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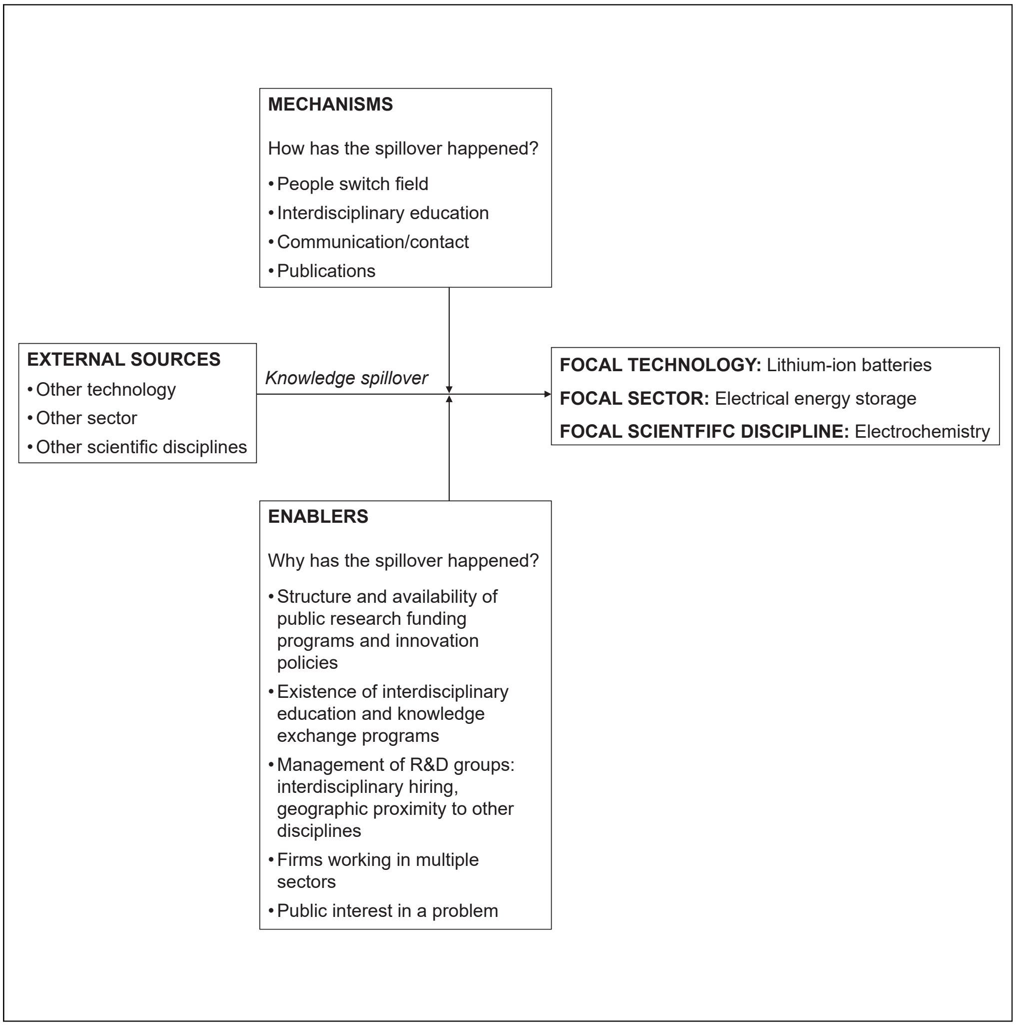

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HIGHLIGHTS

We study how spillovers in important LIB innovations come about

Important LIB innovations have benefitted from spillovers from a variety of sources

We identify mechanisms and enablers underlying spillovers in (LIB) innovation

We identify factors that might affect future (LIB) R&D and spillovers

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How has external knowledge contributed to lithium-ion batteries for the energy transition?

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SUMMARY

Innovation in clean-energy technologies is central toward a net-zero energy system. One key determinant of technological innovation is the integration of external knowledge, i.e., knowledge spillovers. However, extant work does not explain how individual spillovers come about: the mechanisms and enablers of these spillovers. We ask how knowledge from other technologies, sectors, or scientific disciplines is integrated into the innovation process in an important technology for a net-zero future: lithium-ion batteries (LIBs), based on a qualitative case study using extant literature and an elite interview campaign with key inventors in the LIB field and R&D/industry experts. We identify the breakthrough innovations in LIBs, discuss the extent to which breakthrough innovations—plus a few others—have resulted from spillovers, and identify different mechanisms and enablers underlying these spillovers, which can be leveraged by policymakers and R&D managers who are interested in facilitating spillovers in LIBs and other clean-energy technologies.

INTRODUCTION

Innovation in clean-energy technologies (IEA, 2015), and specifically energy storage technologies such as batteries (REN 21, 2017), is central to future carbon-neutral energy systems. Given the urgency of climate-change mitigation, policymakers and R&D managers aim to advance innovation in this field (ARPA-E, 2018). Innovation policy and the corresponding national institutions have traditionally focused on funding particular technologies (through the work of the applied R&D offices of the US Department of Energy, DOE, to use the United States as an example) or funding scientific research more broadly (through the work of the US National Science Foundation, to continue with the U.S. example). However, despite some relatively recent exceptions, such as the Energy Frontier Research Centers at the DOE (Anadón, 2012) or Catapults in the United Kingdom (Catapult, 2019), which purposefully aim to bring together different disciplines to solve particular problems, public R&D funding and institutions have rarely acknowledged that technological innovation can sometimes happen by building bridges between different technologies, sectors, and scientific disciplines (Arthur, 2009; Narayanamurti and Odumosu, 2016).

Why are there so few mechanisms for spanning different domains in national innovation policy in general, and in energy innovation policy in particular? A partial reason is the lack of research: although many scholars have underscored the need to invest more funds in energy R&D in general, in particular in the United States and the European Union (Anadon et al., 2014; Anadón et al., 2017; Bosetti and Tavoni, 2009; President's Council of Advisors on Science and Technology, 2010; Kammen and Nemet, 2005; Schock et al., 1999), there has been less research on how such funds can be invested most effectively in terms of institutional design. Scholars in the energy field have recently started to move from the "how much" to the "how" (Acemoglu et al., 2016; Anadon et al., 2016a; Chan, 2015; Howell, 2017; National Academies of Science Engineering and Medicine, 2017), whereas the role of external knowledge, i.e., spillovers, for technological innovation has typically been overlooked.

This is surprising given the fact that spillovers can substantially advance technological innovation (Mowery and Rosenberg, 1998; Scherer, 1982a, 1982b, 1984; Schmookler, 1966) has been shown empirically for innovations in the fields of clean energy (Huenteler et al., 2016a; Nemet, 2012), energy storage (Noailly and Shestalova, 2017), and (lithium-ion) batteries (Battke et al., 2016; Stephan et al., 2019). Recent work has even suggested to use spillovers to hedge against the potential risk of technological lock-in of lithium-ion batteries (LIBs) (Beuse et al., 2020). However, these empirical studies rely on econometric

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analyses of large sets of patent citations and therefore focus on general patterns of innovation (i.e., "what" has happened on an aggregated level). They make no attempt to explain "how" individual spillovers come about. Our understanding of technological innovation follows B. Arthur's broad definition of "novelty in technology" (Arthur, 2009). More specifically, for us, innovation includes advances in both products and processes throughout the entire technology life cycle. We thus follow previous research that goes beyond the Schumpeterian understanding (Schumpeter, 1942) by building on an interactive model of the innovation process (Kline and Rosenberg, 1986) and applying a systemic perspective (Anadon et al., 2016b). Our understanding of spillovers encompasses unintentional (Griliches, 1979; Jaffe, 1986), involuntary (Hoppmann, 2016), intentional (de Jong and von Hippel, 2009), and strategic (Harhoff, 1996) transfers of knowledge to a technology from external sources such as other technologies, sectors, or scientific disciplines. Moreover, all these types of transfer can occur via a range of different channels (Wang et al., 2017).

In this article, we look "inside the black box of technological innovations" (Rosenberg, 2008) by investigating how knowledge from other technologies, sectors, or scientific disciplines is integrated into the innovation process. Besides benefitting public policy, a better understanding of how spillovers come about could also increase the efficacy of public research organizations such as national laboratories or universities. These organizations have to manage their research processes carefully to create innovation most effectively (Anadon et al., 2016a). Recent developments in organizations' R&D strategies—such as open innovation concepts (Bogers et al., 2017)—further demonstrate that sourcing external knowledge is crucial for innovation.

