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The Triple Helix within the lithium-ion battery research network: a case study of JCESR

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Abstract

The Joint Center for Energy Storage Research (JCESR) attempts to fuse together basic research, battery design, and pathways to market, bypassing the high-risks, high-costs, and market entry-challenges of sustainable energy technology. Focusing on JCESR's publications record, this paper highlights qualities of the Triple Helix model of government-university-firm interactions, particularly the nearly ten thousand instances of research collaboration, the nearly three thousand collaborative instances among JCESR's affiliated institutions and beyond, and the expanding disciplinary focus. These findings are confirmed with the first-ever survey of lithium-ion battery researchers. Despite intentions to commercialize battery technology in line with the tenets of the Triple Helix paradigm, battery storage research under JCESR remains primarily basic in orientation, thus diminishing opportunities for public-private research collaboration and commercialization. Nonetheless, JCESR provides a foundation for continued efforts to leverage synergies across the Triple Helix of battery storage research.

Introduction

This paper examines innovation policies that attempt to bridge basic and applied research for commercializable products. For government research institutes (GRIs), universities, and the private sector, the frame within which this dynamic occurs is the Triple Helix model (Etzkowitz and Leydesdorff 2000, Etzkowitz 2003, 2008, Leydesdorff 2006). More specifically, GRIs, universities, and firms have varying foci on basic and applied research, but their complementary skills and interests can be leveraged. Government funding is crucial for fostering the pillars of the Triple Helix model, facilitating universities' and GRIs' basic research, while university-based spinoffs and larger firms focus on applied research, patenting, and prototype development for later introduction to the marketplace. Such funding is even more significant when it is intended to produce innovations with social import, such as those that reduce energy costs and air pollution, particularly carbon emissions.

The focus here is on research and development (R&D) surrounding battery storage and lithium-ion batteries. Two-thirds of all electricity generation is fossil fuel-based, and approximately two-third of all carbon emissions originate in the electricity grid and transportation sector (U.S. Energy Information Administration 2017). Advances in electricity-related science can thus improve the well-being of society in terms of health outcomes as well as energy-related savings. For example, costs can be reduced and power quality can be improved in an urban electricity system with bi-directional charging of electric vehicles and stationary batteries (Kaschub *et al* 2014, Battke and Schmidt 2015). In the U.S., public policies that address these goals have focused on shifting energy demand. By 2024, the California Public Utilities Commission will require the installation of energy storage with a capacity of 1 percent of 2020 peak loads (California Public Utilities Commission 2013)[1]. Renewable portfolio standards also raise the importance of energy storage-related research as 13% of electricity sales nationwide are projected to be sourced from renewable energy sources by 2030 (Barbose 2017). Battery storage must improve to the point that it offsets the intermittency of solar and wind power.

[1] This has since been addended with AB 2868, which adds 500 MW of behind-the-meter energy storage (Maloney 2017).

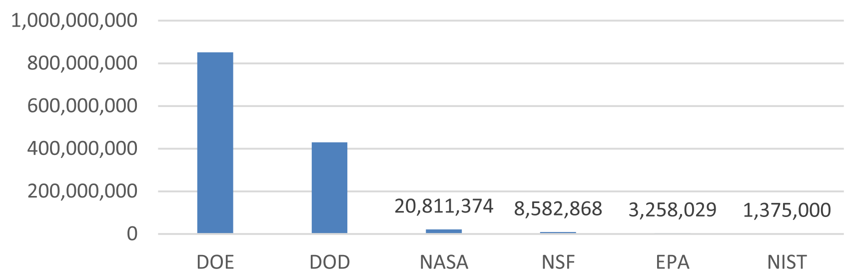

Figure 1. Agency battery and energy storage initiatives and funding obligations (dollars), 2009–2012. Source: (U.S. Government Accountability Office 2012).

It is assumed that the Triple Helix paradigm is present in translational battery storage research. National Science Foundation and Department of Energy (DOE) funding promotes centers to bring together researchers from the public and private sectors as well as to provide training to researchers regarding the commercialization process. Under its Innovation Hub program, the DOE provides particular R&D funding to make advanced energy storage technologies cost competitive as well as to seamlessly integrate them with existing energy systems (U.S. Department of Energy 2013). The DOE's battery storage Innovation Hub—the Joint Center for Energy Storage Research (JCESR)—is the particular focus of this paper. In light of the challenges faced by past sustainable energy research consortia, the goals of this study are three-fold. First, to identify how the research network is structured, JCESR is discussed in the context of other large-scale sustainability-oriented R&D projects in the U.S. that highlight the science-commercialization divide. Second, the JCESR case is framed within the technology innovation systems literature to legitimize its specific focus. Third, the Triple Helix model is invoked to identify the development of connections among individual researchers, the institutions with which they are affiliated, and the scientific and engineering disciplines in which they specialize.

Battery storage R&D policy

Battery storage R&D has roots in policies targeting energy efficiency and pollution. These policies originally pushed firms to redesign their R&D programs around new technology that responded to lower emissions standards. Beginning with the Clean Air Act in 1970 and later via California's Zero-Emission Vehicle regulation, automobile companies became the hub for pollution-reduction technologies (Gerard and Lave 2005, Lee *et al* 2010, Sierzchula *et al* 2012, Bergek and Berggren 2014). This was accompanied by agreements among the European Car Manufacturing Association, the Japan Automobile Manufacturers Association, and the Korea Automobile Manufacturers Association to reduce carbon emissions. Finally, this manifested in the U.S.'s Partnership for a New Generation Vehicle that eventually led to the Toyota Prius (Bohnsack *et al* 2015). Lithium-ion battery-related research among firms in the automotive and chemical sectors, however, did not preclude the need for government intervention to support cross-sector innovation between the public (universities and GRIs) and private research sectors (von Delft 2013, Attias and Mira-Bonnardel 2017). It also did not guarantee that the output would be battery technology appropriate for a host of applications (Muller *et al* 2017, Reddy and Jung 2017).

Research funding for to improve electric vehicle battery performance was initially deficient given the DOE's ambitious battery performance goals, particularly the call for non-incremental technological improvements (Gibson *et al* 2017). In response, and reflecting the DOE's primacy in energy storage-related funding, as shown in figure 1 (U.S. Government Accountability Office 2012), the DOE's Office of Science/Basic Energy Sciences selected JCESR as its Batteries and Energy Storage Energy Innovation Hub. Specifically, JCESR was tasked with focusing on lithium-ion batteries that could provide advances in terms of performance and cost for the transportation and electricity grid sectors (Crabtree 2015a), thus addressing 'the scientific and engineering research needed to advance the next generation of electrochemical energy storage for both transportation and the grid' (U.S. Department of Energy 2013, 56). This focus on new energy storage chemistries was consistent with JCESR's '5/5/5' goal, i.e. having five times the energy density of the present battery systems at one-fifth the cost within 5 years (U.S. Department of Energy 2013). Basic research, battery design, and pathways to market are fused together at JCESR by integrating discovery science, battery design, research prototyping, and manufacturing collaboration[2]. This requires the careful and sustained promotion of Triple Helix-based linkages among vital players in the energy storage research community, namely interactions with JCESR's industrial partners, advisory committees, and regional events to address specific grid and transportation issues. The entire venture is focused on

[2] Comparable efforts include Japan's RSING and Ogumi, J.M. in France, and Supergen in the U.K.

prototyping as well as to encourage evaluations and assessments from both the scientific and industrial advisory committees.

The collaborative process at JCESR intends to integrate different forms of research and prototyping, but it also calls for periodic review of research outcomes and a strategic selection of prototype concepts (Crabtree *et al* 2015, Brushett *et al* 2016). Also, with a dual focus on both transportation and electricity grid prototypes, JCESR can benefit from economies of scale in research, i.e. aspects of next-generation lithium-ion battery technology can be applied to more than one sector. More significant for the Triple Helix paradigm, if a university or GRI-based researcher were interested in entrepreneurial activities, JCESR could provide opportunities to collaborate with firms or found new companies. In this way, JCESR is similar in function to other publicly funded R&D initiatives attempting to bridge the science-commercialization divide, such as Cooperative Research and Development Agreements (CRADAs). CRADAs ultimately increase private sector patenting and investment (Adams *et al* 2000); however, commercializable products result are not likely to result (Crow and Bozeman 1998). JCESR is also similar in content to several of the DOE's Energy Frontier Research Centers (EFRCs) focusing on battery storage research. EFRCs are distinct from Innovation Hubs in that they are less intentional in creating collaborations but focus instead on gathering together researchers in closely related disciplines (U.S. Department of Energy 2017).

