- All JBEI inventors receive 35% of net royalty income for their licensed inventions, regardless of their institution's royalty policy. This includes 35% of any equity stake taken in a licensee.

The DOC and JBEI patent attorney present patent filing recommendations and industry partnership issues to the RC at bi-monthly meetings. Inventors are invited to present their technologies and the RC decides whether or not JBEI will fund 50% of any given patent application. In this approach, the patenting decisions benefit from the experience of JBEI senior management, patenting and licensing issues are surfaced to ensure broad alignment on tactics and strategies, and inventors are showcased to management, all of which contribute to improving the quality of JBEI IP and commercialization activities.

JBEI management reviews planned publications to identify IP that has not been disclosed to the LBNL TTD. In addition, the Director of Commercialization and technology transfer staff periodically brief JBEI personnel on IP disclosure and management procedures and on progress towards JBEI's commercialization goals.

The JBEI Industry Advisory Committee (IAC)

The JBEI IAC, which meets annually, includes senior representatives from companies working in almost all segments of the emerging cellulosic biofuels industry. Members are recommended by the RC and appointed for a 12-month term, renewable by mutual agreement, upon advisement to the DOE. Companies that undertake significant collaborative research projects with JBEI are also invited to join the IAC.

At the annual IAC meeting, researchers and senior management provide an overview of JBEI research directions and progress, and IAC members hold panel discussions on topics of particular interest to their industry and attend a poster session. During feedback sessions and Q&A periods, the IAC provides JBEI with valuable insights from an industry perspective and identifies industry challenges that are not yet being fully addressed. The IAC is also charged with preparing a formal report with feedback and recommendations. The report is delivered to the JBEI CEO, RC, and BoD, as well as to DOE.

JBEI IAC meetings take place on a non-confidential basis. In 2014, the IAC and SAC meetings were combined and integrated into the annual JBEI retreat. JBEI did require IAC and SAC members to sign NDAs if they wanted to attend the non-IAC portions of the retreat. About half the members of the IAC chose to do so.

An IAC offers the following benefits:

- Provides researchers with an industry perspective on technical challenges and opportunities that may benefit their research
- Provides a great opportunity to develop relationships that may lead to collaborative research and cost-share partners for proposals for federal funding
- Exposes graduate students and postdoctoral appointees to opportunities to continue research careers beyond academia

The IAC experience led to the following lessons learned:

- Hold the IAC portion of any meetings without asking companies to sign NDAs. Ensure that any relevant patent applications are filed before presenting research to the IAC.
- Ensure that the companies understand that their charge is not to review the research but to add a commercial perspective.
- Create opportunities for IAC members to participate in the meeting on panels or by presenting talks.
- Invite companies for a one-year term, renewable by mutual consent.

IAC members and titles are shown in Table JBEI-1.

Table JBEI-1 JBEI IAC Members

Company	Title
Arborgen	Chief Science Officer (early member, no longer a member)
Amyris	Senior VP of Research
Boeing	Tech Leader, Energy & Emission (early member)
BP	VP, Technology (early member)
Burrill & Company	Partner

Table JBEI-1 JBEI IAC Members, continued

Company	Title
Ceres	VP, Trait Development
DuPont Genencor	Head of BioChemistry
DuPont	Director, DuPont Central R&D (early member)
General Motors	GM Technical Fellow, R&D (early member)
Genomatica	Executive VP and Chief Technology Officer
LS9	VP, R&D (no longer a member)
Monsanto	Technology prospecting lead
Novozymes	Sr. Dir. Bioenergy R&D (early member)
Pacific Ethanol	VP (early member)
PerkinElmer (Caliper)	R&D Expert (no longer a member)
POET	Senior Director of Research (early member)
StatOil	Biofuels Project Manager (early member)
Total Energies Nouvelles Activites USA SAS	VP R&D (early member)
Total Energies Nouvelles Activites USA SAS	Head, Biotechnology R&D (early member)
Weyerhaeuser	Director, Technology Partnerships (early member)

JBEI Startup Track

The JBEI startup track approach leverages the industry perspective provided by the RC, Director of Commercialization, UC Berkeley Haas Business School's Cleantech to Market program, and the internal LBNL entrepreneur advisor, to create potential JBEI startup companies. Every year JBEI works with at least one interdisciplinary team of graduate students in business, engineering, and science from the Cleantech to Market program, which prepares a go-to-market plan for the most promising JBEI IP.

Inventors are exposed to relevant business concepts and educated about the variety of roles they can play in a startup, many of which do not involve leaving a current career. The benefit of this approach is that IP is not undervalued via fragmented licensing or undiscovered applications, and inventions that might otherwise languish are more quickly developed and commercialized. Startups are often the best avenue for commercialization of IP because they often license inventions that are either too risky for existing companies or that need more focused and dedicated development than existing companies are often prepared to provide.

Commercialization program results

Table JBEI-2 lists results of JBEI partnerships.

Table JBEI-2 JBEI Partnership Results

	Company	Agreement Status	BIP/ CRADA IP
	Abengoa	Successfully completed; in discussions to renew	No optioned BIP/No CRADA IP
	Afingen	Ongoing Small Business Innovation Research (SBIR)	Optioned BIP/No CRADA IP
	Afingen	Ongoing SBIR	Optioned BIP/No CRADA IP
	Bridgestone	Ongoing	Optioned BIP/No CRADA IP
	Compact Membrane	Successfully completed SBIR	Optioned BIP/No CRADA IP
	Statoil	Successfully completed	No BIP/No CRADA IP
	Total	Research on lignin (typically a waste stream) successfully completed, extended; could lead to new applications for lignin	Optioned BIP/ Two CRADA inventions
	Total	Efflux pump research successfully completed; discovered new pumps to eliminate toxic products from cells	Optioned BIP/ Two CRADA inventions
	Total	Hexene research completed but unsuccessful; pivoting to two new projects	Formerly optioned BIP/ No CRADA IP
	Total	Biological hydrogenation research ongoing	No BIP/No CRADA IP
	Virdia	Successfully completed, with results indicating current method may not be economically viable; in discussions to renew. Research on HMF production	Three CRADA inventions
	POET	Biomass deconstruction ongoing	Optioned BIP/No CRADA IP
		Technology holding ongoing as SBIR	Optioned BIP/No CRADA IP
	Recap	**Six ongoing; six successfully completed (three of those are in discussions to renew); one unsuccessfully completed**	**Eight new CRADA inventions**
10 WFOs	Boeing	TEM successfully completed	Licensed BIP/ WFO software
	BP	Successfully completed	No BIP/No WFO IP
	Braskem	Successfully completed	No BIP/No WFO IP
	COFCO	Ongoing	
	GM	TEM successfully completed	Licensed BIP/ WFO software
	TeselaGen	Successfully completed	No BIP/No WFO IP
	Statoil	TEM successfully completed	Licensed BIP/ WFO software
	Statoil	Microalgae successfully completed	No BIP/No WFO IP
	University of Queensland (with Boeing, GE, Sugar Research Australia)	Successfully completed	BIP not licensed/No WFO IP
	Virdia	Successfully completed	No BIP/No WFO IP
	Recap	**1 ongoing, 9 successfully completed, one extended under a CRADA No BIP/No WFO IP**	

Funding

Total funding from all CRADAs and SPPs has equaled $4,848,000

Technoeconomic Models

As shown, many of the SPPs involve TEMs. In 2008–2009, JBEI began to develop a TEM of a cellulosic biorefinery, based on existing SuperPro software. The approach comprises building models that describe the material and energy flows in a virtual biorefinery (material and energy balances), which become the basis for capital and operating cost calculations. The TEM allows investigation into the impacts of various technologies, research strategies, and business decisions on the economics of biofuel production. The TEM has been used to evaluate and make adjustments to JBEI research goals and technologies.

Co-Location

Some partner companies, such as Afingen, Total, Virdia, COFCO, and Braskem, have embedded their employees at JBEI to work side-by-side with JBEI researchers under CRADA and SPPs. This has increased JBEI's awareness of industry barriers to commercialization and improved JBEI's ability to address these barriers through discovery and innovation.

Other Agreements

JBEI also negotiated a significant loan agreement with an equipment supplier, resulting in hundreds of thousands of dollars in equipment and software being located at JBEI at no cost. JBEI has informal collaborations with many other companies that involve exchange of materials, information, and data on a regular or one-time basis.

Example: Strategic Partnership with Total Energies Nouvelles

JBEI has had several strategic partnerships with industry. One of the most successful of these is with Total Energies Nouvelles Activites, USA, SAS. The strategic partnership with Total is unique in that a series of CRADAs were implemented under a master NDA, personnel management plan, steering committee charter, and CRADA option agreements. It took many months to execute the first CRADA, but implementing new projects has subsequently been extremely efficient.

The following is a summary of the relationship as described by the Total scientist managing the JBEI relationship and projects:

> *Total Energies Nouvelles Activites, USA, SAS has been and is involved in several partnership projects with JBEI. The goal is to discover novel and economic technologies that could lead to the production of molecules of interest for Total, either by valorizing plant residues (collaboration with the JBEI Deconstruction division), or by developing new pathways in microbes (collaboration with the JBEI Fuels Synthesis division).*
>
> *To perform this research, Total, under CRADA agreements, has provided funds and employees (Total postdocs and scientists) who work side by side with JBEI researchers. The projects have a precise scope of work and follow defined milestones that are reviewed every three to four months during joint steering committee meetings.*
>
> *The steering committee is comprised of two voting members from each partner. The members are senior research scientists who are also senior managers. The IP advisors and the JBEI Director of Commercialization also attend most of the meetings. The purpose of the committee is to present research results, evaluate progress towards milestones, advise*

the scientists, and adjust the project, if necessary, to make sure the goals of both partners are aligned. These meetings offer the opportunity to discuss potential scientific bottlenecks and new ideas and approaches, and for the senior industrial and academic managers who are not directly involved in the collaborative projects on a daily basis to develop relationships. Most importantly, the steering committee makes crucial decisions such as whether or not to file patent applications or pursue new research projects.

Total employees, seconded at JBEI and working under a broad mutual NDA, have been perfectly accepted and integrated into teams of the various JBEI divisions and benefit from the advanced technologies and platforms available in the institute. JBEI directors involved in Total collaborative projects have developed their research with respect for Total industrial objectives. The collaborations between Total and JBEI have resulted in a patent application that has been drafted by both parties to ensure that it will cover Total needs. Two additional invention disclosures are being evaluated for patent applications. Total anticipates using the discoveries and commercializing the products in a relatively short time period and is highly supportive of its collaborative projects with JBEI.