Specifically, we focus on secondary (rechargeable) LIBs for three main reasons. First, due to their ability to serve energy and power requirements (Dunn et al., 2011), LIBs can cope with the requirements of both a decarbonized electricity system (Battke et al., 2013; Crabtree, 2019; IEA, 2015) and the electrification of transportation (Crabtree, 2019; Dunn et al., 2011; IEA, 2019; Lowe et al., 2010); (lithium-ion) batteries can even become the critical element toward widespread electric vehicle diffusion, and innovating countries might benefit from economic and geopolitical benefits (Crabtree, 2019). This potential dual role, together with the need for further innovations in this field (Crabtree, 2019; Sivaram et al., 2018; Trahey et al., 2020)—especially to overcome barriers to high electric vehicle market shares (Deng et al., 2020)—and potential economic and geopolitical benefits for innovating countries (Crabtree, 2019), underpins the interest of many policymakers in fostering LIB technology development (IEA, 2019; REN21, 2016). Second, previous research has indicated that innovations in LIBs have extensively built upon external knowledge, which has been measured by patent citations across technologies (Battke et al., 2016; Clausdeinken, 2016). Finally, LIBs have made substantial technological and economic progress in the last few decades (Crabtree et al., 2015; Winter et al., 2018): they make up more than half of the world's stationary electricity storage projects (Malhotra et al., 2016), have "significantly changed our lives in the 21st century" (Winter et al., 2018) and allowed to enter a new age (Stephan, 2019), and have resulted in the award of the Nobel Prize in Chemistry in 2019 (NobelPrize.org, 2019). While the history of LIBs has been told in detail (Crabtree et al., 2015; Winter et al., 2018; Xie and Lu, 2020), the ultimate goal of this article is to gain a deeper understanding of the mechanisms and enablers that allow a spillover to take place.

This article complements the extant quantitative work by conducting a qualitative case study to allow us to understand *how* (Yin, 2009) the integration of external knowledge happened. Our analysis draws on two data sources: literature research and semi-structured elite interviews with key actors in the LIB field, i.e., R&D and industry authorities/experts and well-known senior-level inventors of LIB innovations. Elite interviews are an essential and rigorous method for process tracing (Tansey, 2007), and they are the most suitable method for identifying causal mechanisms (George and Bennett, 2005) and are widely used for this purpose in the social sciences. We spoke to ten interviewees, half of whom were inventors and half were R&D and industry authorities/experts, including two Nobel laureates.

We focused on key breakthrough innovations, which took place during the early stages of the development of LIBs, complemented by findings from additional and more recent commercialized innovations. In doing so, we ensure relevance to the future evolution of the LIB field, and also cover a variety of innovations and potential spillover sources, mechanisms, and enablers that made it possible to inductively develop a framework for analyzing spillovers. The starting point of our analysis is the year 1970, which is when a first pathway for rechargeable LIBs at room temperature was established (Crabtree et al., 2015). We considered knowledge to be external—i.e., we identified spillovers—if it was developed for application in other technologies, sectors, or scientific disciplines. Hence, we identified a spillover if the transferred knowledge was not developed for LIBs (technology); if it was not related to the development, production, and use of electrical energy storage (sector); or if it originated from a scientific discipline other than ''electrochemistry.'' Spillovers between countries (Jaffe and Trajtenberg, 1999), regions (Jaffe et al., 1993; Maurseth and Verspagen, 2002), and firms (Henderson and Cockburn, 1996) have already been widely investigated, and are beyond the scope of this article. More details on our methodological approach can be found in the Transparent Methods.

RESULTS

LIB history and key breakthroughs

Many LIB innovations, including the breakthroughs, have benefitted from and been built upon work carried out by many researchers in academia and industry. Here, we focus on the breakthrough LIB innovations identified in our elite interviews and briefly introduce them as part of the historical context of innovations in LIB. The aim is to enable a better understanding of the spillovers discussed in the subsequent sections, which is the focus of this article. We would like to refer the interested reader to extant work on the history of LIBs (Blomgren, 2017; Crabtree et al., 2015; Scrosati, 2011; Winter et al., 2018; Xie and Lu, 2020; Yoshio et al., 2009) for more details and a broader account of the numerous innovations and the researchers involved. Since the 1970s, research into new generations of rechargeable batteries has gained rising interest, triggered by—among other causes—the oil crisis, which led to widespread international searching for alternative power sources to fossil fuels (Thackeray, 2020; Winter et al., 2018). Although other types of batteries such as sodium sulfur (NaS) batteries were also investigated—by the Ford Motor Company, for example—LIBs attracted interest for their potentially favorable properties, such as high cell voltage, energy density, and cycle capacity (Dunn et al., 2011). However, LIBs were only commercialized successfully for the first time in 1991 by Sony, after several attempts by other companies that failed due to safety and/or life cycle issues (Crabtree et al., 2015; Winter et al., 2018), directly followed by A&T Battery, a joint venture of Asahi Kasei and Toshiba in 1992 (Yoshio et al., 2009).

Since the mid-1990s, battery manufacturers have built upon four breakthrough ideas that had emerged over the previous 20 years of research (reference numbers for the interviewees who provided confirmation are given in brackets): the mechanism of *electrochemical intercalation* (I1, I2, I3, I4, I9); *lithium cobalt oxide, $LiCoO_2$ (LCO),* as a cathode material (I1, I2, I3, I6, I9), *graphite* as an anode material (I1, I2, I3, I4, I6, I9); and an *ethylene carbonate*-based electrolyte (I1, I3, I5, I6, I7, I9). A schematic illustration of the basic functioning of LIBs can be found in Figure S1.

Electrochemical intercalation—i.e., the insertion and extraction (i.e., reversible intercalation) of ions into another material without destroying the cathode structure—into a TiS_2 cathode can be attributed to the pioneering work of Stanley Whittingham and his colleagues, then working at Exxon, in the early 1970s (Crabtree et al., 2015; Whittingham, 1974, 2012). In 1980, John Goodenough and his colleagues built on this mechanism and discovered *LCO* as a highly energy-dense cathode material (Mizushima et al., 1980). Successful commercialization would not have been possible without discovering the reversible intercalation of lithium in carbon materials, whereof *graphite* has become standard today (Crabtree et al., 2015). Although several researchers (had) worked on graphite intercalation at that time (Besenhard and Fritz, 1983), the patent by Samar Basu (Basu, 1983) and the article by Rachid Yazami and Philippe Touzain (Yazami and Touzain, 1983) are two of the pioneering works that paved the way for the use of graphite. Since the early 1980s, intercalating carbon materials have been used as anodes, and—together with intercalating cathode materials—formed the so-called rocking-chair battery (Armand, 1980; Lazzari and Scrosati, 1980; Scrosati, 1992). Such a double-intercalating battery using LCO and petroleum coke (not graphite, as yet) was first patented and successfully assembled by researchers from the Asahi Kasei company in research teams led by Akira Yoshino and Isao Kuribayashi (Xu, 2019; Yoshino, 2012; Yoshino et al., 1987), drawing inspiration from the work of Yazami and Touzain (Winter et al., 2018). However, it was Sony, with researchers such as Yoshio Nishi and Kazunori Ozawa (Blomgren, 2017; Nishi, 2016; Ozawa, 2020), that succeeded in commercializing these first-generation LIBs, based on the ideas of the Asahi Kasei researchers (Blomgren, 2017; Winter et al., 2018). Modern LIB generations, however, combine LCO with graphite, and use *ethylene carbonate* as the solvent for the electrolyte (in combination with a linear carbonate, e.g., dimethyl carbonate, to reduce viscosity and the salt $LiPF_6$). Ethylene carbonate has replaced propylene carbonate and forms a passivating solid-electrolyte-interface layer during the first initial cycles of the LIB, as researchers from Jeff Dahn's group published in 1990 (Fong et al., 1990). This layer helps to prevent the detrimental side reactions that have affected previous material combinations (Crabtree et al., 2015; Whittingham, 2012; Winter et al., 2018). The importance of the research that has been done in this field has also been recognized by the Nobel Committee; the 2019 Nobel Prize in Chemistry was awarded jointly to John Goodenough, Stanley Whittingham, and Akira Yoshino ''for the development of lithium-ion batteries'' (NobelPrize.org, 2019).