What distinguishes JCESR from these other examples of the Triple Helix paradigm is its research management style. CRADAs operate in ways consistent with the affiliated GRIs' historical missions but are flexibly managed (Ham and Mowery 1998). JCESR, however, engages in research prototyping and 'science sprints', meaning that research efforts are distilled into focused 1–6 month-long projects for 5–10 collaborators (Crabtree 2015a, 2015b). Under these parameters, each sprint is closely guided and managed and incorporates a large number of graduate students and postdoctoral researchers who are required to share responsibilities as well as lead individual sprints. This management style reflects a high degree of 'publicness' of the JCESR innovation hub, i.e. the control exerted by government actors to shape the laboratory's research agenda and structure in pursuit of specific goals of innovation (Crow and Bozeman 1998), battery storage in this case.

Literature review

In the context of the Triple Helix paradigm, the relevant literature can be divided into research focusing on energy innovation policy and research focusing on R&D collaborations. Given the connections between battery storage R&D and renewable energy, there is an overarching theme of sustainability-oriented research. Underlying this literature is the assumption that public-private R&D collaboration and interdisciplinary research under the Triple Helix model result in increased avenues for transferring basic research to the market.

Battery technology innovation systems

Public-private R&D collaboration may occur without government intervention (David *et al* 2000, Scott *et al* 2001, OECD 2004), but there is a tendency for market failure in R&D, requiring corrective policies to address learning costs and to promote linkages (Lall 2000). Policies promoting the Triple Helix paradigm are thus consistent with those that promote a complex 'innovation system', i.e. the human capital, infrastructure, and investments of a particular geography, as well as their alignment to the economy (Nelson 1993, Nelson and Rosenberg 1993). One may examine innovation processes—knowledge development, knowledge diffusion, and entrepreneurialism—within a single technology and thus establish a 'technological innovation system' (Carlsson *et al* 2002, Hekkert *et al* 2007, Bergek *et al* 2008). Relevant studies of technological innovation systems have examined their dynamics with regard to the renewable energies and the electrical grid in Kenya (Hansen *et al* 2018) and the technology value chain of battery technology in Japan (Stephan *et al* 2017). There is evidence that electric vehicle R&D occurs in firms that are connected with local university-based research partners (Sarasini 2014). Deficiencies in firms' battery storage capabilities have also been studied to show that low-emission standards could have been achieved simultaneously with a bolstered knowledge base around battery technology, to which some attribute the success of the Japanese electric vehicles sector (Magnusson and Berggren 2011, Pohl and Yarime 2012, Bohnsack *et al* 2015).

The technological innovation system's contribution to specific research goals extends beyond standard measures, such as publications, patents, and invention disclosures. In the wake of advances in science and technology studies accounting for synergism, one must account for whether large scale research projects such as JCESR capitalize on synergistic opportunities. These phenomena are represented in figure 3 by the interaction of both the public and private sectors simultaneously, shown as δ_1 and δ_2, which can be compared to the non-collaborative research dynamic presented in figure 2. The overall impact between the collaborative and non-collaborative case may be measured by change in the social rate of return to research (Jones and Williams 1998), represented graphically as the difference between the sum of the outputs of figures 2 and 3. To this end, the synergies offered through the DOE's Innovation Hub provide a challenge to the standard market model of innovation

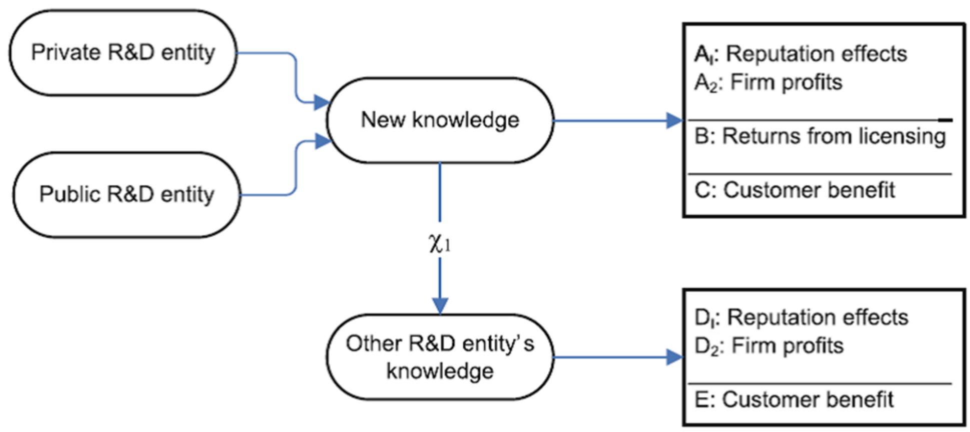

Figure 2. Returns to R&D and information channels without collaboration. Source: Shapiro (2012). © Akadémiai Kiadó, Budapest, Hungary 2011. With permission of Springer.

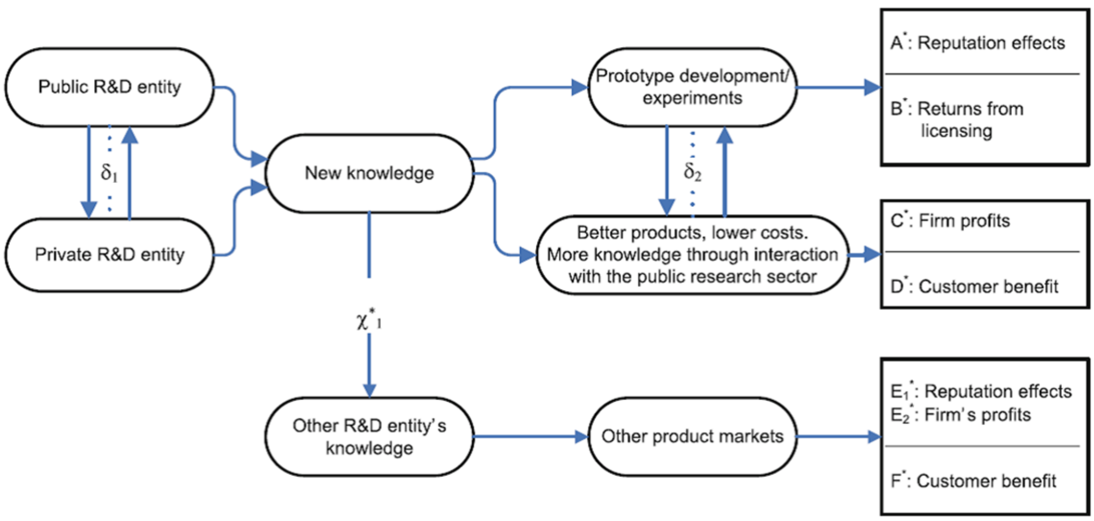

Figure 3. Returns to R&D and information channels with collaboration. Source: Shapiro (2012). © Akadémiai Kiadó, Budapest, Hungary 2011. With permission of Springer.

emphasizing the role of incumbent research institutions that may innovate initially but lack subsequent incentives (Schumpeter 2008, Sosa 2009, Buenstorf 2016).

New researchers continue to join the innovation process from the public and private research sectors given government funding, and the size or past achievements of existing innovators does not limit new entrants in the innovative pursuit. In other words, it can be claimed that large-scale projects such as the DOE's Innovation Hub limit incumbent advantage and lowers barriers to innovation through its collaborative mandate. It is thus posited that there is greater inclusion in JCESR's innovation process, representing an expanding technological innovation system surrounding lithium-ion battery research. Growth of the network could also be a function of the inherent advantages of participating in networks of learning (Powell *et al* 1996). To test for the presence of a viable technological innovation system with minimal incumbent advantage, it is hypothesized that the JCESR-based research network has increasing breadth and decreasing density, i.e. is it growing and becoming less cohesive. In light of JCESR's science sprints, also considered here is an exploratory analysis of the effects on the integrity of the JCESR research network from sub-collaborations and divisions of labor.

Interdisciplinarity

Interdisciplinarity is a crucial component of innovation (Bordons *et al* 1999, Lundvall 2001). While there is variance in how it is conceptualized (Rau *et al* 2018), interdisciplinarity contributes to sustainable research (Rau and Fahy 2013). Applying this to battery storage-related research, we can build on Trajtenberg *et al* (1997) finding that diversity of existing knowledge increases diversity of subsequent knowledge. For example, Battke *et al* (2016) argue that specialized knowledge within a particular battery technlogy increases knowledge flows within that technology but not across technologies. This was shown through an analysis of more than 42,000 battery technology-related patents issued from 1980 to 2010, specifically lead-acid, lithium-ion, and nickel battery patents. If specialization leads to more specialization in terms of battery-related knowledge, innovation hubs such as JCESR must avoid the tendency to restrict the scope of its research. Successful innovation requires increased interdisciplinarity, i.e. increases in the degree of 'diversified and peripheral knowledge', to adopt the language of Battke *et al* (2016). In this way, it is claimed that research efforts at JCESR are aligned with translational science and innovation when the disciplinary content of these efforts is expanding. Given the DOE's mandate for its battery storage innovation hub, it is hypothesized that JCESR's research has increasing breadth and decreasing density across disciplines, i.e. it is growing and becoming less cohesive.