— Florence Mingardon, PhD, JBEI-TOTAL Coordinator, Total New Energies USA, Inc., April, 2015

Technology Transfer Metrics between 2008 and 2015

Table JBEI-3 lists technology transfer and industry engagement metrics between October 2008 and September 2015.

Table JBEI-3 JBEI Technology Transfer Metrics

Metric	Measure
Invention disclosures	192*
Patent applications filed	99*
Active JBEI IP licensed or optioned (whether or not license/option has expired)	59* (includes U.S. and foreign patents and patent applications, and copyrights licensed exclusively)
Total License/Option agreements	23*
Startups	4
Industry visits	~ 275**

*data compiled from LBNL's Sophia Technology Transfer database
**data compiled from JBEI monthly DOE reports

New invention disclosures and patent applications are reported to DOE on a monthly basis. The goals of the DOC (and all JBEI staff) are clearly defined and related to milestones in a performance management system, which is updated monthly by the DOC, and reviewed by JBEI management periodically during the year. The IP/industry engagement data is presented at JBEI retreats, seminars, and IAC/SAC meetings, and frequently at JBEI and LBNL industry meetings, tech transfer-related conferences, and in talks around the world by JBEI senior management.

Many of JBEI's synthetic biology, mass spectrometry and omics tools and methods are not patented but are also making an impact in industry and academia. These tools and methods have been transferred through over 400 JBEI publications[39] as well as through collaborations. JBEI is starting to gather data to quantify these impacts.

The cellulosic advanced biofuels industry is still nascent. Most industry players are still building or perfecting first generation cellulosic ethanol plants. It is anticipated that JBEI biomass deconstruction technology will be incorporated into second-generation cellulosic ethanol plants. Third-generation plants may adopt JBEI fuel synthesis technology to tackle the production of biofuels that are direct replacements for diesel and jet fuels. Due to long development times for new feedstocks, JBEI's plant technologies are not likely to be adopted for 10–15 years. Once the industry starts to mature, JBEI's impact should be measured based on such metrics as products on the market, jobs created, dollars saved, and contribution to carbon savings.

Commercialization Strategic Plan

In 2012 the Director of Commercialization worked with the JBEI team to develop a strategic plan for commercialization. The strategic plan reenergized technology transition and industry partnership efforts. The plan identified innovation, teamwork, and excellence as core values. These core values apply as much to the industry/IP program as they do to the scientific program. Under the plan, JBEI as a whole developed the following vision statement:

> *JBEI will be the place that made possible a sustainable, sugar-based fungible fuels industry by creating the most innovative model of mission-driven research and commercialization of recent decades.*

The strategic objectives follow:

1. Demonstrate significant return on investment to DOE, Congress, and U.S. taxpayers
    - Track the following metrics: inventions, patents, patents licensed, startup companies, CRADA/SPP outcomes, industry visits; ultimately report on downstream results, e.g. products on the market, jobs created, dollars saved, contribution to carbon savings
    - Communicate impact by telling the stories behind the IP data, communicate impacts of Open Source tools and resources
    - Pursue these goals:
        - Streamline tech transfer process, accelerate execution of agreements
        - Develop JBEI templates and new template language that resolves common issues (license, option, CRADA option, bailment)
        - Increase IP relevance by deepening JBEI employee understanding of industry challenges and increasing market awareness
        - Discover unrealized and possibly valuable applications of JBEI research and resulting IP
2. Expand research funding through industry interactions to:
    - Deepen and broaden the research base
    - Enable more seamless transition of inventions to the next readiness level and/or to the marketplace
    - Pursue these goals:
        - Industry-funded collaborations
            - Market our expertise and capabilities, not just our IP
        - Partnerships with industry for federal grants
            - Hold grant-writing seminars at JBEI covering mechanics, agency dynamics, and how to secure industry partners

- Targeted business development
  - Develop list of priority companies for each division
  - Contact three potential private-sector partners per month that JBEI has not interacted with in a significant way, five total
  - Continue to emphasize outreach to potential U.S. partners
- Startup Track: Cultivate startups
  - Grow single inventions into IP portfolios that have the potential to support a startup
  - Write Lab navigation guide/checklist for researchers interested in starting a company (will cover conflict of interest practices, information on licensing your own IP from LBNL, etc.)
  - Provide more intensive entrepreneurial guidance and business and legal resources
  - Identify near- and long-term applications and low-cost value inflection points for de-risking tech and increasing fundability
- After Startup track
  - Introduce startups to investors
  - Refer potential industry partners to startups when JBEI can't meet the need
  - Enable fast turn-around SPP agreements so startups and other small companies can more easily access unique JBEI expertise and equipment

Summary

The demonstrated benefits of JBEI to the taxpayer are significant. JBEI has spun out four U.S companies[40] that have already begun to create jobs, with three potential startups in the queue. It has also established seven platform technologies, supported by substantial patent portfolios. Several of these portfolios have been licensed, and companies are embarking on commercialization steps, such as greenhouse trials, fermentation scale up, and integration of software into customer technology platforms.[41]

It has yet to be seen how the JBEI technologies will be employed at scale in the cellulosic biofuels industry. However, many of these technologies have applications beyond biofuels and will inevitably be commercialized in one or more fields of use. Non-fuel applications may play a critical role in paving the way for ultimate production of biofuels, especially if experience curve effects in manufacturing are obtained, such that continued experience making chemicals by fermentation leads to continually reduced costs.

JBEI has also published over 430 publications with an average h-index of 37 and 16.6 average citations per publication, some of which have depended on formal or informal industry engagement.[42] Sixty alumni have moved on to industry jobs, taking with them cutting-edge research techniques, a deep knowledge base in their fields, and typically a more sophisticated understanding of IP, partnership management, team science, and industry drivers than one would be exposed to in most academic or national laboratory settings.

JBEI has used standard DOE CRADA and SPPs and licensing mechanisms to achieve impacts that far exceed what one would expect out of a national lab or typical academic environment. This is attributable to both the JBEI model itself and the personnel executing the model. JBEI practices and approaches, and the management philosophy described in this overview, could be beneficially applied at other institutions.

Public-Private Consortia and Technology Transition Case Studies:

The Joint Center for Energy Storage Research (JCESR)

Purpose

JCESR is a public-private partnership devoted to developing high performance, inexpensive next generation electricity storage with the potential to transform transportation and the electricity grid. JCESR comprises 14 founding partner institutions, six funded collaborators at other institutions, and 180-200 researchers spanning graduate student, postdoc, early career, and senior investigators. It is an Energy Innovation Hub funded by the Department of Energy at a level of approximately $25M/year for five years, subject to congressional appropriations. More information can be found on the JCESR website, www.jcesr.org.[43]

JCESR operates under six organizing principles:

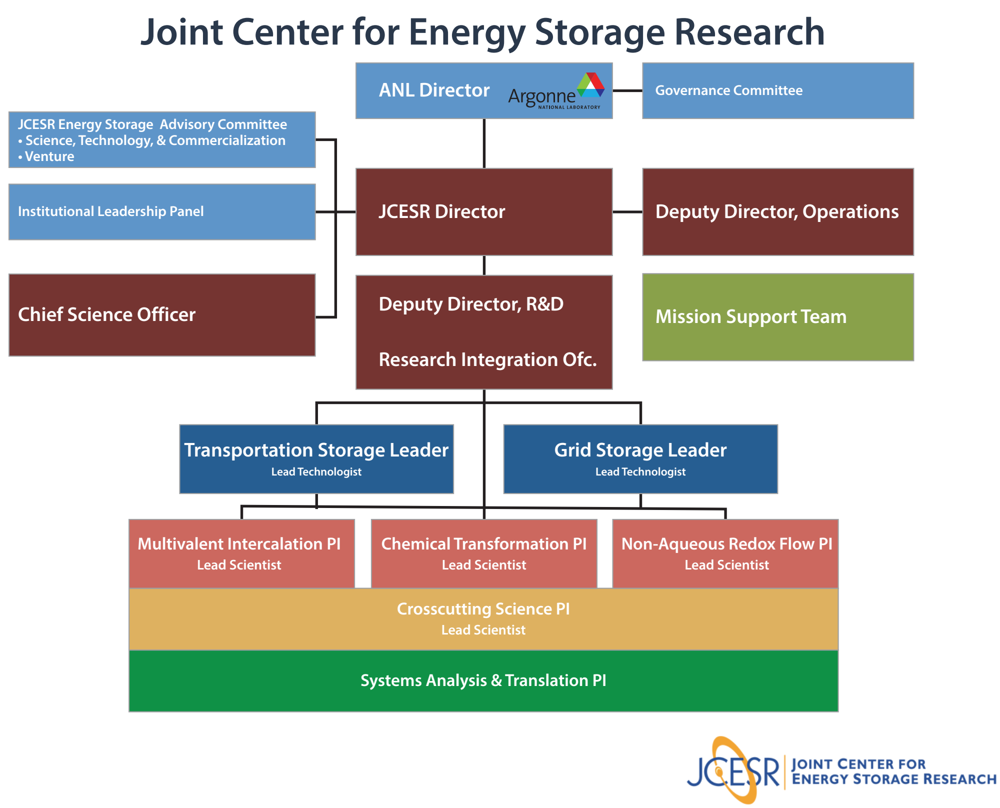
- Focus exclusively on beyond lithium-ion batteries with the potential for transformative advances in performance and cost for transportation and the electricity grid.
- End-to-end integration of discovery science, battery design, research prototyping, and manufacturing collaboration.
- Strategic selection of a few promising prototype concepts, which drive mission-driven research directed to discovery, design, prototyping, and manufacturing of the selected prototype concepts.
- Quarterly review of progress and comparison of existing and alternative research directions, annual adjustment of strategy and funded research directions to implement strategy.
- Critical evaluation and guidance from scientific and industrial advisory committees.
- Continuous improvement of operating procedures supporting the above organizing principles.