Since these breakthroughs, LIB cells have been continuously improved, e.g., by using other—specifically, differently structured—materials that allow for higher energy density, longer cycle life, better safety, or a decrease in material cost (Crabtree et al., 2015). On the anode side, LIBs have used different carbon materials and commercial improvements were rather incremental once they had moved from disordered carbons over several forms of artificial blends of graphite to layered natural graphite (Crabtree et al., 2015; Yoshio et al., 2009), whereas most new materials relate to the cathode side. Examples are compositions of materials that partly replace the expensive cobalt, so-called NMC (lithium nickel manganese cobalt oxide) and NCA (lithium nickel cobalt aluminum oxide) cathodes, and other materials with other structures such as spinel (LMO, lithium manganese oxide) or olivine (LFP, lithium iron phosphate) structures (Crabtree et al., 2015). These other structures contain metals (e.g., Fe and Mn) that are relatively cheap; LFP is also safer and LMO is suitable for power applications, where lower energy capacities can sometimes be tolerated (Dunn et al., 2011; Whittingham, 2012).

Besides cheaper and more energy-dense materials, LIBs have been driven along the learning curve by increasing adoption of stationary and mobile batteries, and therefore also mass production, resulting in substantial cost reduction (Nykvist and Nilsson, 2015; Schmidt et al., 2017). Although LIB diffusion started with consumer electronics and mobile applications where high density was critical (Trahey et al., 2020), it has shifted toward power and transportation applications (Chung et al., 2015) with higher capacity, and lower cost and charging time (Trahey et al., 2020). Today, even stationary applications of LIBs in the electricity grid can be attractive for investors (Stephan et al., 2016). Each different application hence brings its own different economics and scale and imposes different requirements (Trahey et al., 2020) (I10)—from medical applications where price is not a driver, but safety and reliability are critical, through to grid-scale applications where size, cost, and lifetime are dominant (I10), and from immediate returns on investment to economic long-term benefits from climate change mitigation (Trahey et al., 2020). Especially the widespread diffusion of electric vehicles still requires policy support until economics will take over (I1).

Spillovers in breakthrough and further LIB innovations

In our analysis, we identified the occurrence of a number of spillovers—i.e., transfers of external knowledge—that have made a substantial contribution to LIB development. Given that the strength of the qualitative method is detail and depth, but not comprehensiveness (it is not feasible to trace the mechanisms and enablers from all the possible contributions), we focused our analysis on the contribution of spillovers to breakthrough innovations. We also added further commercialized (mainly process) innovations. In doing so, we consider innovations that occurred at different times in the technology life cycle, and cover both product and process innovations, as well as those that differed in terms of the type of organization where the inventor worked (e.g., academia and industry). This allows us to inductively identify a variety of the sources of spillovers (i.e., the external technology, sector, or scientific field from which they originate), and the mechanisms and enablers that could facilitate them, and to derive a framework that can be used to identify more general patterns, and that can be further tested and expanded in future research. We identified a wide range of spillovers coming from various sources, listed in Table 1. As we discuss below, we find that all the breakthrough innovations, and also the smaller ones, have only occurred due to various factors coming together, of which spillovers represent a relevant part. For half of our LIB innovations, it was even the combination of insights from different sources that ultimately enabled the advancements. All the innovations listed in Table 1 have been commercialized.

Electrochemical intercalation: a spillover from sodium sulfur batteries and superconductors

One of the fundamental ideas that underlie current LIB functioning is the electrochemical intercalation on the cathode. Stanley Whittingham was one of the key figures to exploit this mechanism while working at Exxon Research and Engineering Company in the early 1970s (Whittingham, 1974, 2012). Whittingham

Table 1. Overview of the analyzed breakthrough and additional (mainly process) LIB innovations (#) with associated spillovers sources (a–d)

#	Innovation	Spillover sources from other technology (T), sector (S), and scientific discipline (SD)	Short description of how spillover came about
1	Electrochemical intercalation (cathode)	a) NaS (sodium sulfur) batteries (T)	S. Whittingham had worked on NaS batteries in Stanford before he transferred the mechanisms of intercalation that he and his colleagues discovered at Exxon to the battery field
		b) Superconductors (T,S)	S. Whittingham worked in superconductors at Exxon and discovered the mechanisms of electrochemical intercalation. He was able to transfer this idea to LIBs and discovered TiS_2 as a cathode material
2	Cathode (LCO, lithium cobalt oxide)	a) Solid-state physics (SD)	J. Goodenough, who was trained as a solid-state physicist, often worked with solid-state chemists
		b) Digital data storage (T,S)	J. Goodenough, inspired by the Ford Motor Company, wanted to apply his research ideas related to digital data storage in the battery field
3	Anode (graphite)	a) Material science (SD)	R. Yazami was trained in the two scientific fields of material science and electrochemistry
		b) Physical chemistry (T,S)	R. Yazami built upon the interdisciplinary knowledge and funding existing in his research group. Physical chemistry, including thermodynamics, was one of the foci of R. Yazami's group
		c) Heat storage (T,S)	R. Yazami built upon the interdisciplinary knowledge and funding existing in his research group. Heat storage was one of the foci of R. Yazami's group
4	Cathode (LMO, lithium manganese oxide)	a) Crystallography (SD)	M. Thackeray was trained as crystallographer
		b) ZEBRA (sodium/metal chloride) batteries (T)	M. Thackeray further developed his knowledge from materials used in high-temperature ZEBRA batteries to those used in room-temperature LIBs
		c) Digital data storage (T,S)	J. Goodenough knew about spinels from his prior work in digital data storage
		b) Nature (geology) (SD)	M. Thackeray's ideas have built on his interest in the structural stability of materials produced in the geological world.
5	Electrode coating	a) Cassette/magnetic tape production (T,S)	Sony produced the first LIB electrodes on cassette-tape manufacturing equipment that had been standing idle Leclanché produced battery electrodes at an old BASF manufacturing plant for magnetic tapes. Leclanché furthermore used the trained personnel who were available
6	Battery slurry manufacturing	a) Printing-ink production (T,S)	Bühler, a Swiss technology provider, had developed a revolutionary electrode slurry manufacturing process, which originated from the organization's knowledge in developing printing-ink production equipment

A schematic illustration of the basic functioning of LIBs can be found in Figure S1.

had been trained as a chemist at Oxford and worked in the group of Peter Dickens (Inorganic Chemistry Laboratory). During Whittingham's time at Oxford, his research was funded by the US Air Force (London office) and the Gas Council (London). During his doctorate, he was given the freedom of search in his studies by his research sponsor. During his postdoctoral research at Stanford, funded by the US Office of Naval Research, he applied the insights he gained from his previous work to sodium sulfur (NaS) batteries (Table 1, 1a). This was possible because Exxon, prompted by the oil crisis, established a research center inspired by Bell Labs. In 1972 (Whittingham, 2012), Exxon hired Whittingham and several other researchers from Stanford to work on superconductor topics in an explicitly designed interdisciplinary team. While experimenting with superconducting materials at Exxon, Whittingham discovered a combination of materials that allows for electrochemical intercalation (Table 1, 1b). He realized the potential to transfer this knowledge to battery energy storage because of his earlier work on NaS batteries at the Stanford University, and because industry and academia showed great interest in battery research at that time. Due to the oil crisis and the potential to enter the electric vehicle field, Exxon management decided to invest in the area, and hence allowed Whittingham to further work on battery materials, despite the fact that the focus of his work was meant to be on superconductivity. This experience with intercalation ultimately led to the development of TiS_2 as an intercalating cathode material. (I1, I2, I4)

Lithium cobalt oxide (LCO) cathode: spillovers from training in solid-state physics and digital data storage (random access memory)

LCO is the layered-oxide cathode material that was used in the first commercialized LIBs, and it is still widely used today (Pillot, 2017). Koichi Mizushima and John Goodenough discovered the applicability of LCO as a cathode material in 1980 (Mizushima et al., 1980). Note that at roughly the same time LCO as the intercalation cathode material, which operated at high temperatures, was independently discovered by Ned Godshall and his colleagues at the Stanford University (Godshall et al., 1980). Trained as a solid-state physicist at the University of Chicago (University of Texas at Austin, 2019) (Table 1, 2a), Goodenough worked on fundamental research on oxides intended for use in random access memory (RAM) for digital computers at the Lincoln Lab (MIT, Physics Department), funded by the US Air Force. At that time, the Ford Motor Company had started work on NaS batteries, in response to the oil/energy crisis. Goodenough was asked by the US Government to monitor Ford's activities, where he was inspired to devote his research to the energy/battery field. Given that the research at the Lincoln Lab had to be focused on digital computers and not energy, he took a faculty position at the Oxford University. Equipped with another grant from the US Air Force to form his group in inorganic chemistry at Oxford, Goodenough pursued energy/battery research alongside solid-state chemists and ceramists. While he initially worked on NaS batteries, a graduate student's work on layered oxides reminded him of his research investigating the magnetic properties of LCO for RAM-related applications (Table 1, 2b). Together with the electrochemical knowledge from neighboring research groups centered around figures such as Peter Dickens at Oxford, and Whittingham's and Brian Steele's research on electrochemical intercalation, which was published in conference proceedings, this ultimately resulted in the discovery of LCO as a cathode material for LIBs (I1, I2) (Mizushima et al., 1980).