This claim is consistent with the literature regarding technology lock-in[3]. While lock-in potential is a function of technological path-dependency (David 1985, Arthur 1989), a technology-neutral policy instrument—i.e. one that is sufficiently general in its stated objectives (Jaffe *et al* 2005)—is less likely to result in lock-in. There remains a tension between technology-neutral policy instruments and commercializability, but this can be overcome with sufficient coordination between the basic and applied segments of the technology production chain (Schmidt *et al* 2016). In other words, strategic implementation of the Triple Helix paradigm can help establish balance between technological neutrality and commercializability. In this light, the evolution of lithium ion battery technology has been described as a breakthrough in research leading to a cross-discplinary expansion of research, followed by a contraction or convergence of research, which is subsequently followed by yet another research breakthrough and cross-disciplinary expansion (Hung *et al* 2014). This model is based on an analysis of 'key-routes' or citation networks of research on a particular technology, within which JCESR may be playing a crucial role conditional on its interdisciplinarity.

Method

To address the aforementioned hypotheses and the exploratory research question, the primary method of analysis will be network analysis. Social network methods approach an S_{ij} matrix where i and j are nodes and the value between the two represents their internal relations. Invoked here is Wasserman and Faust (1994) in that various node types are analyzed: individual researchers, research institutions, and research disciplines. The primary indicators of interest from social network analysis are betweenness centrality and density, but it is also relevant to examine the groupings among nodes based on clustering algorithms, an approach well employed in research on collaborations in science (see, for example, Barabasi *et al* 2002). One could also tabulate frequencies of connections across researchers, institutions, and disciplines, but this provides ambiguous evidence regarding the nature of the larger network.

Betweenness centrality and density capture, respectively, the connectedness and cohesiveness of a network. More specifically, betweenness centrality measures how connected each node is to other nodes that are not connected to each other. In this sense, betweenness measures the extent to which a node—researcher, institution, or discipline—serves as a bridge within the battery storage-based technology innovation system (Wasserman and Faust 1994). Where reported below, betweenness is presented in absolute values. The second measure of interest, density, is measured by the total number of connections among nodes divided by the possible number of connections; e.g. $(N\,X\,(N-1))/2$ for a symmetrical matrix, where N represents the number of connections among nodes (Wasserman and Faust 1994). Density is presented in the subsequent analysis as the average of the matrix, consistent with methods employed in existing research (see, for example, Park and Leydesdorff (2009)). In this way, density represents the proximity researchers, institutions, or disciplines are to each other.

The data analyzed are based on the 346 publications sourced from the Web of Science publications database that include the text, 'Joint Center for Energy Storage Research', in the 'funding text (FT)' parameter. To assess connectedness, the nodes of the subsequent network analysis take the form of either researcher, institution, or discipline[4]. When assessing interdisciplinarity, the Web of Science's formal categories are referenced, which is consistent with Bordons *et al* (1999). Co-authorship relations in publications-based data are conventional when examining Triple Helix relationships (Wagner 2008), and citation analysis of 1,531 battery storage-related publications from 1997 to 2012 has already confirmed knowledge diffusion (Hung *et al* 2014). In the present study, however, citation analysis is eschewed given that JCESR's research is ongoing and also that there is a tendency for scientific collaboration to disproportionately increase citation impact given that larger collaborative projects utilize larger proportions of supporting material (Persson *et al* 2004). In essence, while knowledge diffusion is important for the battery storage technology innovation system, it is inferred here as arising from researcher-based, institution-based, and discipline-based networks.

Analyses of publications data tend to be exploratory, identifying patterns of collaboration, interdisciplinarity, and citations across large samples of the population of Web of Science publications (see, for example, Wagner and Leydesdorff (2005) and Olmeda-Gomez *et al* (2009)). In relative terms, the present study of JCESR's publications represents but a narrow slice of the available data on battery storage research. Nonetheless, this sample is entirely sufficient to test for the connections among researchers, institutions, and disciplines. To provide context,

[3] The classic example of technology lock-in is David's (1985) example of continued use of the QWERTY keyboard despite its identified deficiencies.
[4] Alternate spellings of researchers' and institutions' names were consolidated.

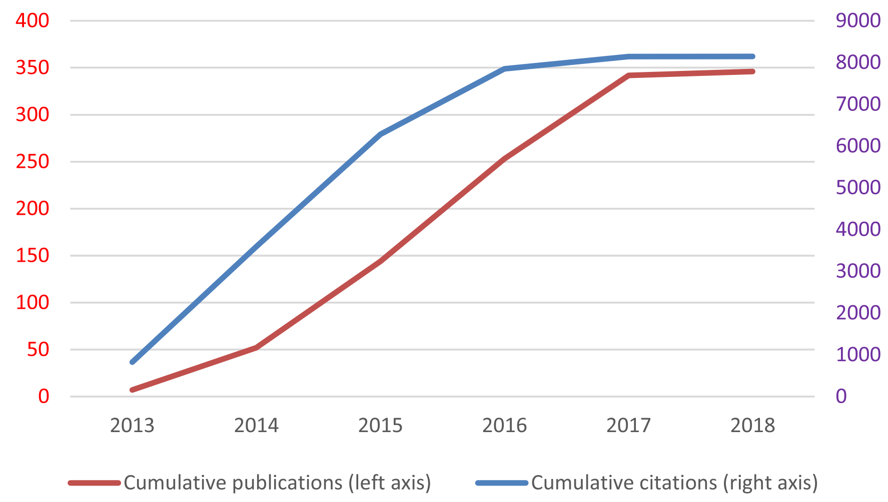

Figure 4. Cumulative counts of publications (left axis) and citations (right axis) for JCESR-funded research. Note: Publications data are based on Web of Science data from JCESR's approximate first publication in April 2013 through March 1, 2018.

Table 1. Statistics for three measures of the JCESR-based research network, 2013–2018.

Node category	Number of nodes	Total number of connections	Average geodesic distance	Density
Researcher	805	9605	3.22	0.020
Institution	136	2890	2.53	0.044
Discipline	28	2150	2.13	0.145

Note: 2018 data based on publications available in Web of Science as of March 1, 2018.

JCESR's publications output will also be compared to five EFRCs that also focus on battery storage technology: Center for Electrochemical Energy Science (CEES), Nanostructures for Electrical Energy Storage (NEES), NorthEast Center for Chemical Energy Storage (NECCES), Center for Mesoscale Transport Properties (M2M), and Fluid Interface Reactions, Structures and Transport Center (FIRST)[5].

A survey-based approach with key actors is consistent with an extensive literature attempting to understand phenomena related to R&D collaboration (Lécuyer 1998, Rahm *et al* 1999, Scott *et al* 2001, Cohen *et al* 2002). Thus, the aforementioned network analysis is coupled with survey results from a questionnaire distributed to JCESR researchers in early March 2018. Among the population of 149 current researchers at JCESR, 47 responded, which is equivalent to a 31.5% response rate. These responses provide further insight into JCESR researchers' views about research productivity, basic/applied research type, connections with firms, research commercialization potential, and degree of interdisciplinarity. It should be noted that this is the first questionnaire of its kind on the topic of government-supported battery storage research in the U.S.[6].

Results

JCESR's publications record begins in 2013 and has increased steadily over time. Both cumulative publications (left axis) and cumulative citations from those publications (right axis) are presented figure 4. Citations are reported to convey the impact of JCESR's research, the total number of which is 8,147, or 23.55 times per article. Fifteen articles have 100 or more citations, another 26 articles have 50 or more citations, and another 70 articles have 20 or more citations. In terms of individual researchers, a total of 805 people have been involved with JCESR-funded research, 259 of whom have been formally affiliated with JCESR. The implication is that approximately 68% of the researchers involved with published JCESR research are engaged via the collaborative efforts of JCESR's affiliated researchers and institutions. Among JCESR's current and alumni researchers, there are 383 total research positions, including director-level positions, scientists, lead scientists, lead technologists, thrust PIs, graduate students, and postdoctoral researchers. For those JCESR researchers contributing to the Web of Science-based sample of publications, 145 (39 scientists and 106 graduate students/postdocs) are JCESR alumni, while 114 (63 scientists and 51 graduate students/postdocs) are current affiliates of JCESR[7].