Governance Model

JCESR is organized into three research lines, Transportation Storage, Grid Storage, and Cross-cutting Science, and one analysis line, Systems Analysis and Translation (Figure JCESR-1). Cross-cutting Science and Systems Analysis and Translation address broad challenges in the materials, phenomena, and performance of electricity storage systems; the Transportation and Grid research lines develop materials and phenomena for three concepts, Multivalent Intercalation, Chemical Transformation, and Non-aqueous Redox Flow, and integrate these materials and phenomena into battery test cells and prototypes. Each research line and concept has a Principle Investigator in charge of budget and strategic directions, and a Lead Scientist who advises the Principle Investigator on strategy, scientific directions, and budgets. The research and analysis lines report to the Executive Committee composed of Director, Deputy Directors for Operations and for Research and Development, and the Research Integration Officer. The Executive Committee makes final strategic and funding decisions. The Executive Committee is advised by the Energy Storage Advisory Committee composed of distinguished external scientific and industrial leaders, by the Institutional Leadership Panel composed of senior managers at JCESR's partner institutions, by JCESR's Chief Science Officer, and by JCESR's External Integration Officer. JCESR's Director reports to Argonne's Laboratory Director, who chairs JCESR's Governance Committee composed of the CEOs of JCESR's partner institutions.

JCESR's governance model expresses the organizing principles outlined above. Strategy and funding are set by bottom-up discussion and recommendation by the research and analysis lines, followed by review, amendment and approval by the Executive Committee. Research progress and strategic directions are evaluated frequently

Figure JCESR-1 JCESR organization chart



at in-person meetings (weekly for working groups within the research and analysis lines, monthly for research and analysis lines, quarterly for JCESR research leaders). Strategic directions and funding are adjusted annually. This frequent evaluation and nimble adjustment of research directions and strategy is central to JCESR's governance model.

JCESR promotes strong links to the energy storage community through its Affiliates, comprising nearly 100 industrial, university, trade, and non-profit organizations in 25 states with an interest in next generation electricity storage. JCESR maintains regular contact with its affiliates through regional events and the Affiliates Newsletter. To date, JCESR has held seven regional events highlighting specific grid and transportation issues and will highlight additional issues at future events.

IP Strategy

JCESR has several established mechanisms to promote the transfer of information and technology to the R&D community. First, JCESR publishes papers and files invention disclosures - after three years of operation JCESR has produced over 170 publications, and filed 43 invention disclosures and 25 patent applications. Second, JCESR introduced a new concept, the Electrolyte Genome, to simulate the properties of thousands of liquid organic molecules before they are selected for experimental development and incorporation into batteries. JCESR has now added over 16,000 organic molecules to the curated Electrolyte Genome in the Materials Project database. Hundreds of scientists use these databases each day, with more than 4500 users worldwide. Third, JCESR has robust interactions with industry through industrial partners, advisory committees and councils (including approximately 15 industrial representatives in addition to the four direct partners), links with industry through its partners, funded collaborators, and the Affiliates group and regional meetings. These connections promote an ongoing dialogue with nascent and established industries to discuss results and potential new directions in the energy storage field.

The first piece of JCESR funded intellectual property was licensed in 2016. JCESR is aware of at least two start-ups ready to launch based on JCESR-developed intellectual property. Finally, JCESR transfers human capital to industry, through its support of over 100 graduate students and post-doctoral researchers who will carry the intellectual expertise they developed in JCESR to long-term careers in academia, the national laboratories, and industry.

Funding Strategy

The opportunities for beyond lithium-ion batteries are too numerous to systematically explore in Edisonian fashion. Instead, JCESR strategically chooses the most promising opportunities, identifies the most critical challenges to realizing those opportunities, and funds research targeting those challenges. Success with this funding strategy requires continuous evaluation of progress on the chosen research targets, timely decisions on continuing, de-emphasizing, or eliminating a research direction in favor of a more promising one, and consequent adjustments of funding to reflect strategic decisions as they are taken. The collective wisdom of JCESR's knowledgeable researchers, their awareness of the latest developments in the field, and the ability to nimbly adjust funded research directions to reflect changing strategic targets are particular strengths of JCESR that support this funding strategy.

Success Factors

JCESR's experience in its first three years revealed important success factors: the value of in-person communication, continuous improvement of JCESR's operational paradigm balancing divergent and convergent research, and changing directions early when new opportunities arise or established directions begin to founder.

- **In-person communication:** JCESR promotes in-person communication as a top priority for exchanging information and strategic evaluation, for the body language it displays, the faster discussion it enables, and the informal hallway, dinner, and coffee break conversations that promote increased relationship-building and the emergence of creativity and vision.
- **Continuous improvement of the operating paradigm:** In JCESR's first three years several opportunities arose to organize and execute more effectively. Examples include supplementing some research teams by funded collaborators outside the partner institutions; revising the strategy and execution of funding new directions; establishing a robust, thorough, transparent and inclusive evaluation procedure for adjusting strategy and funded research directions, and balancing research between divergent and convergent modalities.
- **Balancing divergent and convergent research:** Divergent research discovers or identifies promising opportunities for prototypes; convergent research drives the development of these promising opportunities. The challenge is to balance divergent and convergent research to ensure that the most promising opportunities are pursued and that rapid progress in advancing those directions is achieved. 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. An example of timely strategic decision-making is JCESR's decision to de-emphasize lithium-oxygen research in favor of lithium-sulfur research in Year 2 of the program, freeing resources for faster progress on more promising, nearer-term opportunities.

Public-Private Consortia and Technology Transition Case Studies:

Trustworthy Cyber Infrastructure for the Power Grid

TCIPG was a project funded by DOE and the Department of Homeland Security under DOE Cooperative Agreement award number DE-OE000097 at a level of $18M ($15M federal funding, $3M cost share). The period of performance was September 30, 2009–August 30, 2015. The partnership included the University of Illinois at Urbana-Champaign (lead institution) with partner institutions Arizona State University, Dartmouth College, and Washington State University.[44] In 2015, the Office of Electricity of Electricity Delivery and Energy Reliability made two awards in for academic consortia. One of the awards went to the University of Illinois as the lead to support a Cyber Resilient Energy Delivery Consortium (CREDC), and had a formal start on 10/01/2015. The research, however didn't get on track until the start of 2016. The CREDC is scheduled to run for five years from the start date. It is not a renewal of TCIPG, but retains the execution model of academic-industry applied research partnership.

TCIPG's technical focus was cyber security and resiliency of the power grid, with research activities combining disciplines of computer science, computer engineering, electric power, education, and economics. Research addresses multiple issues in cyber-physical resiliency in generation-transmission, distribution, vehicle-to-grid integration, demand response, synchronization of wide area measurements, and demand response.

TCIPG had no investors. Public benefits of the technology transfers included the following:

- A commercial tool, NP View (the portfolio centerpiece of the startup Network Perception) to assess security of utility networks by identifying routable paths to critical cyber assets[45]
- A pilot deployment in real-world utility environments of innovative technologies to secure AMI
- The open-source transition (in the Bro analysis framework) of security tools that detect attacks against supervisory control and data acquisition (SCADA) protocols, considering cyber and physical aspects of the defended system
- Prototypes to secure device firmware that have transitioned into vendor products
- Outreach to the sector in the form of an annual workshop, a bi-annual summer school, and a modular training course to advance workforce and faculty development
- Emphasis on results and developing roadmaps, standards, guidelines, best practices, and policy recommendations
- Workforce training: student researchers, internships, post-doctoral fellowships, industry participation in the biannual summer school, and placement of graduates in industry and laboratories
- Outreach to K–12 and to the public promoting issues of security awareness and "smart energy" on the part of consumers

Partnership Formation

TCIPG followed from the National Science Foundation–funded Trustworthy Cyber Infrastructure for the Power Grid project, which dates to 2005. At that time, awareness of cyber security and resiliency in grid systems (and in control systems in general) was low, and the term "smart grid" was not in wide use. The partnership was formed from a team of academic researchers with a shared vision for the importance of research in this area and a commitment to producing impactful results by early involvement of industry. From the TCIPG standpoint, industry consisted of utilities (investor-owned as well as cooperatives) and system vendors (who sell technology to the utility sector). At a high level, interaction involved these actions:

- Identifying needs in security and resiliency (in consultation with utilities and vendors)
- Developing solutions collaboratively
- Validating solutions in a utility setting, leveraging testbeds for technology development, validation, and risk mitigation.
- Transitioning technology to the private sector as licensed technologies or as open-source software, with associated training

To address an ongoing challenge to research in this sector, the sensitivity of utility operational data, TCIPG relied on NDAs and analysis on air-gapped systems, data collection on utility test systems, and data anonymization, and mainly by earning the trust of the sector through a reputation for responsibility and integrity.

TCIPG also partnered with industry in the form of technology demonstration and deployment, student internships, workshops, and training. Following are some of the TCIPG collaborative relationships:

- Schweitzer Engineering Laboratories, a leading vendor of substation equipment and a generous donor of equipment to the TCIPG testbed
- Ameren, focused on validation of the predecessor of NP View and interaction on substation security research
- FirstEnergy, focused on AMI security
- American Transmission Company, focused on phasor measurement unit (PMU) data quality and security
- Association of Illinois Electric Cooperatives, focused on outreach efforts

In addition to leading TCIPG, University of Illinois had synergistic projects funded by DOE in partnership with Schweitzer Engineering Laboratories, ABB Group, EPRI, and the Grid Protection Alliance. These projects took a deep, focused look at specific topics of interest, such as software defined control networks in utilities and the security of time-critical distributed substation protection schemes. TCIPG had also partnered with the DOE national laboratories:

- A partnership with SNL on quantum key distribution
- A partnership with INL on integration of NP View with INL's Sophia visualization tool

Partnership Governance

TCIPG was led by a principal investigator, Professor William H. Sanders, head of Illinois Department of Electrical and Computer Engineering University of Illinois at Urbana-Champaign. He was supported by a leadership team with experts and leaders from the partner academic institutions and the Information Trust Institute at Illinois. This leadership team met weekly via teleconference.[46]

TCIPG participated in formal quarterly technical reviews with both funding agencies. These alternate between teleconference and in-person meetings.

TCIPG had an External Advisory Board (EAB) that participated in quarterly reviews and serves as a resource for identifying critical sector needs as they evolve. The EAB was formed by identifying and recruiting thought leaders and stakeholders involved in technology, management, or research that supports electricity delivery and energy control systems.

The advisory board consisted of:

- Dennis Gammel, Schweitzer Engineering Laboratories
- Marija Ilic, Carnegie Mellon University
- Jeff Katz, IBM

- Himanshu Khurana, Honeywell
- Doug McGinnis, Exelon
- Scott Mix, North American Electric Reliability Corporation
- Paul Myrda, EPRI
- David Norton, Federal Energy Regulatory Commission
- William Souza, PJM

The EAB was supplemented by a larger Industry Interaction Board (IIB) composed of industry stakeholders who participate in TCIPG events, such as the annual workshop, the summer school, or monthly seminars. While TCIPG actively recruits the EAB, stakeholders may request to join the IIB.