Graphite anode: spillovers from materials science, physical chemistry, and heat storage

Although graphite is the predominant anode material used in today's LIB cells, it was petroleum coke, pioneered by a team around Akira Yoshino, that was the preferred type of carbon anode in Sony's first LIB products (Xie and Lu, 2020). In the early 1980s, Samar Basu at Bell Labs filed patents for lithiated graphite as the anode material in high- (Basu, 1981) and room temperature (Basu, 1983) cells; the technology was later licensed by Sony. Around the same time, in 1983, Rachid Yazami and his PhD advisor Philippe Touzain published on the reversible electrochemical intercalation of lithium into graphite in an all-solid-state lithium-polymer cell in scientific literature (Yazami and Touzain, 1983) while they were working at INPG (Institut polytechnique de Grenoble). Yazami, trained in the two scientific disciplines of materials science (Table 1, 3a) and electrochemistry, drew on this "dual culture" to develop his research ideas. He originally worked on graphite as a cathode material for LIBs during his PhD, based on his group's previous work on graphite intercalation compounds. When discovering the possibility to intercalate lithium into pure graphite during that time, he realized how graphite could also work as an anode material. Yazami benefitted substantially from the interdisciplinary knowledge in his group in Grenoble, because the group he worked in at INPG focused on electrochemistry and physical chemistry (e.g., thermodynamics), specifically in graphite materials (Table 1, 3b), and heat storage (Table 1, 3c). Besides providing knowledge, the existence of these different foci in his group also contributed to a relative abundance of funding available to his group—especially as the other foci were hyped during that time—which gave the scientists freedom in their search. Yazami was supported by his classmate Philippe Rigaud, who served as a discussion partner and helped him prepare the electrolyte that finally enabled the intercalation of lithium into graphite. (I5, I4, I6)

Lithium manganese oxide spinel cathodes (LMO): spillovers from crystallography, ZEBRA batteries, digital data storage (RAM), and nature (geological world)

LMO is a material that was developed during the early 1980s and is widely used today as a cathode material (Pillot, 2017). Its so-called spinel structure allows for fast charging and discharging and enhanced safety (Crabtree et al., 2015). Moreover, it does not contain expensive cobalt, and hence is cheaper (Crabtree et al., 2015). Based on earlier work by James Hunter, who discovered (the preparation of) a new form of MnO_2 (λ-MnO_2) (Hunter, 1981a, 1981b) and patented its use as cathode material (Hunter, 1982), which has, however, never been manufactured for commercial use due to several drawbacks (Thackeray, 2020), Michael Thackeray was one of the key figures driving spinel-structured cathode materials for commercial use forward. As a crystallographer, he had worked at the CSIR (Council for Scientific and Industrial Research) in South Africa in the mid- to late 1970s (Table 1, 4a). Due to the oil crisis, he and his supervisor, Johan Coetzer, initiated a search for new electrochemical systems in the energy storage/battery field. During their search for electrode materials for the high-temperature sodium/metal chloride ZEBRA battery

(Table 1, 4b), they discovered that iron oxides with a spinel-type structure operated reversibly by lithium insertion and iron extrusion reactions. Thackeray's ideas were inspired by linkages between science and industrial application, more specifically, by attending scientific conferences that attracted both academics and industry practitioners, and by reading scientific publications. Thackeray approached Goodenough in Oxford, because he saw the potential for spinel structures to be used as cathodes in room-temperature LIBs rather than high-temperature ZEBRA batteries. Goodenough was familiar with spinels due to his previous (RAM-related) research (Table 1, 4c) and promptly invited Thackeray to Oxford. Thackeray was funded by the CSIR, a government research agency, and South African industry (Anglo American Corporation). Together with Bill David and Peter Bruce (Thackeray, 2020), Thackeray discovered that lithium could be inserted into iron-oxide and manganese-oxide spinels (Thackeray et al., 1983). On his return to the CSIR, Thackeray and colleagues extracted lithium from LMO—demonstrating its suitability as a cathode material for high-voltage lithium cells. Besides Thackeray's crystallographic knowledge and Goodenough's understanding of the spinel structure, this innovation was inspired by Thackeray's interest in the structural stability of materials produced by nature, i.e., in the geological world (Table 1, 4d) (I2, I6) (Thackeray, 2011, 2020).

LIB mass manufacturing: a spillover from cassettes/magnetic tapes

Besides driving commercialization, Sony was the first company to mass manufacture LIBs. Sony had a strong interest in developing small and powerful batteries for the growing market for their own portable consumer electronics such as handheld video cameras. Although Sony had already entered into a joint battery-manufacturing venture in 1975 and sold primary dry cell batteries under the Sony-Eveready brand to the Japanese market (Blomgren, 2017; Sony Corporation, 2020a), the desire to also create rechargeable batteries to power their devices grew in the mid-1980s (Sony Corporation, 2020b). Around that time, many of Sony's manufacturing lines that had originally been used for coating audio tape with magnetic slurry were standing idle because compact discs were replacing cassette tapes. Sony realized that these manufacturing lines were well suited for LIB production, and therefore brought together its knowledge on batteries with its existing cassette-tape manufacturing equipment and personnel for coating LIB electrodes (Table 1, 5a) (Blomgren, 2017; LeVine, 2015; Ozawa, 2020).

A similar story unfolded in Europe more recently. In 2012, the Swiss battery manufacturer Leclanché bought the German chemical company BASF's old production facility in Willstädt (Germany) to produce LIB electrodes. Until 2004, BASF had used this facility for manufacturing magnetic tapes. Since the takeover, Leclanché has therefore been able to use both idle manufacturing equipment and available qualified personnel for LIB purposes (Table 1, 5a) (Janzing, 2015).

LIB slurry production: spillovers from continuous processing of printing-ink production

The Swiss technology provider Bühler has recently developed an electrode slurry manufacturing process, which has been used in Lishen's (one of China's largest battery manufacturer) LIB production line since 2016 (Bühler, 2016). The concept underlying this slurry manufacturing process originates from Bühler's activities in continuous processing—more specifically, their experience in twin-screw extrusion—which they had previously applied to, e.g., printing-ink production equipment. Due to the shrinking business opportunities for printing-ink production (people increasingly read from screens), Bühler started to search for new applications for their continuous processing knowledge. They attended industry conferences and read reports and publications to learn about other sectors' needs in terms of slurry production. They started thinking about batteries as soon as the early 2000s. Although the battery business seemed too small for Bühler's production technology at that time, Bühler eventually became interested in applying their continuous processing knowledge from printing ink and human and financial resources to batteries around 2006/2007 (Table 1, 6a), when the battery market started to grow. Similarities in battery and printing-ink slurry enabled this knowledge transfer. However, Bühler's successful entry into the battery field was only possible when the industry became interested and knowledge transfer happened via trials with battery companies, driven by market opportunities and partly supported by government grants and the development of pilot projects (I7, I8).