[5] Details regarding these five EFRCs can be found at the following webpage: https://science.energy.gov/bes/efrc/centers/.
[6] The exception may be Yue and Sun (2015), which is an incomplete project emphasizing government assistance and measures of research activity/defensiveness.
[7] These reflect the JCESR roster as of March 1, 2018.

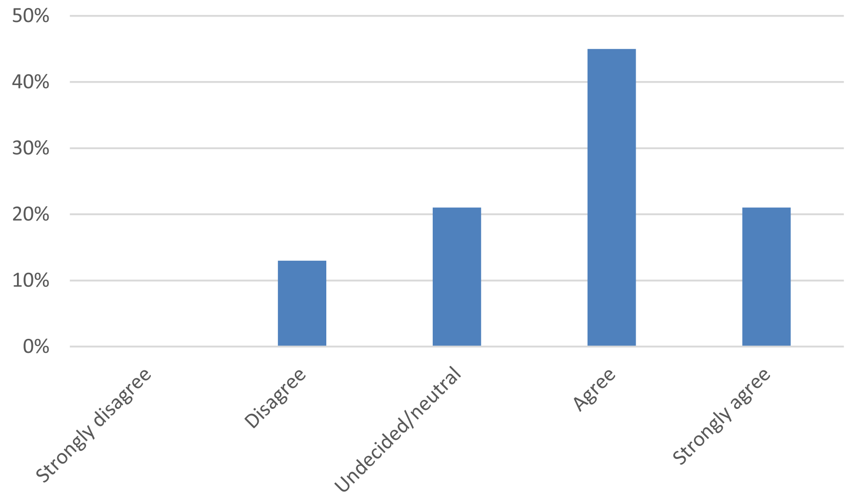

Figure 5. Distribution of responses to the following: '*My JCESR-related research exceeded my expectations in terms of productivity*'. *Do you agree with that statement?*

To test for whether the JCESR-based research network has increasing breadth and decreasing density, we refer to the first row of table 1. For the 805 researchers involved with JCESR's publication output, there are a total of 9,605 collaborations. Density is 0.020, and the average geodesic distance is 3.22; i.e. the average distance two researchers are separated from each other is approximately three other researchers. Longitudinal analysis of connections, distance, and density from 2013 to 2018 shows that there has been a steady pattern of outreach to new researchers. For example, the annual number of connections was 368 in 2013, 1,012 in 2014, 2,750 in 2015, 2,877 in 2016, and 2,566 in 2017. Simultaneously, density dropped from 0.047 in 2014 to 0.035 in 2017.

A closer examination of the researcher-based network helps explain why approximately 66% of researchers felt that productivity was greater than expected, a view conveyed graphically in figure 5. This will also address the exploratory research question regarding divisions of labor within the JCESR network. First, JCESR's affiliated researchers have been divided into two groups—scientists and grad students/postdocs—to examine differences in their betweenness centrality. Graphically, the network of researchers is presented in figure 6 via the Harel-Koren Fast Multiscale graph[8]. While it is common to examine network structure with force-direct graphs such as the Fruchterman-Reingold force-directed algorithm, which plots nodes more collaborative nodes near the center (Fruchterman and Reingold 1991), the Harel-Koren Fast Multiscale layout is recursively coarsened using principal components analysis (Harel and Koren 2001). These principal components are, one could argue, representations of the science sprint approach employed by JCESR. In this way, figure 6 reveals a concentration of scientists (blue) and grad students/postdocs (red) near the center of the graph, but there are also many small clusters peripheral to this central group.

Further examination of the differences between scientists and grad students/postdocs affiliated with JCESR illustrates the relative importance of each group for the overall network. In table 2, it is shown that there are researchers with exceptionally high betweenness centrality from both the scientist and grad student/postdoc groups. When distributed across the spectrum of between centrality scores, presented in figure 7, nearly 40% of grad students/postdocs have no betweenness centrality. Yet, the betweenness centrality scores of the remaining grad students/postdocs are distributed equitably. This contrasts with the concentration of JCESR scientists at the high end of the betweenness centrality scale, yielding a scientist group average of 5,410 and a median of 2,604. However, scientists and grad students/postdocs are similar at lower thresholds of betweenness centrality. For example, 33 grad students/postdocs and 31 scientists have centrality scores of 1,000 or greater. One can conclude that there is not a major imbalance between scientists and grad students/postdoc in the research network, although a small number of scientists do play a critical role in the overall network.

Shifting to the network of institutions in the JCESR-based research network, the second row of table 1 indicates that the network is comprised of 136 different institutions with 2,890 total connections, and that the network has an average geodesic distance of 2.53 and a density of 0.044. Longitudinal analysis confirms that the number of connections has increased and that density has decreased. For comparative purposes, the network of institutions across the five EFRCs reveals a total of 273 institutions[9], 1,714 total connections, an average geo-

[8] This graph is a force-directed graph with springs between nodes, where the attractive force is the number of collaborative papers, and there is an artificial repulsive force to keep the nodes from collapsing.

[9] Comparisons between JCESR and the five battery storage-oriented EFRCs was not possible for the researcher network given the absence of rosters to confirm the identity of EFRC participants.

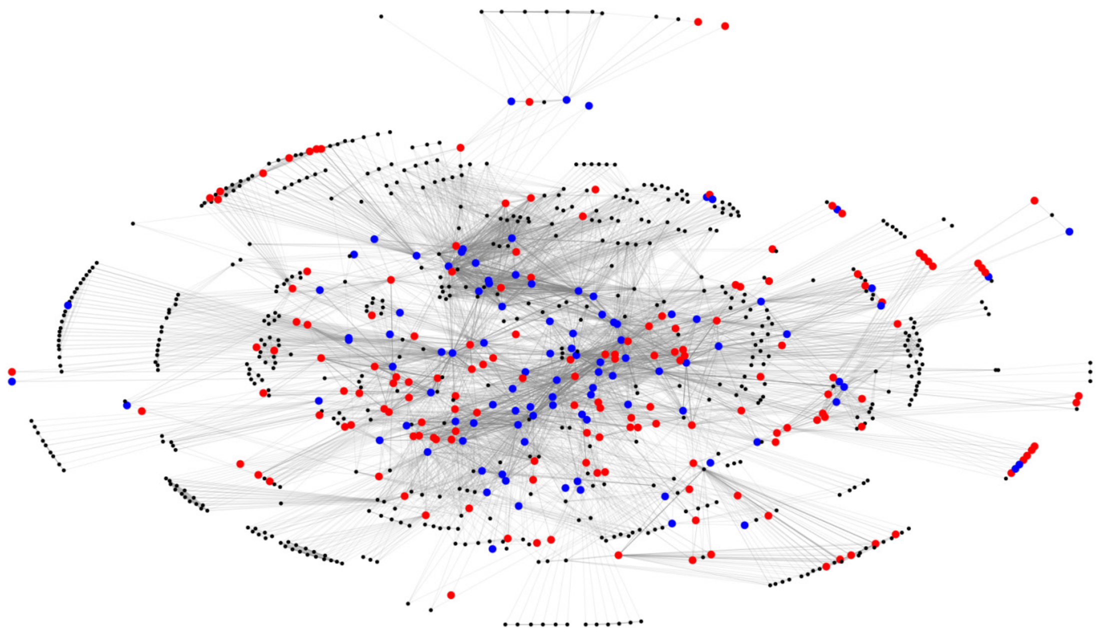

Figure 6. Harel-Koren Fast Multiscale graph of JCESR researchers, Web of Science publications. Note: Grad students/postdocs are red, scientists are blue, and all other non-JCESR researchers are black.

Table 2. Ten most-central scientists and grad student/postdocs.