R&D Execution

TCIPG was divided into technical clusters addressing resiliency and trust in wide area systems (generation and transmission, including wide area measurement systems such as PMUs), local area (distribution, AMI, home area networks), cyber event management and response, and trust assessments. TCIPG also has cross-cutting thrusts focused on education and workforce development, industry interaction and technology transition, and research analysis and validation with an advanced cyber-physical testbed facility. Research activities were identified from industry interaction, the EAB, or anticipation of cyber security issues likely to emerge as smart grid or Energy Delivery System (EDS) technology evolves.

Research teams typically consisted of a faculty research lead and one or more student researchers. As an academic consortium, TCIPG produced publications in conferences and journals, as well as student theses and dissertations, as important outputs. The consortium also actively sought opportunities to validate solutions in realistic utility environments, which were not typical of an academic consortium. For example, the pilot deployment of the AMIlyzer AMI security technology had been in place at First Energy for two years, and has grown in that time from 12,000 to 50,000 meters monitored.

The entire team met most weeks via an all-hands teleconference. Such meetings typically consisted of technical presentations from students, faculty, or visiting researchers. In addition, student researchers met in a weekly reading group to develop cross-discipline knowledge and understanding of computer and power engineering as it applies to power grid cybersecurity.

Faculty and student researchers were encouraged to collaborate closely with industry at all stages of research, forming what an advisory board member has termed the "engagement journey." Industry stakeholders were invited and encouraged to participate in TCIPG's Annual Industry Workshop and serve as part of our Industry Interaction Board. These efforts resulted in numerous opportunities for pilot technology deployments, as well as synergistic projects with individual industry partners.

The leadership and senior researchers met periodically to plan project direction, and TCIPG held workshops with sector stakeholders to identify gaps and research needs. One outcome of the leadership-researcher meetings was an internal research activity proposal mechanism that allowed vetting of researcher ideas by the cluster lead and the senior leadership.

Partnership Results

TCIPG support contributed to a variety of technologies that were in some stage of transition to industry via licensing, pilot deployment, and open-source software, including to the following:

- Startups Network Perception (NP View;) and River Loop Security (ZigBee security, applicable to home area networks)

- Software to secure Linux-embedded systems kernels (part of the architecture for the kernel security solutions in new security enhanced linux (SEL) products and in parallel being transitioned through the GNU-not Unix (GNU) General Public License (GPL) path.
- Security of SCADA protocols using protocol specification and real-time systems state, open sourced in the Bro security framework
- AMILyzer for security of AMI, in pilot deployment at First Energy
- Open-source training for security in utility systems
- Patents applied for in secure time synchronization of wide area measurement systems

TCIPG recommended that the government retain government-use rights to developed IP, while the partner institutions retained commercial rights. The consortium routinely entered NDAs with industrial partners as appropriate, although these agreements typically addressed confidentiality of sensitive data, rather than jointly-developed IP.

Lessons Learned

TCIPG was successful by following its vision of creating leading-edge research with real-world impact. This was been achieved by involving industry early and maintaining ongoing contact through all stages of research effort.

The consortium learned that different solutions call for different transition models. In an academic consortium, it was important to establish relationships with university TT organizations (for example, the Office of Technology Management at Illinois). The existence of an associated technology incubator (i.e., EnterpriseWorks at Illinois) was also useful for an academic consortium in the early stages of startup.

The following were aspects of TCIPG that were critical to its success:

- Multi-university consortium
- Research activities organized into clusters led by senior faculty, complemented with cross-cutting research efforts
- External Advisory Board
- Activity proposal process that resulted from a 2012 summer retreat
- Reading group/student development
- Quarterly review of research activities
- Mechanisms to deliver industry guest lectures and to arrange visits to industry by faculty and students
- Internships by students to industry, and industry hiring graduates
- Collaboration with other organizations such as Power Systems Engineering Research Center, FREEDM, and Center for Ultra-Wide Area Resilient Electric Energy Transmission Networks
- Teaming with industry on responses to FOAs

The TCIPG project ended in August, 2015. The following suggestions were put forward to improve upon the TCIPG model for a new consortium of this type, the Cyber Resilient Energy Delivery Consortium, CREDC consortium, http://cred-c.org/.[47] In some cases, they present changes from what TCIPG presently does. In others, they consist of increased emphasis on the more effective practices TCIPG currently follows. These suggestions are being addressed in a new CREDC consortium.

- Expand scope of impact for research (i.e., broader energy sector or critical infrastructure)
- Promote agile teaming by allowing augmentation of the core consortium by additional partners and subject matter experts for specific activities as appropriate
- Place more effort on specific industry interaction and collaboration, student internship placement and interaction, and technology transfer

- Develop mechanisms for more meaningful involvement with industry partners interested in deep involvement and for serving the needs of partners more focused on information sharing
- More gap analysis workshop/working groups that involve utility/industry/critical infrastructure stakeholders. Outcome of these efforts is intended to result in research activity proposals, internship placements, technology transfer, etc.
- Establish and regularly review/re-evaluate milestones for individual research activities and initiatives.
- Identify more ways to engage industry in testbed efforts, beyond contributing equipment/technology.

Public-Private Consortia and Technology Transition Case Studies:

United States Advanced Battery Consortium (USABC)

Overview

USABC is an umbrella organization for pre-competitive automotive battery research and development among Fiat-Chrysler Automobiles, Ford Motor Company, and General Motors Company. Through USABC, DOE's Vehicle Technologies Office (VTO) establishes CRADAs for R&D to develop a domestic advanced battery industry whose products can meet the performance requirements of a wide range of electric drive vehicles.

As such, USABC's efforts align with VTO's mission of supporting the research, development, demonstration, and deployment of a broad portfolio of advanced transportation technologies that improve the nation's energy security by reducing dependence on petroleum, reduce greenhouse gas emissions, and strengthen U.S. global economic competitiveness. Activities focus on decreasing the cost and improving the performance of a mix of medium- and long-term technologies, including advanced energy storage devices (batteries and ultracapacitors), power electronics and drive motors, advanced structural materials, advanced combustion engines, and fuels and lubricants. VTO funds high-reward/high-risk research at the national laboratories, as well as competitively awarded, cost-shared projects with university, industry, and other partners.

While VTO pursues a portfolio of technologies that, collectively, can reduce dependence on petroleum, vehicle electrification is an essential and significant part of the solution. The global automotive industry is already moving in this direction. A transition to electrification will benefit not only the national economy and energy security but also individual consumers. That is, today's plug-in electric vehicles (EVs) can "fuel" for the equivalent of about $1/gallon, and next-generation vehicles will bring even bigger savings.

DOE's EV Everywhere Grand Challenge set key technical targets for enabling plug-in EVs (PEVs) to be as convenient and affordable as today's gasoline vehicles by 2022. A focus of this effort is energy storage and the development of more cost-effective, longer lasting, and more abuse-tolerant PEV batteries. VTO's energy storage R&D effort includes multiple activities, ranging from focused fundamental materials research to battery cell and pack development and testing. The R&D activities involve both short-term directed research by commercial developers and national laboratories and exploratory materials research generally spearheaded by the national laboratories and universities.

Since 1991, VTO has worked in close collaboration with industry through a series of CRADAS with USABC. USABC has supported the development of energy storage systems for the entire range of vehicle electrification platforms, from 12 volt (V) start/stop through hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) to full battery-powered EVs. With cost share and in cooperation with VTO, the USABC has supported the development of a number of energy storage technologies, including nickel metal hydride batteries, lithium-ion batteries, lithium metal batteries, ultracapacitors, hybrid ultracapacitor cells, and hybrid systems that contain both lithium-ion batteries and ultracapacitors.

Activity Focus and Funding

The VTO-USABC cost-shared R&D activities focus mainly on the development of robust battery cells and modules to significantly reduce battery cost, increase battery life, and improve battery performance and abuse tolerance. For high-energy and high-power energy storage technologies, the USABC undertakes these activities:

- Develops electric drive vehicle battery performance requirements and test procedures

- Solicits, reviews, and selects proposals to develop advanced battery technology
- Manages ongoing contracts and assures progress toward achieving the VTO-USABC Partnership goals

The current cooperative agreement between VTO and the USABC was awarded after an open, competitive solicitation (FOA 0000722 dated November 30, 2012)[48] in which the DOE sought applicants that would "be led by associations or consortia which include automobile manufacturers that intend to commercialize electric vehicles." VTO provides funding for most of the battery development contracts awarded through the consortium, which are 50% cost-shared by the battery developer. The U.S. automakers supply personnel for "in kind" contributions to the consortium.

Benefits of the Cooperative Agreement between DOE and USABC to the U.S. Taxpayer

The DOE-USABC Cooperative Agreement allows the combined technical and financial resources of DOE, domestic OEM automakers, battery development partners, and independent testing laboratories to join forces in conducting advanced battery research and development. This cooperation yields several advantages:

- Furthers DOE's goal of reducing the nation's dependence on foreign oil
- Ensures cost-sharing of the critical R&D needed by U.S. battery companies to compete with (predominantly) Asian companies that currently dominate the energy storage field
- Enhances both the relevance and the potential for success of the R&D programs, as the automakers bring the perspective of the end user directly to the R&D effort

USABC Formation

Industry Input and Membership

The USABC was formed in 1991 by the "big three" U.S. automakers, General Motors, Ford Motor Company, and Chrysler, to engage in pre-competitive R&D in emerging energy storage technologies for automotive use. (One year later, in 1992, the same U.S. automakers formed the United States Council for Automotive Research LLC, or USCAR, to facilitate collaborative R&D across a broader technology portfolio.) Under USABC, automakers sought to share the costs and the benefits of the long-term effort needed to bring electric drive energy storage technology to market. From its inception, USABC has stressed the collaborative use of metrics-driven research, standards for both performance and cost estimates and requirements, and independent testing to validate claims and results.

Mission

USABC's mission is to develop electrochemical energy storage technologies that support commercialization of electric drive vehicles. The USABC seeks to promote long-term R&D within the domestic electrochemical energy storage (EES) industry and maintain a consortium that engages automobile manufacturers, EES manufacturers, the national laboratories, universities, and other key stakeholders.