Mechanisms and enablers of spillovers

While the variety of spillovers and their sources identified (Table 1) already underlines the importance of the transfer of external knowledge for innovations in the LIB field, we focus on the mechanisms behind and enablers for these spillovers in the following discussion to derive implications for policymakers and R&D managers. Figure 1 shows a summary of the mechanisms and enablers of spillovers from the various sources, including the respective examples from Table 1; more details can be found in Table S1. Note that although

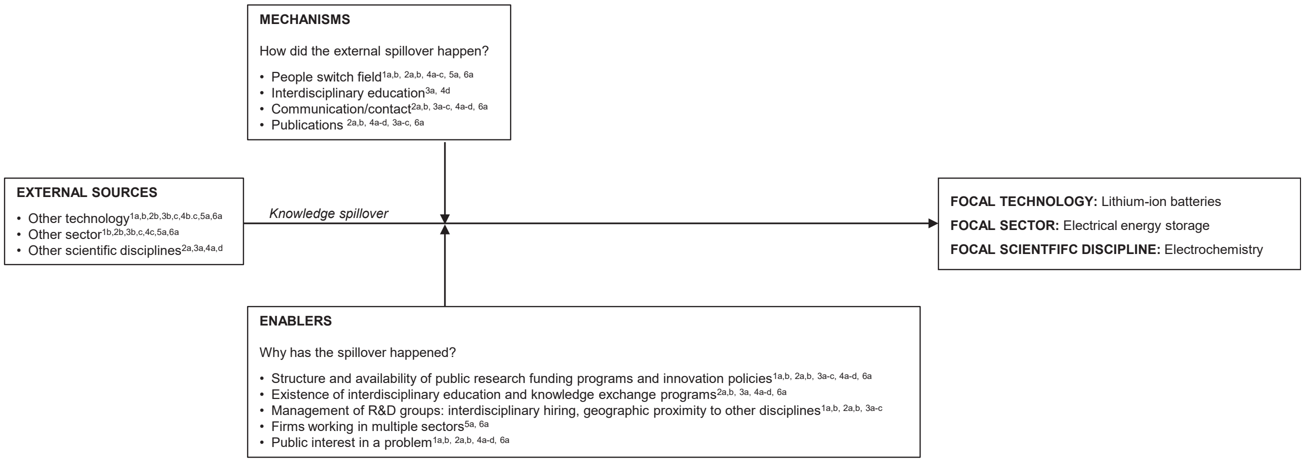

Figure 1. Mechanisms and enablers of knowledge spillovers, including examples of spillovers and their source
See also Table 1 for spillover sources and examples, and Table S1.

Figure 1 is based on specific examples, many of the mechanisms and enablers were also mentioned by our R&D and industry authorities/experts in general terms.

Mechanisms

Our analysis and data support four different mechanisms of how spillovers can happen. First, spillovers can occur because people (e.g., inventors) switch technological field or sector, or move between different scientific disciplines. This allows them to transfer their previously acquired knowledge to a new technology, sector, and/or scientific field. For example, in the LIB field, Whittingham, Goodenough, and Thackeray moved into LIBs from NaS batteries and superconductors (Table 1, 1a, and 1b), digital data storage (Table 1, 2b, and 4c), and the ZEBRA battery (Table 1, 4b), respectively. In doing so, Goodenough also switched scientific discipline from physics to electrochemistry (Table 1, 2a), and Thackeray from crystallography to electrochemistry (Table 1, 4a). A similar mechanism also unfolded in industry, when Sony and Bühler shifted their human resources from working on cassette tape (Table 1, 5a) and printing-ink (Table 1, 6a) manufacturing, respectively, to battery manufacturing.

Second, and related, spillovers can occur because people (inventors) receive interdisciplinary education or nurture interdisciplinary interests. For example, in the LIB field, researchers were trained in more than one scientific discipline, such as Yazami's dual education in material science and electrochemistry (Table 1, 3c), or had a personal interest in understanding other disciplines that they could also build upon, such as Thackeray's interest in geology (Table 1, 4d).

Third, spillovers occur because of communication or contact between individuals. In our examples, these contacts happened both intentionally and by accident. The former occurred when people approached each other to exchange ideas (Table 1, 2a and b, 4a–d, and 6a), or strategically attended conferences in search of new applications for existing knowledge (Table 1, 6a), whereas the latter happened when Goodenough monitored the Ford Motor Company (Table 1, 2a and b), or when Yazami learned about the electrolyte from his colleague through casual interdisciplinary knowledge exchange (Table 1, 3a–3c).

Fourth, the access to and the reading of publications such as academic papers, industry reports, and press releases can also help to acquire external knowledge, as happened in the field of LIB innovations (Table 1, 2a and b, 3a–c, 4a–d, and 6a) and which may have been less common 40 years ago than it is today.

Enablers

Our findings indicate five different enablers for spillovers. Although we cannot prove that the spillovers would not have happened without these enablers, we found substantial regularity in our interviews regarding ''circumstances'' that have fostered the integration of external knowledge. Table 2 shows exemplary quotes from our interviewees that support these enablers.

Table 2. Exemplary quotes from our interviewees that support the enablers

Enabler	Subgroup	Exemplary quote	Source
Structure and availability of public research funding programs and innovation policies	Freedom of search	"Life is full of choices of one kind or another [...]. And either you play it safe or you do what you feel you need to do" (on that you have to take some risks that might turn out very successful) "But the thing came about again simply by a student deciding he'd like to do something I said couldn't be done and he ended up with something different that worked." (on that innovations happened because people were allowed to pursue their research interests)	J. Goodenough
		"I got a three year scholarship from the Gas Council in London. [...] So, my job was essentially to look at catalysis to convert coal gas into something more like natural gas. So, they said, 'We're not interested in what you're doing but you've got your funding for the next three years,' because they had all the gas they wanted." (on why he was able to pursue his research in the way he wanted to)	S. Whittingham
		"Mostly was actually the money that the [French] government gave to the lab [...][and] yes at that time yes there was some kind of freedom, but of course CNRS has a right to see what's going on in the lab." (on how his research was sponsored and how much freedom of search he had)	R. Yazami
		"And he would say 'from a structural standpoint, there is no energetically-favorable interstitial space in a spinel to allow lithium insertion', but he also said 'you can go ahead and try.'" (on how Goodenough allowed him to pursue his ideas)	M. Thackeray
	Availability of different funding options	"At that time they [Lincoln Lab/US Air Force] were quite supportive as long as you were asking questions and solving their problems." "One of the advantages in America is that there is more than one source of funding so that if some people turn you off you can turn to another and hope that you can get some support."	J. Goodenough
		"In Oxford in the chemistry degree you do bookwork for three years then you spend a year doing research for your bachelor's degree. [...] And that was funded by the United States Air Force as of the London office."	S. Whittingham
		"Our research was really supported by CNRS, but my boss also could get some funds for other projects related to graphite intercalation compounds but not for batteries."	R. Yazami
	Funding not targeted to energy storage	"In my group, we had a group on electrochemistry but there was another groups who was working on physical chemistry and also some on heat storage—and so also a lot of projects. My boss could get some money from other projects and then use it for my projects."	R. Yazami
		"As a crystallographer at the CSIR in South Africa during the oil crisis in the mid-1970s, I was looking for a PhD project topic when my supervisor said, 'We have to get involved in energy storage materials research even though we are structural chemists, not electrochemists."	M. Thackeray
	General market support	"We considered and discussed already in 2002 about the battery slurries and at this time the volumes seemed to be much too small. And then, seven years later, eight years later [...] new research showed that the quantities are growing substantially and then it was the time to enter to this market."	Bühler employee

(Continued on next page)