	Scientist name and centrality score		Grad student/postdoc name and centrality score	
#1	Persson, Kristin	50,526.244	Rajput, Nav Nidhi	12,003.010
#2	Zavadil, Kevin	34,202.822	Feng, Zhenxing	9,259.778
#3	Curtiss, Larry	30,698.053	Thelen, Jacob L.	4,953.719
#4	Liu, Jun	25,063.874	Sevov, Christo S.	4,354.068
#5	Cabana, Jordi	24,348.845	Adams, Brian	4,291.588
#6	Moore, Jeff	22,694.627	Fan, Frank Y.	3,862.610
#7	Cui, Yi	19,595.113	Pan, Baofei	3,157.065
#8	Brushett, Fikile	18,510.660	Huang, Jinhua	3,117.160
#9	Gewirth, Andrew A.	15,453.522	Chen, Wei	3,000.568
#10	Connell, Justin G.	14,360.489	Sa, Niya	2,871.602
Total	*Average of 102 scientists*	*5,410.067*	*Average of 157 grad students/postdocs*	*663.949*

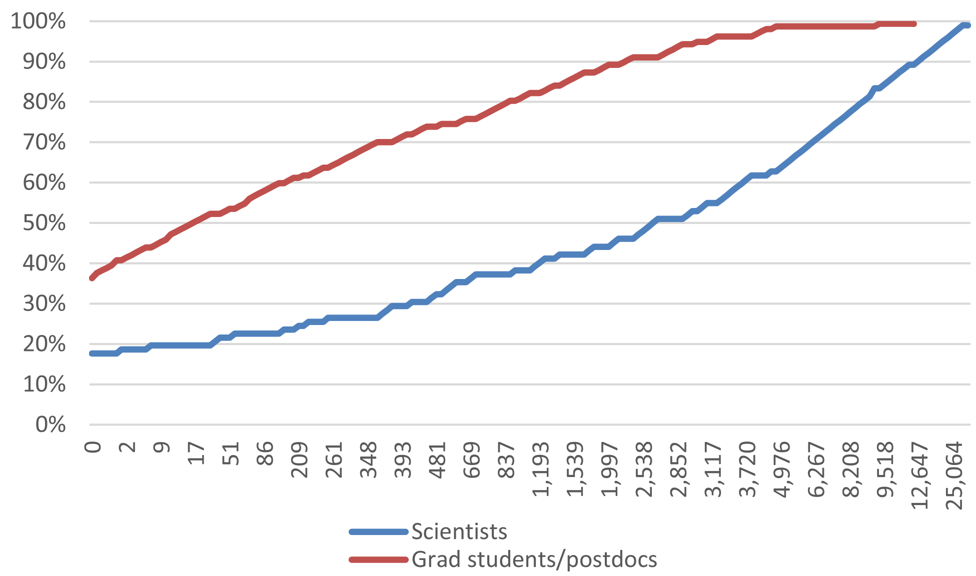

Figure 7. Distribution of betweenness centrality scores across JCESR research groups. Note: *x*-axis not linearly scaled.

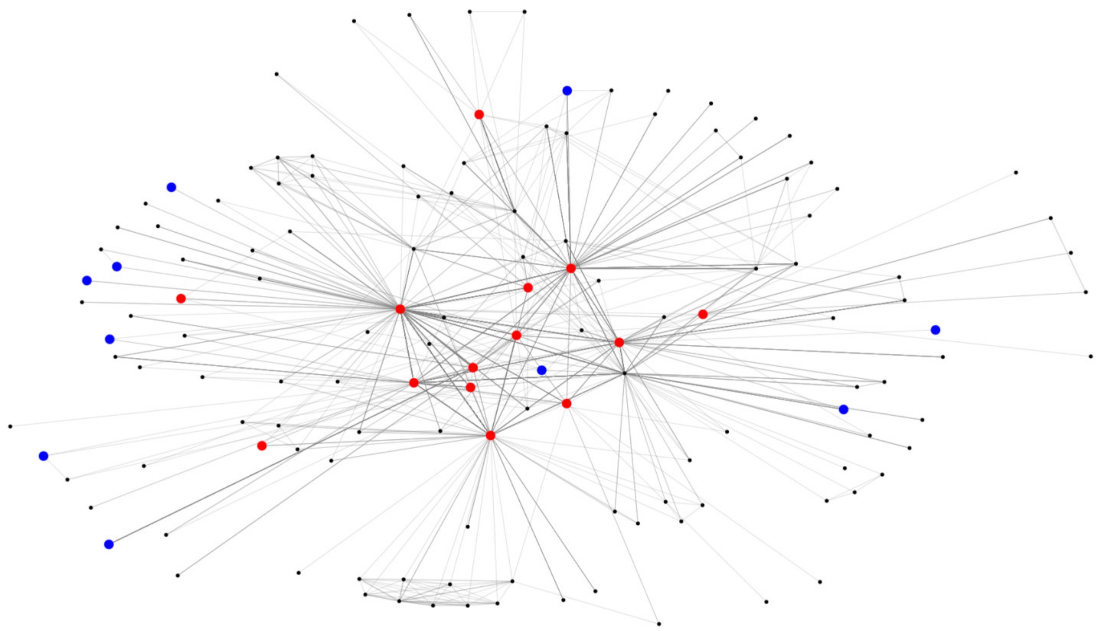

Figure 8. Harel-Koren Fast Multiscale graph of JCESR institutions, Web of Science publications. Note: JCESR institutions are red, firms are blue, and all other non-JCESR institutions are black.

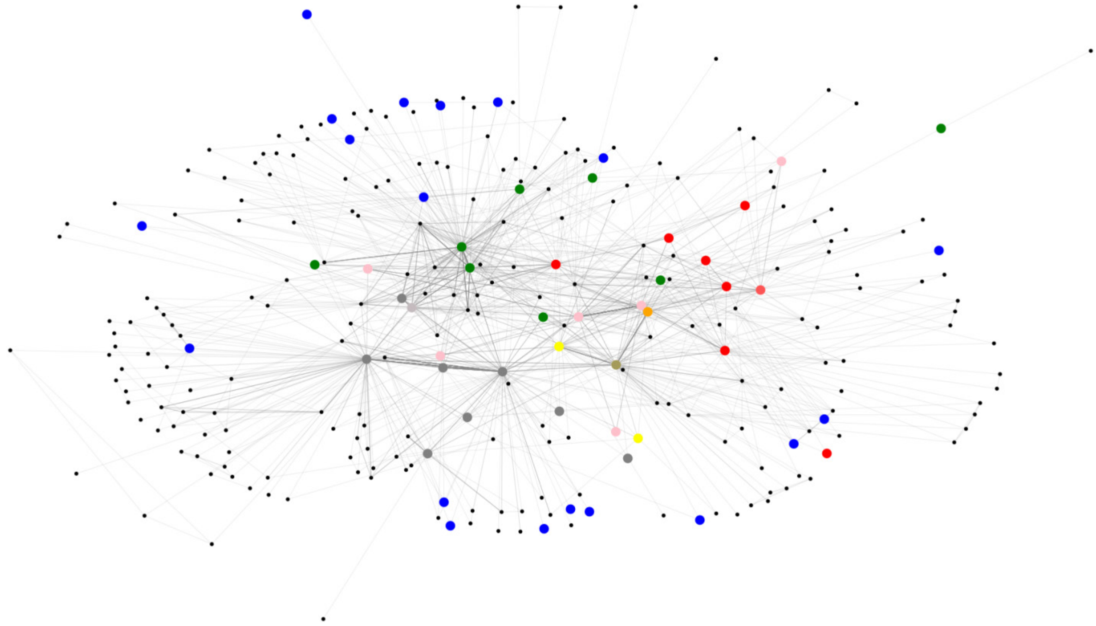

Figure 9. Harel-Koren Fast Multiscale graph of EFRC institutions, Web of Science publications. Note: Firms are blue, NECCES institutions are red, NEES institutions are green, CEES institutions are yellow, M2M institutions are pink, FIRST institutions are gray, appropriate color mixtures (Argonne National Laboratory, University of Illinois, UC Berkeley, and Georgia Tech) represent partnerships with multiple centers, and all other non-EFRC institutions are black.

desic distance of 2.70, and a density of 0.026. It is apparent that JCESR has much more intensively engaged in research collaborations. Although EFRC publications data represent the entire 2010–2018 period, as the EFRCs were established in 2009[10], collaborations are prioritized less than creating groups of researchers in closely related disciplines (U.S. Department of Energy 2017). Harel-Koren Fast Multiscale graphs of both the JCESR and EFRC institutions-based networks, presented in figures 8 and 9, respectively, indicate an imbalance between the GRIs and universities (non-blue/non-black nodes) and the firms (blue nodes). Based on the results of the questionnaire, conveyed in figures 10–12, the Triple Helix paradigm is sufficiently imbalanced to the point that commercialization is hindered. Nearly 80% of respondents classify their research as either 'completely basic' or 'more basic than applied', and nearly 90% of respondents are engaged in research in which companies are

[10] The exception is M2M, which was established in 2014.