DOE-USABC Cooperative Agreement Governance

Management Structure

USABC is organized into several management layers. The USABC Management Committee comprises one management employee from each of the auto companies; one of these individuals serves as Chair. The MC makes both personnel and funding level decisions for the USABC: they allocate staff to various USABC functions and decide if a given proposal will be funded. The MC meets at the USCAR headquarters in Southfield, Michigan, once per quarter, and holds a teleconference in between each in-person meeting.

The cooperative agreement calls for "substantial involvement" by DOE regarding program direction, funding, proposal review and selection, and project review. An appropriate DOE employee participates in MC meetings related to the technical and contractual activities of the cooperative agreement. The DOE representative to the MC is supported by the Technical Project Officer from the Federal contracting organization (currently NETL). The DOE representative provides input on DOE policies and goals to the MC. He/she can (and does) veto any DOE funding of a battery development project that the Department does not support. Note that the USABC can fund development programs, or hire consulting staff, with non-DOE funding.

The Technical Advisory Committee provides technical guidance and recommendations to the MC. The TAC is made up of 20–30 technical experts in the battery development field and is drawn from each of the automotive OEMs, DOE, and the national laboratories. TAC members write the requests for proposals, perform technical reviews of those proposals, oversee and manage ongoing battery and ultracapacitor development programs, develop energy storage requirements for various applications (like HEVs, PHEVs, and EVs), and develop standardized test procedures. A subset of TAC members forms a work group that is assigned to a specific development program. Work groups hold quarterly reviews with that developer and report back to the full TAC during in-person quarterly meetings in Southfield. In addition, teleconferences are held in between each in-person meeting.

The TAC has established a number of working groups that perform specific tasks, such as developing or updating test procedures, developing or modifying performance or cost requirements, or researching a specific technical area (e.g., the means of inducing an internal short circuit in a battery cell). DOE representatives participate in these working groups.

The OEM members to the MC and TAC bring a wide breadth of information, experience, and expectations to their respective teams. They concentrate on automotive requirements, specific automotive needs that battery developers may be unaware of, and development of test procedures that would be of most value for automotive use. The national lab staff who work with the TAC bring testing expertise, electrochemical (scientific) knowledge, and experience from decades of battery R&D. Similarly, DOE representatives to the TAC bring a long history of exploratory and applied research funded by the DOE, technical expertise, and a critical perspective regarding the U.S. government's interests and needs to the USABC.

USABC Technical Review

USABC and its projects are reviewed each year at the VTO Annual Merit Review.[49]

NDA and Conflicts of Interest

USABC members do not sign formal NDAs, but they do designate all information provided to the USABC by developers as "protected information" and commit to holding that information within the USABC for five years from the conclusion of a development program. Under the terms of the cooperative agreement, information that is "protected information" may not be released under the Freedom of Information Act while it is in "protected" status.

The objectives of the cooperative agreement are to develop electrochemical energy storage technologies in a pre-competitive environment, which support commercialization of electric drive vehicles. The USABC automakers do not manufacture batteries but purchase them from suppliers. Conflicts of interest that may arise occasionally are mitigated before the start of any battery development project.

R&D Execution

Technical Engagement of National Labs

As mentioned above, several members of the national laboratory R&D community participate in TAC activities, including members from ANL, INL, LLBL, NREL, and SNL. National laboratory researchers participate in the quarterly TAC and project working group progress review meetings and in the conference calls. They provide independent performance, thermal, and abuse testing support, technical input, and analysis of test and diagnostics data.

Project Planning

USABC requires the inclusion of milestones and deliverables in every development contract that it issues, considered to be a best practice by DOE. Baseline deliverables are required at the beginning of each contract to allow objective and quantitative measurement of advances throughout the period of performance.[50] In all cases, final deliverables are required (interim deliverables are also required in most cases) in order to gauge progress at mid-points of each program.

Other best practices are also followed:

- USABC develops and publicizes electric drive vehicle battery performance requirements and test procedures before the solicitation of battery development proposals for a specific vehicle architecture.
- USABC tests the baseline technology of companies before it will engage in a full development contract. This practice has helped USABC to greatly reduce the likelihood of embarking on long (as long as three years) and expensive (in excess of $10,000,000 in total cost) contracts with companies who are unable to perform at the expected level.

Independent Validation Testing

Each developer is required to subject its cells, modules, and packs to internal testing following the USABC test procedures. When the developer is confident in the performance of its deliverables, prototype battery cells and modules are sent to one or more national laboratories for independent performance, thermal, and/or abuse testing in order to independently confirm or validate the battery developers' results.

Contract Solicitation, Review, and Approval

When USABC prepares to issue a new request for proposal information on an existing or new topic (HEV batteries, PHEV batteries), a TAC working group is formed to lead the request for proposal development, create or update existing quantitative proposal review forms, and technically review the submitted proposals. The working group typically contains members of each OEM and one or more national laboratory researchers; one or more DOE members also participate in these discussions. The quantitative review forms are a critical component of the review process, permitting a fast and accurate measure of each organization's support for a proposal. The results of each stage of this process—development, review form development, and quantitative review of each proposal—are presented to the full TAC for review and approval, and in the case of request for proposals and proposal reviews, to the MC for approval.

One challenge with national laboratory participation in USABC activities is the potential for a conflict of interest between a staff member's research activities and the R&D activities of the industrial battery developer. DOE has taken a very active role in removing any such conflict of interest, or appearance of conflict of interest, by ensuring that national laboratory researchers refrain from participating in any meetings involving topics in which they are actively engaged.

USABC Results

A 2013 analysis by RTI International in Research Triangle Park, NC determined that the DOE's $971 million R&D investment in advanced battery technology for electric drive of vehicles from 1991–2012 directly led to the commercialization of the 2.4 million electric drive of vehicles sold between 1999–2012 that incorporate nickel–metal hydride and lithium-ion batteries, which are projected to reduce U.S. fuel consumption by $16.7 billion through 2020.[51] The study also found that VTO-funded research contributed to the knowledge base in energy storage that resulted in 112 patent families in energy storage over the period 1976 to 2012 and is ranked first in patent citations among the top 10 companies.

Technologies Produced

USABC has a long track record of helping to develop energy storage technologies that have been subsequently commercialized as detailed below.

Nickel–Metal Hydride Battery Technology for Hybrid Vehicles

In 1992, under a cooperative agreement with DOE, the USABC initiated development of nickel–metal hydride battery technology. DOE funding through that cooperative agreement was instrumental to the development of nickel–metal hydride technology at two manufacturers, Energy Conversion Devices, Inc. (ECD Ovonics) and SAFT America. ECD Ovonics' nickel–metal hydride technology is now manufactured at COBASYS, LLC, its 50-50 manufacturing joint venture with Chevron Technology Ventures, LLC. ECD is also licensing its technology to Sanyo, which supplies nickel–metal hydride batteries for the Ford Escape, Cmax, and Fusion hybrid vehicles; to Honda, for its hybrid vehicles; and to Panasonic, which supplies batteries for Toyota hybrid vehicles. Under the terms of the original ECD contract, a small fraction of these licensing fees have been remitted to DOE and USABC.

Lithium-ion Battery Technology for Hybrid Vehicles

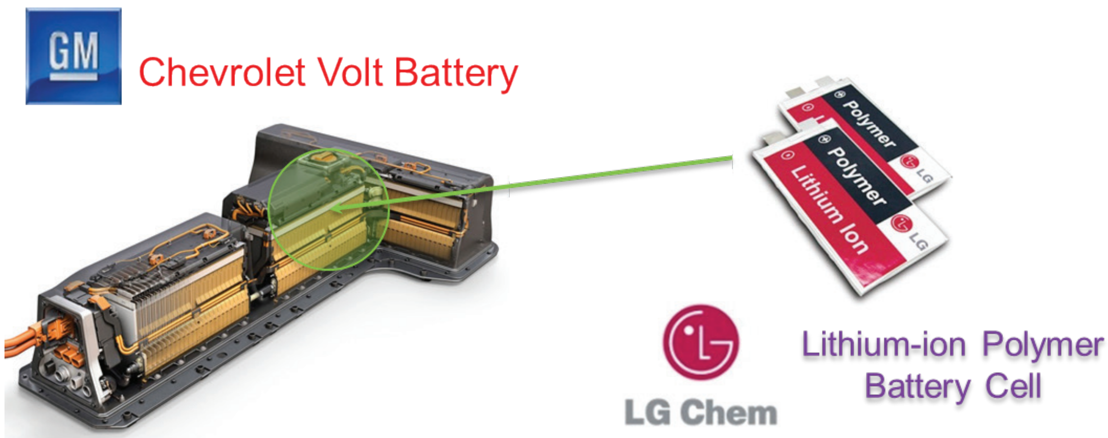
From 2003 to 2008, the USABC awarded Johnson Controls, Inc. (JCI) contracts to develop a 40 kilowatt (kW) lithium-ion HEV battery. Under this program, JCI developed the VL6P lithium-ion battery cell, which offers twice the energy and power for the same weight and volume of NiMH batteries and at a lower cost (Figure USABC-1). In 2009, JCI launched production of its lithium-ion battery for the Mercedes-Benz S400, the first lithium-ion HEV battery to be commercialized. JCI received production contracts with BMW for its 7 series ActiveHybrid in early 2010. In 2014, JCI announced that it is supplying lithium-ion batteries for the Hybrid Range Rover.

Figure USABC-1 JCI High Power lithium-ion battery for the BMW ActiveHybrid 7 Series, featuring the VL6P cell developed with support from DOE and USABC

Lithium-ion Battery Technology for Plug-in EVs

Later, in the early 2000s, USABC supported the development of the core cell technology that is currently used in the Chevrolet Volt PEV battery (Figure USABC-2) and the Ford Focus EV battery. The cell, which contains a graphitic anode and a mixture of layered and spinel oxides, was developed in collaboration with LG Chem Michigan from early 2004 through 2012.

Figure JCESR-2 Chevrolet Volt Battery and LG Chem Lithium-ion Polymer Battery Cell



Ultracapacitor Commercialization

Figure USABC-3 Maxwell BoostCap Ultracapacitor

Maxwell Technologies developed higher voltage, higher-energy ultracapacitors as part of a USABC 42V start stop[52] development program in the mid-2000s. The cell developed in that program (Figure USABC-3) was eventually commercialized and used to power hybrid buses in China, and today, Maxwell ultracapacitors are installed in over 1 million vehicles on the road.