Table 2. *Continued*

Enabler	Subgroup	Exemplary quote	Source
Existence of interdisciplinary education and knowledge exchange programs	Interdisciplinary education	"I was in Grenoble at that time in France and the school where I took my PhD was one of the best I think and even now is the best schools in electrochemistry, so my background is material science and electrochemistry [...]. I have a dual culture."	R. Yazami
	(Regular) exchange between science and industry	"[I was] [...] introduced to the battery field, because I was asked by the government to monitor work at [the] Ford Motor Company." (on his exchange with industry)	J. Goodenough
	Conferences	"I was not at the conference, but I've looked up the proceedings of the conference" (on how he got to know about electrochemical intercalation)	J. Goodenough
		"But at the same time, one of the greatest advantages of living in South Africa was that we had to travel and attend international conferences abroad. Every time I went to a conference, even though I wasn't expecting much, I would return with new ideas that were sparked by conversations with scientists—from both academia and industry—and listening to what they were saying and doing."	M. Thackeray
		"That is going to conferences, [...]" (on how they systematically searched for new process knowledge applications) "And so we went to all these conferences on a regular basis [...] and we continuously looked at what is needed there in slurries [...] we tried a number of things until we came up with the batteries."	Bühler employee
Management of R&D groups: interdisciplinary hiring, geographic proximity to other disciplines	Intra-group management	"So, we had a mixed disciplined group with Exxon, chemists, material scientists, physicists, [...] that in the end was critical to understanding the role of intercalation."	S. Whittingham
		"You just happen to have the right background at the right time" (on how his background fitted the new challenges in Oxford)	J. Goodenough
		"Within my group some people were doing physical chemistry and heat storage [...]. I was curious about everything. I wanted just to know the properties of that material [...]—by which mechanism and why and so on. So, all of this was a very enriching experience."	R. Yazami
	Inter-group management	"When I went to England there were people there who did electrochemistry so I had an opportunity to be exposed [to their knowledge] and to learn a little bit about electrochemistry."	J. Goodenough
		"I think in France [...] that was really the best place and the best moment to do that research, because you have this critical side of very knowledgeable professors and researchers in material science and in electrochemistry—both of them together. You put them together and this is where actually interdisciplinary is very important. [...] So in the second floor of the school we were mostly material scientist. I go to the third floor they called themselves The Lab Of Electrochemistry And Energetic. So, I mean, it's only a matter of ten stairs or twenty stairs from one I would say planet to another planet but they are all together."	R. Yazami

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Table 2. ***Continued***

Enabler	Subgroup	Exemplary quote	Source
Firms working in multiple sectors		"Increasingly popular compact discs were beginning to erode the market for cassette tapes, of which Sony was also a major manufacturer. […] Looking around the company, Sony's lithium-ion managers now noticed much of this equipment, and its technicians, standing idle." (on how Sony manufactured the first batteries for their video cameras)	LeVine (2015)
		"And there were employees with the perfect skills, because BASF had used the location for coating magnet tapes since 1966. However, this business [BASF magnet tape coating] ended because of the digitalization." (on why Leclanché chose Willstädt as its production location)	Translated from Janzing (2015)
		"There have been for example companies, which started producing lithium-ion batteries and they bought an old production line for producing audio tapes; the audiotapes have a certain coating as well. And from these coating technologies several things were transferred also to the production of lithium-ion batteries or at least the coating process."	D.U. Sauer
		"Technically, for continuous processing you need a substantial production volume. It became relatively early clear that if electromobility and a number of other initiatives will take off to whatever extent, there would be a need for high productivity processes and that was basically the slot where our continuous processing expertise perfectly fitted."	Bühler employee
Public interest into a problem		"At that time I went there in '72, about '73 was the first gas petroleum crisis. […] Exxon said they are going to be in the energy business so this can propel them to get them interested in electric vehicles. "	S. Whittingham
		"The energy crisis had come, so I turned and said 'Well, I'll use my experience in oxides to think about what I can do on the energy side.'." "[…] plus the energy crisis started to make people think a little bit that maybe there are other ways to make batteries than the traditional way."	J. Goodenough
		"Well, I mean, at that time, you know, there was a lot of excitement about the lithium chemistry and batteries."	R. Yazami
		"At the time of the Middle East oil crisis—when the price of oil really spiked—there was a concern about supply and the need for an alternative power source for transportation (electric vehicles); the result was that the battery R&D community got a real shot in the arm." "No, it was because of the oil crisis that we complemented our crystallographic interests with electrochemistry to study structure-electrochemical property relationships in electrode and electrolyte materials." (on why he and his supervisor started investigating battery materials at the CSIR.)	M. Thackeray
		"It was the time when we saw that solar was kind of going down and there was a lot more of talking, publications, press releases and all that on the battery side […] yes, you could call it public interest."	Bühler employee

First, various aspects related to public research funding and other innovation policies can play an important role in enabling spillovers. Our interviewees mentioned multiple times that "freedom of search" granted by the respective research sponsor and/or supervisor had allowed inventors to try things out (Table 1, 1a and b, 3a–c, and 4a–d). The availability of different funding options, including the mobility of funding, e.g., overseas funding, enabled the transfer of ideas to new applications (Table 1, 1a and b, 2a and b, and 3a–c). Our results, furthermore, show that research funding not specifically targeted to electricity storage—such as the research on digital data storage sponsored by the US Air Force (Table 1, 2a and b) and funding related to physical chemistry and heat storage (Table 1, 3a–c)—or basic research on chemical structures (Table 1, 4a–d) also enabled spillovers. Moreover, our interviews indicate that both industry R&D support and general market support, such as electric vehicle targets, can be important to stimulate the industry's interest in a certain technology and incentivize companies to transfer their knowledge to new business fields (Table 1, 6a, and presumably also 5a).

Second, the existence of knowledge-exchange programs for both industry and academia, deepening the interdisciplinary education mentioned before, can enable spillovers. These can consist of a (regular) exchange between science and industry (Table 1, 2a and b), conferences (Table 1, 4a–d and 6a), or interdisciplinary training (Table 1, 3c). This last avenue, in particular, enables graduates to understand and interpret the knowledge and (research) cultures of other fields.

Third, the management of R&D groups plays an important role. This relates to both intra-group management, e.g., hiring, and the management of several groups at a specific location (inter-group management). Our interviewees frequently mentioned that interdisciplinary research groups (Table 1, 1a and b, 2a and b, 3b and c), as well as geographic proximity between different scientific disciplines at a university (Table 1, 2a and b, and 3a), had been crucial for spillovers.

Fourth, firms working in multiple sectors (or using equipment from other sectors) can enable spillovers. For example, Sony and Leclanché have mass-manufactured LIBs using their idle capacity on manufacturing equipment originally used for cassette/magnetic tapes (Table 1, 5a). Bühler were able to enter the battery field due to their continuous processing knowledge, which had previously been used, e.g., printing inks (Table 1, 6a). Hence, the activities of a single organization in different sectors (Sony) or the search for activities and/or equipment in other sectors (Leclanché, Bühler), together with innovations in other sectors—such as music reproduction or media in this case—resulting in idle industrial capacity (i.e., innovations in other sectors such as music reproduction or media) and the scope for experimentation regarding physical assets and staff, enabled spillovers from other sectors to the LIB technology.

Fifth, the public interest in a problem that requires a (global and technological) solution, such as the oil/energy crisis or climate change, does not just enable innovation in general (Arthur, 2009), but enabled spillovers in particular. Although the existence of the oil/energy crisis, together with inventors' interest in searching for solutions, was a main driver, especially for the spillovers in the early LIB innovations (Table 1, 1a and b, 2a and b, 3a–c, and 4a–d), increasing public interest in battery development to mitigate climate change and hence market potential enabled Bühler to finally enter the battery field (Table 1, 6a). This seems to be particularly important for technologies that would need policy support for widespread diffusion, e.g., because they are (still) economically unattractive.

A look into the future

We consider the general mechanisms and enablers identified to be crucial for future technological advances too. However, the experts also mentioned five factors that might affect future LIB R&D efforts, or alter the way in which knowledge is transferred. Table 3 shows exemplary quotes from our interviewees regarding these factors. They are important applications, national economic conditions and public R&D funding, advances in digitalization, technology and market developments within the LIB field, and the complex nature of batteries.

An important application, which has—for LIBs—moved from consumer electronics to electric-vehicle applications that can create high public awareness (e.g., via firms such as Tesla, which gave the technology a face) is expected to generally drive LIB innovations going forward.

National economic conditions that relate to these applications, such as an extant consumer electronics industry (e.g., Sony in Japan) and the prevalence and relevance of the automotive industry today and in the future (e.g., major carmakers in Germany), as well as industry associations, will further influence public funding decisions. This will be critical to battery R&D and hence increase the availability and strength of (national) research efforts and enable knowledge transfers.