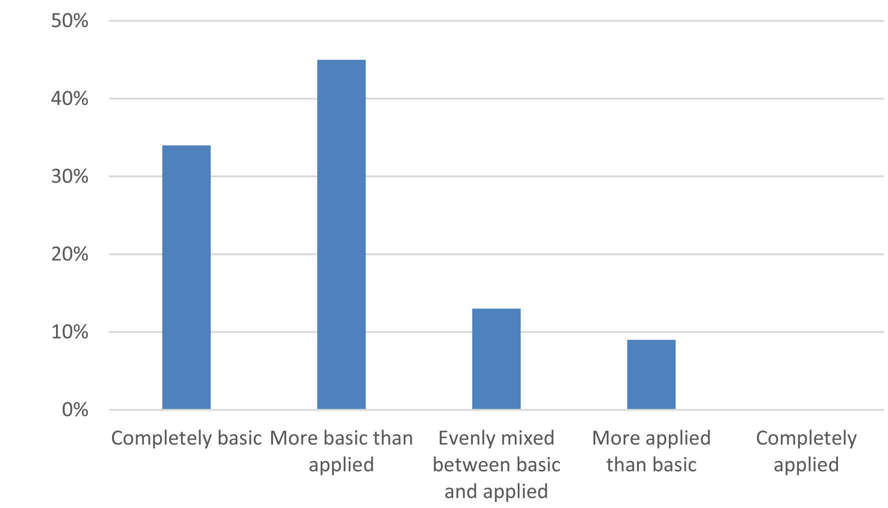

Figure 10. Distribution of responses to the following: '*Is your research for JCESR basic, applied, or somewhere in between?*'

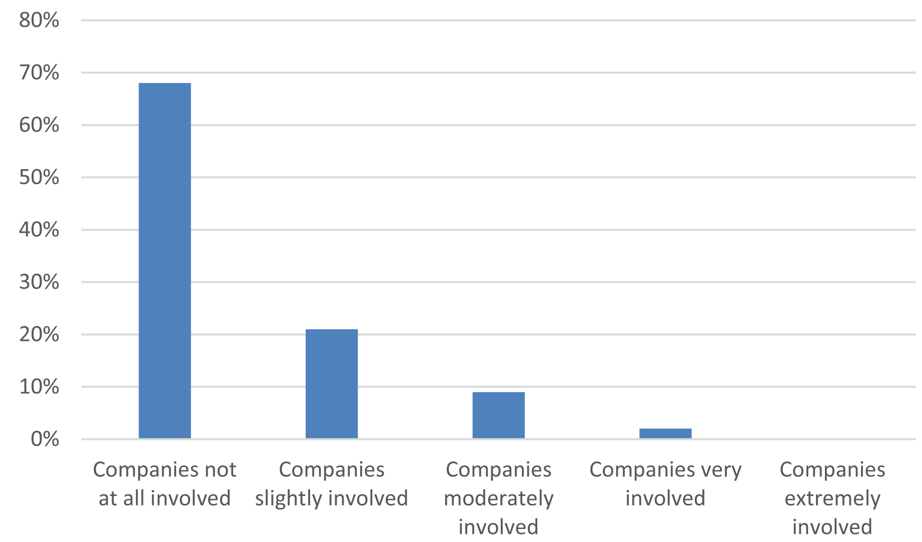

Figure 11. Distribution of responses to the following: '*Does your JCESR-related research involve private companies?*'

'not at all involved' or 'slightly involved'. Simultaneously, 53% of respondents expect that their JCESR-related research will result in a commercializable product in more than five years, and another 19% do not expect that their research will ever amount to a commercializable product[11]. The institutional networks may be strong, but JCESR's (and the EFRC's) connections to the private sector are not.

The network of disciplines arising from JCESR's publications indicates that interdisciplinarity has increased, which is a function of an increasing number of connections and a decreasing density. Aggregated metrics for the discipline-oriented network, presented in the third row of table 1, indicate that there are 28 disciplines with 2,150 total connections among them. Throughout nearly the entire duration of JCESR's publishing record, there has been a focus on physical chemistry, multidisciplinary materials science, applied physics, nanoscience and nanotechnology, multidisciplinary chemistry, condensed matter physics, energy and fuels, chemical engineering, environmental sciences, and atomic, molecular and chemical physics. From 2014, electrochemistry, coatings and films materials science, chemical engineering, environmental sciences, and green and sustainable science and technology were consistent topics. From 2015, new topics included polymer science and multidisciplinary physics, and there was also a temporary focus on metallurgy and metallurgical engineering and computer science. In 2016, new topics included analytical chemistry, biochemical research methods, nuclear science and technology, environmental engineering, and biotechnology and applied microbiology, while, in 2017, biochemistry and molecular biology, biophysics, and interdisciplinary computer science were new topics.

Overall, battery R&D is inherently interdisciplinary, and 59% of survey respondents confirmed that their research for JCESR was either 'extremely interdisciplinary' or 'very interdisciplinary'. These results are pre-

[11] These expectations regarding commercializability are consistent with the CRADA case (Crow and Bozeman 1998).

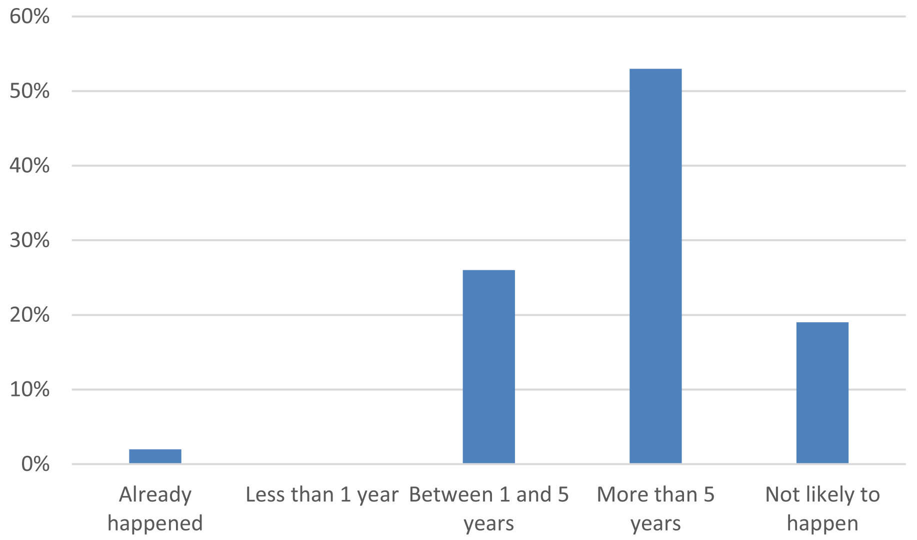

Figure 12. Distribution of responses to the following: '*When do you expect that your JCESR-related research will result in a product to be sold by a company?*'

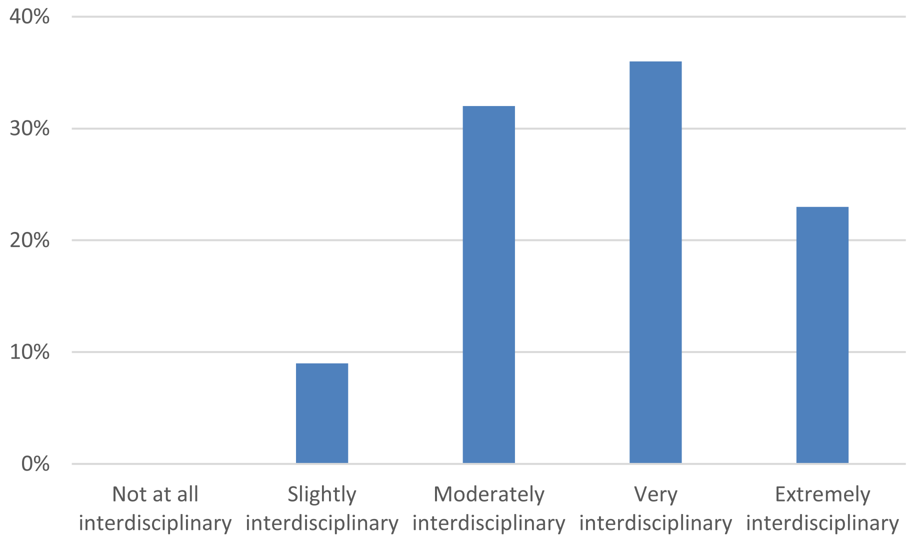

Figure 13. Distribution of responses to the following: '*Is your JCESR-related research interdisciplinary?*'