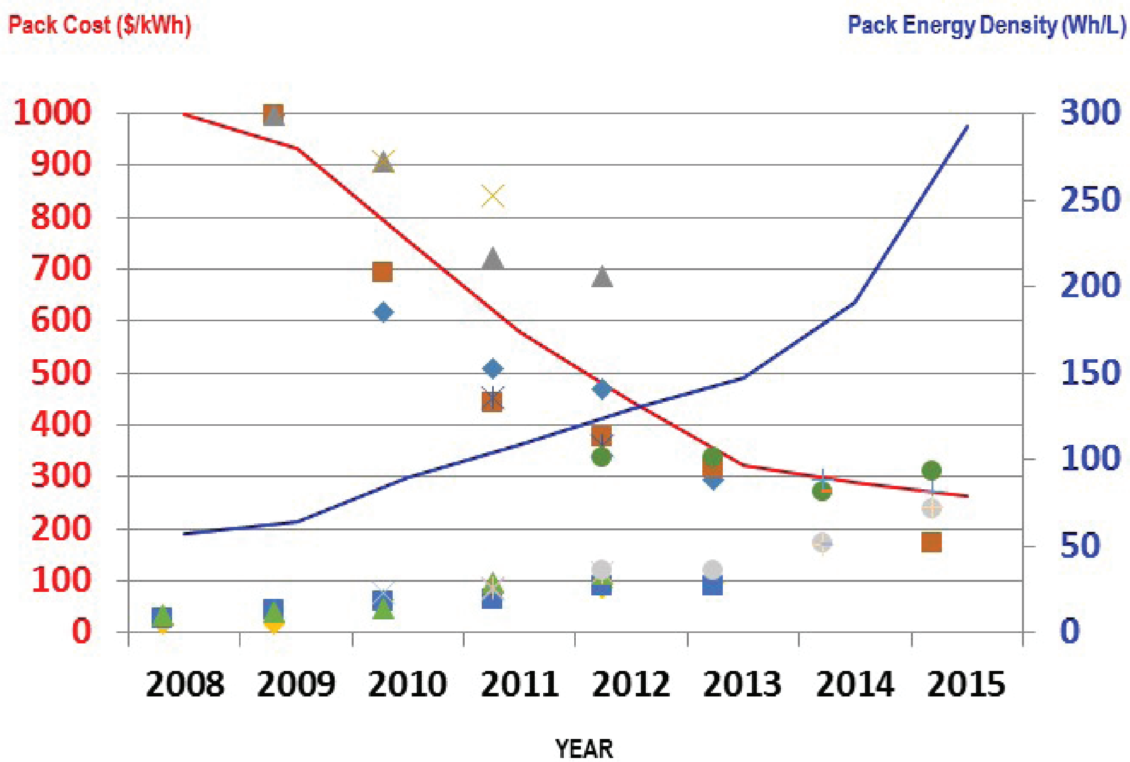
PEV Battery Cost Reduction

DOE, in close collaboration with the USABC, has reduced the cost of lithium-ion batteries by nearly 70% and improved their energy density by 60% during the last five years. As shown in Figure USABC-4, the modeled cost of PHEV batteries under development has been reduced from $1,000 per kilowatt-hour of useable energy in 2008, to a current cost of $289 per kilowatt-hour. Three USABC battery developers have made significant advances in cost reduction using improved cathodes. These battery development projects focus on advanced cathodes, processing improvements, cell design, and pack optimization. Standard electrolytes and graphite anodes were used by each developer. These battery cost projections are derived by the manufacturer using

USABC's battery manufacturing cost model based on a production volume of 100,000 batteries per year for specific battery cell and module designs that meet DOE/USABC requirements for power, energy, and cycle life as well as calendar life.

Concurrently, the size and weight of plug-in EV batteries have also been reduced by over 60% and the battery energy density has increased from 60 watt-hour/liter (Wh)/l) in 2008, to 150 Wh/l in 2013.[53]

Figure JCESR-4 Modeled cost and energy density of PEV batteries developed and tested. DOE R&D supported significant battery costs reductions (3x) since 2008. 2022 target is set at $125/kWh to achieve price parity with Gasoline ICEs.



Monitoring of Goals

The following section describe the methods used to monitor progress toward goals.

Development and Use of Requirements and Testing Standards

One of the other major achievements of USABC has been its development and publication of both electric drive vehicle battery performance requirements and test procedures. Prior to the issuance of a request for proposal on any topic, USABC TAC members either develop or confirm battery requirements through in-depth consultation with staff at their respective companies. National lab staff may aid in this process by performing vehicle simulations using various battery technologies to understand the fuel economy differences among various performance requirements. This process, particularly if it is for new or substantially updated requirements, can take many months, and sometimes more than a year. However, performance targets agreed to by all participants and that permit a quantitative evaluation of multiple technologies is a major benefit of this process. As an example, performance requirements for EVs and 12V start/stop batteries are shown in Table USABC-1 and Table USABC-2.

Table USABC-1 Subset of EV Battery Requirements

Parameter of Fully Burdened System	Units	Long Term Goals
Power Density	Watt (W)/l	600
Specific Discharge Power (80% depth of discharge (DOD), 30 sec)	W/kilogram (kg)	400
Specific Regenerative Power (20% DOD, 10 sec)	W/kg	200
Energy Density (C/3 discharge)	Wh/l	300
Specific Energy (C/3 discharge)	Wh/kg	200
Life	Years	10
Cycle life (80% DOD)	Cycles	1000
Selling price (25k 40 kilowatt-hour (kWh) units)	$/ (kWh)	100
Operating temperature	C	- 40 to +85

Table USABC-2 Subset of 12V Start Stop Battery Requirements

End of Life Characteristics	Units	Under Hood Target
Discharge Pulse (1 second)	kW	6
Max discharge current (.5 sec)	A	900
Cold cranking power at -30 °C	kW	6
Minimum voltage under cold crank	Vdc	8.0
Available energy	Wh	360
Peak recharge rate	kW	2.2
Cycle life	Engine starts/miles	450k/150k
Calendar life at 45 °C	Years	15
Weight	kg	10
Volume	L	7
Price	$	220

Once the performance targets are finalized, TAC members, in collaboration with national laboratory battery testing personnel, either create or update existing test procedures. This process, like the requirements definition process, can take several months. The way a device is tested can have a major impact on the results, and as such, USABC and DOE take great care to ensure that the test procedures are as relevant to the auto industry as possible, and that they maximize the ability of the USABC and DOE to compare results from generation to generation along a development path. A sample of currently published test procedures is shown in Figure USABC-5.

Figure JCESR-5 USABC Test Procedures. Source:[54]

Common requirements and test procedures have been a major factor enabling the comparison of technologies from different developers or comparing multiple versions of the same technology. Many battery developers approach DOE or USABC with claims of vastly superior performance compared to their competitors. Having standard test procedures has, essentially, leveled the field and enabled a fully independent and defensible test of those claims.

Use of Standard "Gap Chart to Track R&D Progress

At each quarterly technical review meeting, developers are required to present standardized "gap charts" (see Table USABC-3), which contain device parameters, associated USABC goals, and hardware performance metrics that are critical to evaluating the progress of the program. Typically, as shown below, the gap chart contains goals, the baseline cell beginning-of-life parameter values, and the parameter values that the cell or system is presently delivering. In the case shown in Table USABC-3, results are shown after 150 EV cycles. Often the parameter values are color-coded to indicate whether they are meeting (green), are just barely meeting (yellow), or are not meeting (red) a specific target.[55]

Table USABC-3 Sample EV Cell Development Program Gap Chart

EV Targets	USABC Cell Level Goal	Quarterly Progress	
		Developer Data	
		Beginning of Test	Present Performance
Power Density (W/l)	460	1215	670
Discharge Pulse Power @80% DOD (W/kg)	300	721	298
Regen Pulse Power @20% DOD (W/kg)	150	1837	1228
Energy Density (watt-hours (Wh)/l)	230	360	345
Specific Energy C/3 Discharge (Wh/kg)	150	214	205
Power/Energy Ratio	2	6	1.45
Calendar Life (years)	10	tbd	0.43
Maximum System Weight (kg)		0.337	0.337
Maximum System Volume (l)		0.2	0.2
Cycle Life 80% DOD (DST profile)	1000	tbd	150
Maximum Operating Voltage (Vdc)		4	4
Minimum Operating Voltage (Vdc)		2	2
Estimated Battery Pack Cost ($/kWh)	$125	$290	$290

Use of Standard Cost Model

USABC has published, and requires its developers to use, a detailed cost model which helps to build confidence in a developer's claims regarding product production cost and selling price. The cost model is based on a sales volume of 100,000 batteries per year and includes material costs, purchased material costs, plant and equipment depreciation, and other costs. The model is available on the USABC website for download.[56]

The USABC uses the independent performance tests on contract deliverables, completed cost models, and the battery requirements to gauge progress towards consortium goals.

IP and Licensing

None of the USABC members directly compete with battery or ultracapacitor developers. Rather, the member organizations are users and purchasers of that technology. As such, IP issues have been rare. In addition, it is relatively difficult, in any research program, for a funding organization to prove that a commercialized technology was developed using that organization's support.

Lessons Learned

The DOE/USABC cooperative agreements have been an extremely successful industry/government collaborative R&D effort.[57] Over 20 years, this collaboration has successfully completed an extraordinarily large number of development programs, developed technology that has been commercialized and put into use, published requirements and test procedures that are recognized and used worldwide, and greatly accelerated the development and adoption of petroleum-saving energy storage technologies across the globe. The Toyota Prius and Honda Insight were launched within several years after the USABC began its HEV battery research, and, in fact, the battery suppliers to both companies licensed the technology developed by the USABC. In addition, the recent enhanced focus on PHEVs and EVs follows closely the USABC's funding of high energy lithium-ion batteries for those applications.

If the program were starting new, DOE could consider permitting a sliding scale of cost-share requirements for developers. The current requirement of 50% cost share is most appropriate for technologies that are more mature. This 50% cost share worked well when developers focused on lithium-ion batteries for hybrid vehicles that had been demonstrated in consumer electronic devices and were already capable of meeting the power and energy targets but fell short on cycle life (10,000 HEV cycles vs. the 300,000 HEV cycle target) and cost ($100/kilowatt (kW) vs. $25/kW).