Table 3. Important factors that affect future LIB innovations and spillovers with exemplary quotes from our interviewees

Factors	Exemplary quote	Source
Important application accompanied by public awareness	"The importance of a 'killer application' should be fully appreciated […].The primary application for Li-ion batteries has historically been personal electronics, a huge market with seemingly insatiable demand. Since the first EVs came out (Nissan Leaf in Japan and the US in 2010), the larger market is becoming transportation, which has very different critical needs for capacity (for driving range), fast charging (for convenience) and low cost (for competitiveness). These metrics are all distant followers in personal electronics. EV application needs will drive a new era of innovation in Li-ion batteries and provide new opportunities for spillover."	G. Crabtree
	"Battery research is driven by its application. We need both, push and pull that means visionary protagonists from application-oriented battery research and demanding users that drive innovations." "Without companies such as Tesla, which has given the technology a face, battery research would not be where it is today." "Public awareness is important. In Germany, for example, the new battery factories by Tesla, CATL or Volkswagen (together with Northvolt), increase public awareness substantially."	M. Winter
Local economic conditions and public R&D funding	"In Germany, battery research has been driven by the automotive industry. Traditionally, the automotive industry in Germany is system relevant due to the many jobs it provides and, therefore, has a huge influence on policymaking."	M. Winter
	"In Germany, the VDMA (Verband der deutschen Maschinen- und Anlagenbauer) has a working group. All those who are interested in the production technologies of lithium-ion batteries come together and they are making a roadmap—together with research institutes, which understand very well what the requirements are. And they try to match this with their knowledge on the machinery they have used in the past. So, I think a very important part of this [innovation] process, which is supported also by these associations like the VDMA or others, is to open new markets for the companies in these emerging markets." "For example the VDMA has organizations like FVA (Forschungsverbund Antriebstechnik) and they have money in hand, which they expand typically to research organizations like ours for example, and the results from these research projects are open to all members." "Specifically in the area of electro-mobility and battery development, the German Government has done all in all quite well. They have spent a really significant amount of money to establish new research activities, new research institutes—not only in academia but also in the industry itself to get to new professorships and institutes at universities to bring forward the number of educated people in this area. […] So, I think government has an important role in this […] And they should not stop at a certain point in time because once they have a lot of new research activities, it is also not a good idea to stop."	D.U. Sauer

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Table 3. ***Continued***

Factors	Exemplary quote	Source
Advances on digitalization	"Freedom of search is a critical enabler for spillover breakthroughs […]. Before digital technology freedom of search depended much more on personal interaction and co-location, as at Bell Labs and Exxon. Nowadays freedom of search is dramatically enhanced by databases like Web of Science and email, no longer requiring co-location with specialists in other fields. However, despite the virtues of the internet, personal interaction seems to remain a critical factor, aided by email and other virtual interactions." "The materials community is poised for another spillover phenomena, where machine learning and artificial intelligence allow very effective sharing of information and phenomena across traditional boundaries. Information on materials behavior and phenomena is rapidly being captured in large databases intended for either high throughput screening or training sets for machine learning, where the specific discipline from which the information came is becoming more irrelevant but the information itself more relevant. When searching for a material with certain properties, machine learning can often find many examples by clever programming, independent of personal interactions or knowledge of the particular use of the material for other applications. This lends a new flavor to spillover and especially how to encourage it."	G. Crabtree
Technology and market developments within the LIB field	"Spillover can be limiting as well as liberating. A good example is Li-ion battery manufacturing, which is done in roll-to-roll processing, initially using unused equipment from magnetic tape manufacturing. Though very successful, it is not clear that this is the best manufacturing route for some Li-ion innovations. Solid state electrolytes have a different set of challenges from organic liquid state electrolytes, for example, and may benefit from another form of manufacturing, such as the nascent laboratory efforts in additive manufacturing for batteries. "	G. Crabtree
	"New firms from other areas, such as the companies providing process equipment or consultancies, will enter the LIB value chain. Everyone will try to be integral part of this rapidly expanding business."	M. Winter
	"For example I talked to a company, which is now producing the cases for prismatic cells. They are producing the equipment for this and they are coming from producing tin cans for soft drinks."	D.U. Sauer
	"Cost concerns reduce innovation because they generally restrict or limit the materials that can be used, particularly in larger batteries. " "The need for batteries to cycle for longer periods of time – for EV and grid applications – means that all degradation mechanisms must essentially be switched off. This is a challenge for a system that operates out of equilibrium once it is charged and has to handle a wide range of temperatures. As we move to higher voltage batteries, we continue to push closer to the fundamental limits of the energy density that can be reversibly extracted from a material."	C.P. Grey

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Table 3. ***Continued***

Factors	Exemplary quote	Source
The complex nature of batteries	"Battery research is interdisciplinary and we need systemic approaches. The different components interact. You cannot only test the anode or the cathode by itself, you also have to test the entire battery cell system."	M. Winter
	"When all these discussions, and it's still ongoing until today, between the automotive industry and the electrical sector started, it became obvious that these people had never talked to each other in the past. Even in today's time, they hardly can discuss successfully with each other because they use different terms, they have different cultures. […] In the automotive sector, they are introducing a new type of car every five to six years […] – so the innovation cycle and also the investment cycle is something like five or ten years. If you go to utilities, they invest into power plants or grids. This is an investment which takes from the day you start planning until you finish the operation […] 40 years–70 years. " "The battery business itself is extremely inter-disciplinary. You start with the chemists, the material guys and go up into the application and the electrical engineering. In-between, you have physics and have mathematics and so on. So, this is something which is difficult—also because our actors or students are typically educated into a certain direction and they are not perfectly educated for such interdisciplinary working groups and work. This is something that will be needed also from the education point of view. But still, I am not really sure if we should have in the future more specialists in the different areas which are well-trained in discussing with specialists from other areas, or if we should have guys who have some knowledge from all the different areas. So this is something, which is still under discussion and we are not really sure how the engineering job profile in the future should look like."	D.U. Sauer

Advances in digitalization could substantially affect how researchers use their freedom of search and, in the process, also boost future spillovers. Digital communication and the availability of online research databases allow for faster knowledge transfers and might further partly replace traditional collaboration methods based on personal contact and co-location. Moreover, machine learning and artificial intelligence could allow for very rapid and effective identification of information and phenomena in large databases without personal interaction—also across traditional boundaries.

Both technology and market developments within the LIB field might require, or benefit from, knowledge spillovers, and attract new firms to enter the LIB value chain. Our experts mentioned that future technological advances will improve the current system in a way that addresses issues of safety, capacity, cycle life, and/or cost—whereof the last avenue can not only spur but also hamper innovation. Future breakthroughs might occur on the anode side (e.g., adding silicon to graphite, or even replacing graphite with—ideally—lithium metal), on the cathode side (e.g., adding aluminum), or entail completely new systems (e.g., lithium sulfur, lithium air, or solid-state batteries). Although these changes might not be easy and cannot exceed fundamental boundaries, they might also (have to) be accompanied by different or more efficient manufacturing processes (e.g., solid-state batteries), as well as developments in end-of-life/recycling of batteries. These advances, along with increasing market size, might attract new entrants and start-ups such as new manufacturing equipment providers, consulting companies, or data managers into the field.

Nevertheless, the complex nature of LIBs—i.e., the interrelatedness between their individual components—will also demand systemic and interdisciplinary approaches in the future. Although these interdisciplinary approaches probably require special education and training programs to overcome differences between the terminologies and/or cultures (e.g., innovation cycles) of the people and firms active in the LIB value chain, it also means that future LIB innovations are also very likely to benefit from external knowledge.

DISCUSSION

This article complements extant literature that has described general patterns of knowledge spillovers in clean-energy technology innovations—typically by analyzing large sets of patent data—by analyzing how individual spillovers come about: the mechanisms and enablers of these spillovers. Based on a review of the literature and an elite interview campaign, we (1) identify the key breakthrough innovations in LIBs; (2) show the extent to which key breakthroughs, and a few others, have resulted from the integration of knowledge from a variety of sources (i.e., different technology areas, sectors, and scientific fields); many spillovers only happened because different sources were combined; and (3) identify different mechanisms and enablers underlying spillovers in LIB innovation, including public research funding granting researchers vital autonomy, and the interdisciplinary structure of education and research teams, as well as factors that might alter future R&D efforts and spillover patterns.