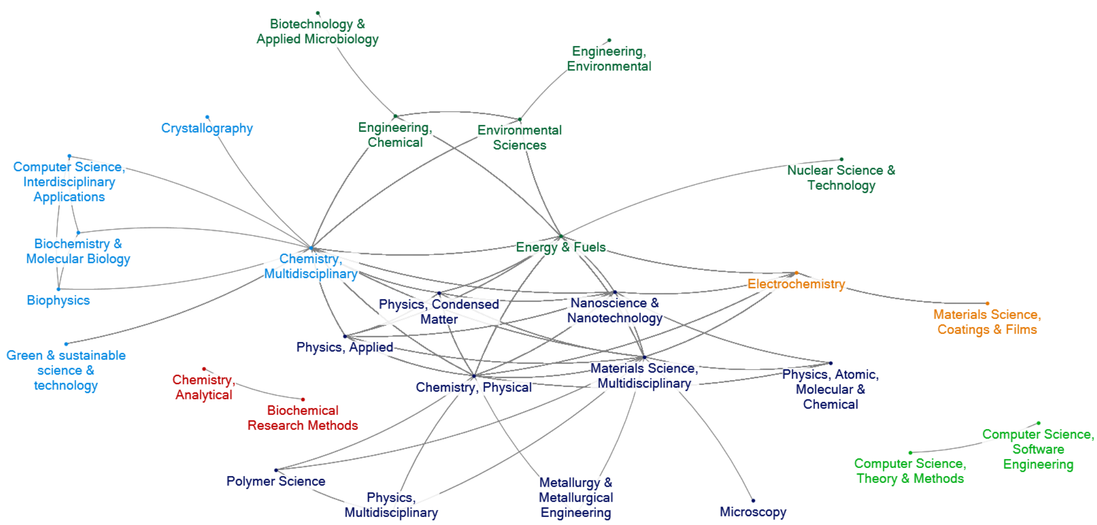

Figure 14. Harel-Koren Fast Multiscale graph of JCESR disciplines, Web of Science publications. Note: Colors represent communities within the network as determined by the Clauset-Newman-Moore algorithm (Clauset *et al* 2004).

sented in figure 13. Another 32% viewed their JCESR-related research as being 'moderately interdisciplinary'. Overall, and visually conveyed in the Harel-Koren Fast Multiscale graph of figure 14[12], electrochemistry is the central activity, embedded in materials science, chemistry, coatings and films, computer science, and energy and fuels. There is very little bioscience-related research, although the organic molecules dealt with in liquid organic electrolytes have biological relatives. For this reason, biophysics and biochemistry and molecular biology are not central to JCESR's research and arose only through publications in 2017. Similarly, while there are environmental implications for some of the materials explored through JCESR-related research, environmental science and environmental engineering serve only complementary functions to multidisciplinary chemistry and energy and fuels. These patterns, however, represent important expansions of JCESR's disciplinary network.

Conclusion

This paper has presented a structural analysis of JCESR's partnerships based on its publications record in an attempt to provide evidence of the Triple Helix paradigm in battery storage research. Over time, it can be observed that a relatively small network has transformed into a large one that encompasses universities, GRIs, and firms that are oriented around battery storage R&D. There is no single dominating institution, but there are dominating collaborations. There is also evidence that the public sector (i.e. GRIs and universities) is emphasized over the private sector. Further, JCESR is unique in its ability to leverage the strengths of both its senior scientists as well as its graduate students and postdoctoral researchers. Sub-collaborations and divisions of labor within and beyond the JCESR network have corresponded with greater opportunities for JCESR researchers to collaborate with non-JCESR researchers, to deny the incumbent advantage, and to tap into synergies across individual researchers, institutions, and disciplines.

There are two broad caveats to this project. First, by examining only the publications record and not the patenting and licensing record of JCESR-based research output, it must be acknowledged that this study engaged in a formal but one-sided analysis of JCESR's impact. The collaborations arising through the generation of patents as well as the knowledge that has diffused from such patents have been ignored. This omission, however, was deliberate, reflecting the significantly fewer number of patents available for analysis. Future analyses of the translational nature of JCESR's work—or next generation battery storage R&D broadly defined—can integrate patents. Indeed, that aspect of JCESR's output may reveal a very different view of JCESR's applied research and commercialization foci. Second, this research project draws attention to the challenges of applying the Triple Helix paradigm to relatively underdeveloped fields that rely much more on basic research efforts. While it is true that the Triple Helix relies on government-university-firm connections, it has been shown here that JCESR is predominantly centered on GRIs and universities. In the case of battery storage technology, we are not yet at the point where the three pillars of the Triple Helix are fully activated given the emphasis on basic and basic/applied research.

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References

Adams J D, Chiang E P and Jensen J L 2000 The influence of federal laboratory R&D on industrial research *Rev. Econ. Stat.* **85** 1003–20
Arthur W B 1989 Competing technologies, increasing returns, and lock-in by historical events *Econ. J.* **99** 116–31
Attias D and Mira-Bonnardel S 2017 Extending the scope of partnerships in the automotive industry between competition and cooperation *The Automobile Revolution* ed D Attias (Berlin: Springer)
Barabasi A L, Jeong H, Neda Z, Ravasz E, Schubert A and Vicsek T 2002 Evolution of the social network of scientific collaborations *Physica* A **311** 590–614
Barbose G 2017 U.S. Renewables Portfolio Standards *LBNL Report Number* LBNL-2001031 Lawrence Berkeley National Laboratory
Battke B and Schmidt T S 2015 Cost-efficient demand-pull policies for multi-purpose technologies: the case of stationary electricity storage *Appl. Energy* **155** 334–48
Battke B, Schmidt T S, Stollenwerk S and Hoffmann V H 2016 Internal or external spillovers—which kind of knowledge is more likely to flow within or across technologies *Res. Policy* **45** 27–41

[12] Colors in figure 14 represent groups within the network as determined by the Clauset-Newman-Moore grouping algorithm (Clauset *et al* 2004).

Bergek A and Berggren C 2014 The impact of environmental policy instruments on innovation: a review of energy and automotive industry studies *Ecol. Econ.* **106** 112–23

Bergek A, Jacobsson S, Carlsson B, Lindmark S and Rickne A 2008 Analyzing the functional dynamics of technological innovation systems: a scheme of analysis *Res. Policy* **37** 407–29

Bohnsack R, Kolk A and Pintske J 2015 Catching recurring-wages: low-emission vehicles, internatioanl policy developments and firm innovation strategies *Technol. Forecast. Social Change Social Change* **98** 71–87

Bordons M, Zulueta M A, Romero F and Barrigon S 1999 Measuring interdisciplinary collaboration within a university: the effects of the multidisciplinary research programme *Scientometrics* **46** 383–98

Brushett F R, Trahey L and Hodge D 2016 The Joint Center for Energy Storage Research: integration of research, development, and demonstration *ECS Meeting Abstracts, MA2016-02 1740*

Buenstorf G 2016 Schumpeterian incumbents and industry evolution *J. Evolutionary Econ.* **26** 823–36

California Public Utilities Commission 2013 CPUC sets energy storage goals for utilities [Press release] (http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M079/K171/79171502.PDF)

Carlsson B, Jacobsson S, Holmen M and Rickne A 2002 Innovation systems: analytical and methodological issues *Res. Policy* **31** 233–45

Clauset A, Newman M E J and Moore C 2004 Finding community structure in very large networks *Phys. Rev.* E **70** 1–6

Cohen W M, Nelson R R and Walsh J P 2002 Links and impacts: the influence of public research on industrial R&D *Manage. Sci.* **48** 1–23

Crabtree G 2015a The Joint Center for Energy Storage Research: a new paradigm for battery research and development *AIP Conf. Proc.* **1652** 112–28

Crabtree G 2015b Written statement of george crabtree before the subcommittee on energy

Crabtree G, Kocs E and Trahey L 2015 The energy-storage frontier: lithium-ion batteries and beyond *MRS Bull.* **40** 1067–76

Crow M and Bozeman B 1998 *Limited by Design: R&D Laboratories in the U.S. National Innovation System* (New York: Columbia University Press)

David P A 1985 Clio and the economics of QWERTY *Am. Econ. Rev.* **75** 332–7

David P A, Hall B H and Toole A A 2000 Is public R&D a complement or substitute for private R&D? A review of the econometric evidence *Res. Policy* **29** 497–529

Etzkowitz H 2003 Innovation in innovation: the Triple Helix of university-industry-government relations *Social Sci. Inf.* **42** 293–337

Etzkowitz H 2008 *Triple Helix Innovation: Industry, University, and Government in Action* (London: Routledge)

Etzkowitz H and Leydesdorff L 2000 The dynamics of innovation: from national systems and 'mode 2' to a Triple Helix of university-industry-government relations *Res. Policy* **29** 109–23

Fruchterman T M J and Reingold E M 1991 Graph drawing by force-directed placement *Software Pract. Exp.* **21** 1129–64