Recently, however, the USABC has moved to supporting R&D involving less mature technologies (such as silicon-based anodes and high-voltage cathodes) that show promise to meet the extremely aggressive EV Everywhere goals. Cells made from these materials often show cycle lives of 100s, as opposed to the 1,000 to 5,000 cycle life requirement. In addition, the materials themselves may not be available in high volume or with high batch-to-batch consistency. More established companies may hesitate to engage in R&D on such high risk technology at the 50% cost share level.

USABC also recommends that other consortia adopt the following USABC procedures and features:

1. Membership that includes end users (automotive OEMs), national lab personnel (for independent testing, outside electrochemical and testing expertise), and DOE
2. Use of quantitative performance requirements for all application
3. Use of quantitative proposal review forms to evaluate all proposals
4. Required use of a standard cost model by all developers
5. Use of standardized test procedures for all performance and abuse requirements by all developers and by testing laboratories
6. Independent performance and abuse testing of all contract deliverables
7. Quarterly technical review meetings with staff and developer teams to permit early identification of potential issues and establishment of timely remediation plans
8. The use of standardized gap charts that contain critical parameters to be tracked at quarterly progress reviews

Conclusion

This review has examined eight public-private consortia and examined the approaches used for transitioning work to the private sector and to markets. Each of the consortia have identified and implemented organizational structures, relationships, research strategies, and IP management plans to help them quickly transition technologies to appropriate industrial entities. As they continue to track their success, using metrics that identify specific performance, operational, and technology transition objectives, they will work with DOE to continue to evolve to provide the greatest possible effectiveness and efficiency—and therefore high value to U.S. taxpayers.

Endnotes

[1] National Academy of Sciences' National Research Council, Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy, "Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978-2000", National Academy Press, Washington, DC, 2001, http://www.nap.edu/catalog/10165/energy-research-at-doe-was-it-worth-it-energy-efficiency . See also:

- USDOE, Office of Energy Efficiency and Renewable Energy, Program Evaluation: EERE Planned and Completed Evaluations, Subsection of Impact Evaluations: http://www.energy.gov/eere/analysis/program-evaluation-eere-planned-and-completed-evaluations

[2] Stevenson-Wydler Technology Innovation Act of 1980, https://legcounsel.house.gov/Comps/Stevenson-wydler%20Technology%20Innovation%20Act%20Of%201980.pdf; Bayh-Dole Act, "Patent Rights in Inventions Made with Federal Assistance", https://www.gpo.gov/fdsys/pkg/USCODE-2011-title35/html/USCODE-2011-title35-partII-chap18.htm

[3] The 2014-2018 Department of Energy Strategic Plan addresses this portion of the mission by committing to "maximize the impact of federal R&D investment in the laboratories, accelerate the transfer of technology into the private and government sectors, and better respond to opportunities and challenges" "U.S. Department of Energy Strategic Plan 2014-2018", https://www.energy.gov/sites/prod/files/2014/04/f14/2014_dept_energy_strategic_plan.pdf

[4] United States Department of Energy. (2015). Energy Department Announces New Office of Technology Transitions [Press release]. Retrieved from http://energy.gov/articles/energy-department-announces-new-office-technology-transitions.

[5] Of course, the specific goals adopted must be appropriate for each program office's mission. For example, basic research programs may seek to bring more commercial users to their user facilities, and increase the number of invention disclosures, patents, and licenses; while more applied programs may place greater emphasis on the number and impact of industry collaborations and the demonstration and deployment of clean energy technologies; and, national security programs may focus more on deployment of technologies to other government agencies.

[6] U.S. Department of Energy, Secretary of Energy Ernest J. Moniz, letter to the Honorable Cynthia Lummis and the Honorable Eric Swalwell, Committee on Science, Space, and Technology, U.S. House of Representatives, July 10, 2013, http://science.house.gov/sites/republicans.science.house.gov/files/documents/Letter%20to%20Chairman%20Lummis%20and%20RM%20Swalwell.pdf

[7] As with the program offices, each laboratory has a unique portfolio of research activities and will have a unique set of mission-appropriate commercialization and deployment goals.

[8] Today, as part of statutory reporting requirements, the Department annually collects from the laboratories a set of data elements tracking readily measured indicators of activity including: the numbers of various types of agreements executed, numbers of inventions disclosed and patented, and royalties and private sector research funding received. The metrics that have historically been collected provide useful benchmarks, but do not capture the breadth of the laboratories' private sector impact.

[9] Because technology transfer by its nature provides private sector entities with access to valuable publicly funded research outputs and capabilities, there are attendant concerns of conflicts of interest and perceived preferential treatment of one prospective partner over another. These concerns increase as the laboratories seek to follow the leads of successful university technology transfer offices by allowing national laboratory staff members to engage directly in the commercialization of their technologies either as entrepreneurs or as consultants. The Department and its technology transfer offices must also ensure compliance with legal and policy requirements including the statutorily mandated preference for United States small businesses and policies designed to enhance United States competitiveness.

[10] Recognizing that any commercialization program carries with it some uncertainty that must be appropriately balanced with the economic benefit the nation can realize through successful laboratory/industry partnerships.

[11] Energy Innovation Portal, since its launch, the portal has been visited more than 300,000 times, and more than 50 transactions (licenses, options and partnerships) have occurred based on the 3,000 leads generated from the site.

[12] The consolidation of science and energy programs under the direction of the Under Secretary for Science and Energy represents an important step toward improving transitions of technology and technology needs between the basic and applied programs. As a first step, the Under Secretary's office developed a Science and Energy Plan to coordinate the progression of technologies from basic to applied programs, and as the plan matures and is coordinated, the technologies should progress more predictably through a the development process. See: U.S. Department of Energy, "FY 2016 Science and Energy Plan", https://energy.gov/under-secretary-science-and-energy/downloads/science-and-energy-plan

[13] Today, prospective partners often find that the laboratories do not have data relevant to their intended use for new technologies and do not have resources available to help them assess the benefits of adopting the technologies.

[14] The PNNL and ORNL Technology Innovation Programs (TIPs) are competitive technology commercialization acceleration programs that simultaneously invest in scientific research and development and in aggressive commercial outreach. The TIPs also provide follow-on funding to facilitate the transfer of supported technologies to licensees. Both programs have been very successful; approximately 75% of the supported technologies have been licensed, optioned, or have otherwise attracted partner funding support.

[15] Beginning as a pilot, SBV intends to foster stronger partnerships between a network of participating DOE National Laboratories and high impact clean energy small businesses, and to promote economic development by improving clean energy small business access to the expertise, competencies, and infrastructure of DOE's national laboratories.

[16] The Energy Technology Commercialization Fund, a $20 million funding opportunity created by statute, leverages the R&D funding in the applied energy programs to mature promising energy technologies with the potential for high impact. It uses 0.9 percent of the funding for the Department's applied energy research, development, demonstration, and commercial application budget for each fiscal year from the Office of Electricity, Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy, and Office of Nuclear Energy. These funds are matched with funds from private partners to promote promising energy technologies for commercial purposes. http://energy.gov/articles/doe-s-office-technology-transitions-issues-first-call-launch-new-energy-technologies

[17] EERE recently announced a Pilot Lab-Corps program modeled after the NSF I-Corps program. Lab-Corps aims to better train and empower national lab researchers to successfully transition their discoveries into high-impact, real world technologies in the private sector by pursuing the development of startup companies, industry partnerships, licensing agreements, and other business opportunities. https://energy.gov/eere/technology-to-market/downloads/lab-corps-documents

[18] Brookings Institute report, "*Going Local: Connecting the National Labs to their Regions to Maximize Innovation and Growth*", 2014, https://www.brookings.edu/research/going-local-connecting-the-national-labs-to-their-regions-to-maximize-innovation-and-growth/

[19] Additional examples include:

- PNNL plays a leading role in the Tri-Cities Research District, and in the Applied Process Engineering Lab, an incubator for local tech-based businesses.
- Working with support from federal and state entities, the INL has successfully created the Center for Advanced Energy Studies (CAES) which brings together researchers from INL, University of Idaho, Idaho State University, Boise State University, and the University of Wyoming.

[20] This program provides small businesses with access to the laboratories' staff and resources to solve technical challenges. Since the inception of the NMSBA Program, 2,341 businesses have been assisted, 4,086 jobs have been created or retained, and $43.7M of technical assistance has been provided. New Mexico Small Business Assistance Program, http://www.nmsbaprogram.org/

[21] Noteworthy examples are BNL's Entrepreneurs Network, Idaho National Laboratory's Technology Based Economic Development Program, LANL's Venture Accelerator Fund and Market Transition Program, LLNL's Entrepreneur in Readiness Program, NREL's Innovation and Entrepreneur Center, ORNL's Bredesen Center Entrepreneurship Program, PNNL's University Technology Entrepreneurship Program, and SNL's Sandia Science and Technology Park.

[22] "*" indicates companies that are no longer actively involved in the industry advisory board due to changing strategic interests with respect to carbon capture. Note that over the five years of the project, other companies have joined the advisory board as they became aware of CCSI's relevance to their ongoing development efforts.

[23] Technology Readiness Levels (TRL) are a method of estimating technology maturity of critical technology elements of a program, as determined through a Technology Readiness Assessment. TRL are based on a scale from 1 to 9 with 9 being the most mature technology. The use of TRLs enables consistent, uniform, discussions of technical maturity across different types of technology.

[24] D. C. Miller, M. Syamlal, D. S. Mebane, C. B. Storlie, D. Bhattacharyya, N. Sahinidis, D. A. Agarwal, C. Tong, S. E. Zitney, A. Sarkar, X. Sun, S. Sundaresan, E. M. Ryan, D. Engel and C. Dale, 2014, Carbon Capture Simulation Initiative: A Case Study in Multiscale Modeling and New Challenges, Chemical and Biomolecular Engineering 5, 301-323.

[25] Link, Albert et al, "Retrospective Benefit-Cost Evaluation of U.S. DOE Vehicle Combustion Engine R&D Investments: Impacts of a Cluster of Energy Technologies", University of North Carolina at Greensboro, 2010, https://www1.eere.energy.gov/analysis/pdfs/advanced_combustion_report.pdf

[26] RTI International, "Benefit-Cost Evaluation of U.S. DOE Investment in Energy Storage Technologies for Hybrid and Electric Cars and Trucks," RTI Project Number 0213238, December 2013. https://www1.eere.energy.gov/analysis/pdfs/2013_bca_vto_edvs.pdf

[27] Because NETL is a federally operated national laboratory, the IAB interacts through the contractor-operated labs, reporting directly through LBNL, to meet the requirements of the Federal Advisory Committee Act.

[28] D. C. Miller, M. Syamlal, D. S. Mebane, C. B. Storlie, D. Bhattacharyya, N. Sahinidis, D. A. Agarwal, C. Tong, S. E. Zitney, A. Sarkar, X. Sun, S. Sundaresan, E. M. Ryan, D. Engel and C. Dale, 2014, Carbon Capture Simulation Initiative: A Case Study in Multiscale Modeling and New Challenges, Chemical and Biomolecular Engineering 5, 301-323.

[29] Link, Albert, et al, "Retrospective Benefit-Cost Evaluation of U.S. DOE Vehicle Combustion Engine R&D Investments: Impacts of a Cluster of Energy Technologies", 2010, University of North Carolina at Greensboro. https://www1.eere.energy.gov/analysis/pdfs/advanced_combustion_report.pdf

[30] Dec J.E. "A Conceptual Model of DI Diesel Combustion Based on Laser-Sheet Imaging*," SAE Technical Paper 970873, 1997, doi:10.4271/970873.

31 Eckerle W..A and Stanton D.W. "Analysis-Led Design Process for Cummins Engine Development," THIESEL-2006: Conference on Thermo- and Fluid Dynamic Processes in Diesel Engines, Sept. 13-15, 2006, Valencia, Spain.

32 International Workshop on Measurement and Computation of Turbulent NonPreMixed Flames, Naples, Italy, July 26-27, 1996,and subsequent workshops at: http://www.sandia.gov/TNF/1stWorkshop/TNF1.html

33 The Consortium for Advanced Simulation of LWRs: A DOE Energy Innovation Hub", http://www.casl.gov/

34 Virtual Office Community and Computing (VOCC) Laboratory. http://www.casl.gov/docs/CASL-U-2013-0043-000.pdf

35 US Department of Energy, "*Critical Materials Strategy*", Washington, DC, December 2011; https://energy.gov/epsa/initiatives/department-energy-s-critical-materials-strategy

36 DOE Genomic Science Program, Systems Biology for Energy and Environment, DOE Bioenergy Research Centers, http://genomicscience.energy.gov/centers/

37 Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda. A Research Roadmap Resulting from the Biomass to Biofuels Workshop, December 7–9, 2005, Rockville, Maryland. http://genomicsgtl.energy.gov/biofuels/b2bworkshop.shtml

38 Total funding was compiled from data in LBNL eSRA and RAPID enterprise systems for managing LBNL proposals and awards.

39 Joint BioEnergy Institute Publications, https://www.jbei.org/research/publications/

40 Joint BioEnergy Institute, JBEI Startups, https://www.jbei.org/industry/jbei-startups/

41 See: Joint BioEnergy Institute, JBEI Startups, https://www.jbei.org/industry/jbei-startups/ and Joint BioEnergy Institute, Industry Engagement, https://www.jbei.org/industry/jbei_industry_engagement/

42 Joint BioEnergy Institute, Publications, https://www.jbei.org/research/publications/

43 Joint Center for Energy Storage Research, www.jcesr.org

44 Professor Scaglione and her team transitioned from UC Davis to Arizona State University in January 2015.

45 NP View, a tool to assess security of utility networks by identifying routable paths to critical cyber assets, is the portfolio centerpiece of the startup Network Perception. http://www.network-perception.com

46 The TCIPG leadership team was as follows: Professor William H. Sanders, head of Illinois Department of Electrical and Computer Engineering, is the overall PI. He was supported by Co-PI's Professor Pete Sauer, a leading authority on power systems, and Professor David Nicol, who heads the Information Trust Institute at Illinois. Site leads at respective academic partner institutions were Professor Carl Hauser (Washington State University), Professor Anna Scaglione (Arizona State University), and Professor Sean Smith (Dartmouth College). Professor Scaglione and her team are transitioning from UC Davis in January 2015. The leadership team also includes Mr. Alfonso Valdes (Managing Director, Smart Grid Technologies), Mr. Tim Yardley (Associate Director, Testbed), and Ms. Cheri Soliday (Research Program Manager), all from the University of Illinois.

47 CREDC consortium. See http://cred-c.org/

48 FOA 0000722 dated November 30, 2012, https://eere-exchange.energy.gov/FileContent.aspx?FileID=af65249e-b4ad-41eb-b2df-fdf967307a6c

49 Weblink to latest merit review and annual report, http://energy.gov/eere/vehicles/downloads/vehicle-technologies-office-2015-annual-merit-review-report

50 I. Bloom, et al., "Testing USABC Deliverables/Benchmarking", DOE Vehicle Technologies Merit Review, February 25, 2008, http://energy.gov/sites/prod/files/2014/03/f12/merit08_bloom.pdf

51 Benefit-Cost Evaluation of U.S. DOE Investment in Energy Storage Technologies for Hybrid and Electric Cars and Trucks, https://www1.eere.energy.gov/analysis/pdfs/2013_bca_vto_edvs.pdf

52 USABC Start Stop Manual, http://www.uscar.org/guest/article_view.php?articles_id=86

53 Overview of DOE Advanced Battery R&D Program. Slides showing data. http://energy.gov/sites/prod/files/2015/06/f23/es000_faguy_2015_o.pdf

54 United States Council for Automotive Research, News, USABC Manuals, http://www.uscar.org/guest/article_view.php?articles_id=86

55 Link to recent Overview and Progress of United States Advanced Battery Consortium (USABC) Activity. http://energy.gov/sites/prod/files/2016/06/f32/es097_elder_2016_o_web.pdf Showing gap charts. Right column is initial performance of the given EV target at the time the test was started. Left column is present performance of given target after 150 EV cycles.

56 Link to USABC Cost Models, http://www.uscar.org/guest/article_view.php?articles_id=143

57 USCAR website. History, technologies, partnerships, publications, significantly funding R&D cooperative agreements, leadership teams, etc. http://www.uscar.org/guest/index.php

Acronyms

AEC	Advanced Engine Consortium
ALAMO	Automatic learning of algebraic models for optimization
AMI	Advanced Metering Infrastructure
ANL	Argonne National Laboratory
ARPA-e	Advanced Research Projects Agency – Energy
BER	Office of Biological and Environmental Research
BES	Office of Basic Energy Sciences
BETO	Bioenergy Technologies Office
BIP	Background intellectual property
BoD	Board of Directors
BRC	Bioenergy Research Center
CASL	Consortium for the Advanced Simulation of Light Water Reactors
CEO	Chief Executive Officer
CO	Carbon monoxide
COO	Chief Operating Officer
CSTO	Chief Science and Technology Officer
CFD	Computation fluid dynamics
CMI	Critical Materials Institute
CRADA	Cooperative Research and Development Agreement
CRF	Combustion Research Facility
CCS	Carbon capture and storage
CCSI	Carbon Capture Simulation Initiative
CCSI^2	Carbon Capture Simulation for Industry Impact
DARPA	Defense Advanced Research Projects Agency
DOC	Director of Commercialization
DOD	Depth of discharge, or Department of Defense
DOE	Department of Energy
EAB	External Advisory Board
ECD	Energy Conversion Devices, Inc.
ECN	Engine Combustion Network

EERE	Office of Energy Efficiency and Renewable Energy, USDOE
EES	Electrochemical energy storage
EPRI	Electric Power Research Institute
EUVL	Extreme ultraviolet
EV	Electric vehicle
FE	Office of Fossil Energy, USDOE
FOA	Funding Opportunity Announcement
FOQUS	Framework for Optimization, Quantification of Uncertainty, and Surrogates
FTE	Full-time equivalent
FY	Fiscal year
GM	General Motors
HEV	Hybrid electric vehicle
IAB	Industry Advisory Board
IAC	Industry Advisory Committee
IIA	Inter-institutional agreement
IIB	Industry Interaction Board
INL	Idaho National Laboratory
IP	Intellectual property
IPMP	Intellectual property management plan
IPP	Industry partnership program
JBEI	Joint BioEnergy Institute
JCESR	Joint Center for Energy Storage Research
JCI	Johnson Controls, Inc.
kg	kilogram
kW	kilowatt
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
LTC	low-temperature combustion
LWR	Light water reactor
MC	Management Committee
MIT	Massachusetts Institute of Technology

MOU	Memorandum of Understanding
MTA	Material Transfer Agreement
NDA	Nondisclosure agreement
NO_x	Nitrogen oxides
OEM	Original equipment manufacturer
ORNL	Oak Ridge National Laboratory
OTT	Office of Technology Transitions
NE	Office of Nuclear Energy, USDOE
NETL	National Energy Technology Laboratory
NIMH	Nickel metal hydride
NREL	National Renewable Energy Laboratory
PHEV	Plug-in hybrid electric vehicle
PMU	Power management unit
PNNL	Pacific Northwest National Laboratory
RC	Research Committee
R&D	Research and development
RDD&D	Research, development, demonstration, and deployment
SAC	Science Advisory Committee
SBIR	Small Business Innovation Research
SBV	Small Business Vouchers Pilot
SC	Office of Science, USDOE
SCADA	Supervisory control and data acquisition
SLT	Senior Leadership Team
SPP	Strategic Partnership Project, formerly known as Work For Others
TAC	Technical Advisory Committee
TCIPG	Trustworthy Cyber Infrastructure for the Power Grid
TEM	Technoeconomic model
TIP	Technology Innovation Program
TNF	Turbulent Nonpremixed Flame Workshop
TRL	Technology Readiness Level
TT	Technology transfer/transition
TTD	Technology Transfer Department

TVA	Tennessee Valley Authority
UC	Uncertainty quantification
UC Berkeley	University of California, Berkeley
UC Davis	University of California, Davis
UM	University of Michigan
USABC	United States Advanced Battery Consortium
USCAR	United States Council for Automotive Research
USDOE	United States Department of Energy
UTRC	United Technologies Research Corporation
V	Volt
VERA	Virtual Environment for Reactor Applications
VOCC	Virtual Office, Community, and Computing
VTO	Vehicle Technologies Office
WFO	Work for Others, currently known as SPPs
W	Watts
Wh	Watt-hour

Glossary

Technology Readiness Level:	A widely used indicator of the degree of development of a technology toward deployment on a scale of 1-9, with 9 being fully deployment-ready
Work for Others:	A type of agreement that allows national laboratories to work for entities other than DOE; now known as Strategic Partnership Projects (SPPs)