Gerard D and Lave L B 2005 Implementing technology-forcing policies: the 1970 Clean air act amendments and the introduction of advanced automotive emissions controls in the United States *Technol. Forecast. Social Change* **72** 761–78

Gibson E, van Blommestein K, Kim J, Daim T and Garces E 2017 Forecasting the electric transformation in transportation: the role of battery technology performance *Technol. Anal. Strateg. Manage.* **29** 1103–20

Ham R M and Mowery D C 1998 Improving the effectiveness of public–private R&D collaboration: case studies at a US Weapons Laboratory *Res. Policy* **26** 661–75

Hansen U E, Gregersen C, Lema R, Samoita D and Wandera F 2018 Technological Shape and size: a disaggregated perspective on sectoral innovation systems in renewwable electrification pathways *Energy Res. Social Sci.* **42** 13–22

Harel D and Koren Y 2001 A fast multi-scale algorithm for drawing large graphs *Graph Drawing* ed J Marks (Heidelberg: Springer)

Hekkert M P, Suurs R A A, Negro S, Kuhlmann S and Smits R E H M 2007 Functions of innovation systems: a new approach for analysing technological change *Technol. Forecast. Social Change* **74** 413–32

Hung S-C, Liu J S, Lu L Y Y and Tseng Y-C 2014 Technological change in lithium iron phosphate battery: the key-route main path analysis *Scientometrics* **100** 97–120

Jaffe A B, Newell R G and Stavins R N 2005 A tale of two market failures: technology and environmental policy *Ecol. Econ.* **54** 164–74

Jones C I and Williams J C 1998 Measuring the social return to R&D *Q. J. Econ.* **113** 1119–35

Kaschub T, Jochem P and Fichtner W 2014 Effects of integrating electric vehicles and stationary batteries in a smart urban electricity network *European Electric Vehicle Congress*

Lall S 2000 Technological change and industrialization in the Asian newly industrializing economies: achievements and challenges *Technology, Learning and Innovation: Experiences of Newly Industrializing Economies* ed L Kim and R R Nelson (Cambridge: Cambridge University Press)

Lécuyer C 1998 Academic science and technology in the service of industry: MIT creates a 'permeable' engineering school *AEA Papers and Proc.: Clio and the Economic Organization of Science* vol 88 pp 28–33

Lee J, Veloso F M, Hounshell D A and Rubin E S 2010 Forcing technological change: a case of automobile emissions control technology development in the U.S. *Technovation* **30** 249–64

Leydesdorff L 2006 The knowledge-based economy and the Triple Helix model *Understanding the Dynamics of a Knowledge Economy* ed W Dolfsma and L Soete (Cheltenham: Edward Elgar)

Lundvall B A 2001 Innovation policy in the globalizing learning economy *The Globalizing Learning Economy* ed D Archibugi and D Lundvall (Oxford: Oxford University Press)

Magnusson T and Berggren C 2011 Entering an era of ferment—radical versus incrementalist strategies in automotive power train development *Technol. Anal. Strateg. Manage.* **23** 313–30

Maloney P 2017 California PUC finalizes new 500 MW BTM battery storage mandate *Utility Dive* (www.utilitydive.com/news/california-puc-finalizes-new-500-mw-btm-battery-storage-mandate/441901)

Muller M, Viernstein L, Truong C N, Eiting A, Hesse H C, Witzmann R and Jossen A 2017 Evaluation of grid-level adaptability for stationary battery energy storage system applications in Europe *J. Energy Storage* **9** 1–11

Nelson R R 1993 *National Innovation Systems: a Comparative Analysis* (Oxford: Oxford University Press)

Nelson R R and Rosenberg N 1993 Technical innovation and national systems *National Innovation Systems: a Comparative Analysis* ed R R Nelson (New York: Oxford University Press)

OECD 2004 *OECD Science, Technology and Industry Outlook 2004* (Paris, Washington, DC: OECD)

Olmeda-Gomez C, Perianes-Rodriguez A, Ovalle-Perandones M A, Guerrero-Bote V P and de Moya Anegon F 2009 Visualization of scientific co-authorship in spanish universities: from regionalization to internationalization *Aslib Proc.* **61** 83–100

Park H W and Leydesdorff L 2009 Knowledge linkage structures in communication studies using citation analysis among communication journals *Scientometrics* **81** 157–75

Persson O, Glanzel W and Danell R 2004 Inflationary bibliometric values: the role of scientific collaboration and the need for relative indicators in evaluative studies *Scientometrics* **60** 421–32

Pohl H and Yarime M 2012 Integrating innovation system and management concepts: the development of electric and hybrid electric vehicles in Japan *Technol. Forecast. Social Change* **79** 1431–46

Powell W W, Koput K W and Smith-Doerr L 1996 Interorganizational collaboration and the locus of innovation: networks of learning in biotechnology *Adm. Sci. Q.* **41** 116–45

Rahm D, Kirkland J and Bozeman B 1999 *University-Industry R&D Collaboration in the United States, the United Kingdom, and Japan* (Netherlands: Kluwer)

Rau H and Fahy F 2013 Sustainability research in the social sciences: concepts, methodologies and the challenge of interdisciplinarity *Methods of Sustainability Research in the Social Sciences* ed F Fahy and H Rau (Thousand Oaks: Sage)

Rau H, Goggins G and Fahy F 2018 From invisibility to impact: recognizing the scientific and societal relevance of interdisciplinary sustainability research *Res. Policy* **47** 266–76

Reddy S S and Jung C-M 2017 Overview of energy storage technologies: a techno-economic comparison *Int. J. Appl. Eng. Res.* **12** 12872–79

Sarasini S 2014 Electrifying the automotive industry: the geography and governance of R&D collaboration *Environ. Innov. Societal Transit.* **13** 109–28

Schmidt T S, Battke B, Grosspietsch D and Hoffmann V H 2016 Do deployment policies pick technologies by (not) picking applications? A simulation of investment decisions in technologies with multiple applications *Res. Policy* **45** 1965–83

Schumpeter J A 2008 *Capitalism, Socialism and Democracy* (New York: Harper Perennial Modern Thought)

Scott A, Steyn G, Guena A, Brusoni S and Steinmueller E 2001 The economic returns to basic research and the benefits of university-industry relationships: a literature review and update of findings *A Report Commissioned by the OST-DTI, SPRU* University of Sussex, Brighton

Shapiro M A 2012 Receiving information at Korean and Taiwanese Universities, industry, and GRIs *Scientometrics* **90** 289–309

Sierzchula W, Bakker S, Maat K and van Wee B 2012 Technological diversity of emerging eco-innovations: a case study of the automobile industry *J. Cleaner Prod.* **37** 211–20

Sosa M L 2009 Application-specific R&D capabilities and the advantage of incumbents: evidence from the anticancer drug market *Manage. Sci.* **55** 1409–22

Stephan A, Schmidt T S, Bening C R and Hoffmann V H 2017 The sectoral configuration of technological innovation systems: patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan *Res. Policy* **46** 709–23

Trajtenberg M, Henderson R and Jaffe A 1997 University versus corporate patents: a window on the basicness of invention *Econ. Innov. New Technol.* **5** 19–50

U.S. Department of Energy 2013 Grid energy storage (https://energy.gov/sites/prod/files/2014/09/f18/Grid%20Energy%20Storage%20December%202013.pdf)

U.S. Department of Energy 2017 Energy innovation portfolio plan FY2018–FY2012 (https://energy.gov/sites/prod/files/2017/01/f34/DOE%20Energy%20Innovation%20Portfolio%20Plan%20FY%202018-22_0.pdf)

U.S. Energy Information Administration 2017 Electricity explained www.eia.gov/energyexplained/index.cfm

U.S. Government Accountability Office 2012 Batteries and energy storage: federal initiatives supported similar technologies and goals but had key differences (U.S. Government Accountability Office) (www.gao.gov/assets/650/647742.pdf)

von Delft S 2013 Inter-industry innovations in terms of electric mobility: should firms take a look outside their industry? *J. Bus. Chem.* **10** 67–87

Wagner C S 2008 *The New Invisible College* (Washington, DC: Brookings Institution)

Wagner C S and Leydesdorff L 2005 Network structure, self-organization, and the growth of international collaboration in science *Res. Policy* **34** 1608–18

Wasserman S and Faust K 1994 *Social Network Analysis: Methods and Applications* (New York: Cambridge University Press)

Yue X and Sun G 2015 Influence of government supports on technology innovation process: the case of Li-ion battery in the United States *Int. Association for Management of Technology 2015 Conf. Proc.*

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