Although many of our findings relate to the breakthrough innovations from the early LIB life cycle and from decades ago, our findings are still relevant for LIB innovations today and in the future, for two main reasons. First, we study two cases of more recent innovations, such as Bühler's slurry production process commercialized in 2016, and we find that the recent spillovers exhibited similar mechanisms and enablers to the early ones. This indicates consistent innovation patterns, despite the fact that what constitutes a spillover (i.e., the source) can change over time as technological fields (in this case LIBs) develop (Dosi, 1982; Sun et al., 2021). However, although we consider these "consistent" patterns to be less prone to rapid changes, they might ultimately adapt, as discussed in the section on the future of LIB R&D. Future research such as patent data analysis can complement our understanding of how the LIB field has developed over time. Second, although improvements have been made in terms of interdisciplinary approaches (e.g., research projects, education programs, conferences, scientific journals) since the 1980s, there is still a need to break down disciplinary silos in R&D management in academia, national laboratories, government, and the private sector (American Academy of Arts and Sciences, 2013; Narayanamurti and Odumosu, 2016), and to reorganize universities and reallocate funds to create a more conducive setting for interdisciplinary projects and collaboration (Irani, 2018; National Academy of Sciences et al., 2005) today. One could wonder whether these improvements have resulted in more recent LIB breakthroughs. Our approach—specifically, the few exemplars of spillovers investigated and the way we identified breakthroughs—does not allow for a comprehensive analysis of breakthrough frequency throughout the technological life cycle. In addition, we lack clear empirical evidence. Extant work indicates that important innovations, especially in LIBs (Clausdeinken, 2016) and energy technologies (Huenteler et al., 2016a; Nemet, 2012), depend relatively heavily on external knowledge to a relatively high extent, which seems to matter less for other technologies (Nemet and Johnson, 2012). However, the occurrence of important innovations might be affected by other aspects, such as the phase of the technology life cycle and the technology's design hierarchy (Huenteler et al., 2016a). In wind technology, for example, spillovers were not only important in early phases but also substantially shaped the technology's trajectory substantially later on (Huenteler et al., 2016a). Still, the efforts needed to facilitate these spillovers are, at least to the best of our knowledge, unclear and not covered in previous research. More research on the relationship between spillovers and the frequency of breakthrough innovations in different phases of the technology life cycle and across more technologies would be necessary to draw clear conclusions about the extent to which spillovers are more important at different times. This study provides both a set of observations and a framework that could be expanded in future work.

We assume that our insights can be transferred to other technologies with similar characteristics as well. Technology characteristics—such as high complexity (Stephan et al., 2017, 2019), or mass production (Huenteler et al., 2016b) in the case of LIBs—typically affect innovation patterns (Huenteler et al., 2016b; Stephan et al., 2017, 2019). In addition, the cost concerns for LIBs in most applications—medical batteries being an exception here—might constrain the materials that can be used and, hence, even limit innovation. We hence assume that our findings are most readily transferrable to other complex mass-produced technologies with high cost pressure such as photovoltaics or fuel cells. In addition, and based on the many insights we obtain from the various early innovations we investigated, our findings might be especially relevant for new technologies that have yet to develop a dominant design, such as other types of batteries (e.g., flow batteries), third-generation solar photovoltaics, and carbon dioxide removal technologies. Future research is needed to investigate spillovers patterns in other technologies as well.

Hence, policymakers and R&D managers might benefit from the mechanisms and enablers of spillovers that we identify, in terms of understanding *how* to foster spillovers more efficiently and effectively—in LIB innovations and other clean-energy technologies. Below, we identify a set of action levers for policymakers and R&D managers who are interested in experimenting with ways of facilitating spillovers. Note that the spillover sources identified vary in terms of distance, i.e., how related the transferred knowledge is. Although our implications do not exhibit systematic patterns regarding the kind and level of support that knowledge spillovers from different levels of distance might need, the distance of the knowledge transferred seems to play a role for innovation (Battke et al., 2016; Stephan et al., 2019); a systematic analysis of the relation between R&D support and the different kinds of knowledge spillovers might enhance the picture. Based on our findings, we emphasize the four most relevant aspects for policymakers before discussing the implications for R&D managers.

First, our results indicate that freedom of search has enabled spillovers in a substantial way. Funds that allow for freedom of search, such as the laboratory-directed R&D (LDRD) funds used by the U.S. National Laboratories, which give researchers the freedom to pursue their interests (National Research Council, 2013), seem to increase innovative output (Anadon et al., 2016a). Our findings further bolster that notion—in particular with regard to spillovers. In our setting, many LIB spillovers happened either because researchers were given the freedom of search by their employers, i.e., researchers were "allowed" to apply their knowledge to other fields (e.g., Whittingham by Exxon), or because they discovered their own means of knowledge transfer (e.g., Goodenough or Thackeray applying for new funding and/or positions). Policymakers could leverage this aspect and design R&D funding programs accordingly, e.g., by offering non-application-specific funding programs, or by explicitly fostering the transfer of knowledge to new fields.

Second, the hiring and funding of individuals, as well as their interdisciplinary education, have played a crucial role in enabling spillovers. Policymakers can explicitly foster the hiring and funding of experts with knowledge from other sectors and academic fields. This includes different funding options (e.g., receiving two different R&D grants has enabled Goodenough to transfer his knowledge from RAM applications to the battery field) and funding overseas activities (e.g., Goodenough was only able to pursue LIB research at Oxford due to a US research grant). These different funding options are necessary to create a knowledge base that is broad and deep enough to serve as the basis for spillovers. In addition, and although progress has been made in the past couple of decades, policymakers can still foster/fund the establishment of interdisciplinary education programs and conferences and consider how to provide at a greater degree of flexibility in funding.

Third, our results indicate that policymakers should incorporate a range of policy types into their debate. Besides technology-push policies, which typically aim to increase the supply of technologies by directly fostering advances in science and technology (e.g., R&D funding), they should also consider both demand-pull and systemic policies, which stimulate demand and improve the entire innovation process and feedback mechanisms, respectively. We find that in addition to traditional R&D funding, both general market support (demand-pull policy) and the establishment of interdisciplinary teams/education/conferences (systemic policies) have fostered spillovers. This confirms the positive effect of all policy types, as well as an appropriate policy mix (Rogge and Reichardt, 2016), on innovation—and this despite the fact that spurring spillovers typically goes beyond the initial intention of technology-push and demand-pull policies. Policymakers could hence repurpose existing policies to extend their intended effect to the occurrence of spillovers too. For example, the availability of different funding options has enabled Goodenough to transfer his knowledge from RAM applications to the battery field. Moreover, companies such as Sony, Leclanché, and Bühler would probably never have entered the battery field without strong support for battery/electric vehicle deployment. Hence, policymakers have to keep in mind the beneficial effect that all policy types can have on spillovers.

Fourth, although the diversity of sources, mechanisms, and enablers we identify indicates that there is no "one size fits all" approach, there are some similarities, which point to the existence of low-hanging fruit that policymakers could consider paying additional attention to. For example, policymakers should consider local conditions, such as the sectors/research programs available in a country, which could provide a knowledge basis for spillovers. A high number of different sectors or research programs in a country indicates a broad knowledge base, which could serve as a basis for spillovers. For example, Goodenough was highly motivated to apply his research to the field of energy storage because of the automotive sector's (Ford) activities and was able to do so because of the experience he had gained in digital data storage. If the existing knowledge base in sectors that could provide related knowledge is small, i.e., there is only little relevant external knowledge available, policymakers could design public R&D funding programs or institutions that have sufficient flexibility to attract researchers with external knowledge from other countries, and/or fund research in other countries (as in the example of the US Air Force funding Goodenough at Oxford).

Besides policy implications, our findings, especially the importance of the freedom of search and interdisciplinary teams, yield implications for R&D managers who want to increase innovation by fostering spillovers. Our results show that the freedom of search granted by placing trust in the researchers' own capabilities (e.g., Whittingham was allowed to apply his ideas to the battery field, even though he worked in the field of superconductivity) can result in important new ideas. Moreover, researchers were inspired by the knowledge they gained from colleagues in their own interdisciplinary teams, or closely located teams from other disciplines (e.g., Goodenough benefitted from the electrochemistry knowledge at Oxford). Moreover, establishing groups of an interdisciplinary nature—which has been initiated in both higher education and industry—can also increase a group's stability in terms of funding, and thereby also allow for research outside the focus areas (e.g., Yazami's group were mainly funded due to their research on physical chemistry). This shows the importance of the structure of research teams, as well as their location, for spillovers, and hence innovation, and yields important lessons for R&D managers—especially when planning new research centers such as national laboratories, and also when creating new groups within universities or industry.

Limitations of the study

Although we discussed the generalizability of our aforementioned findings, the findings of this study are also confined to our data sources and to the LIB innovations that were identified by our interviewees as particularly important. An investigation of additional data sources, e.g. patent data, and of a larger number of innovations, e.g., more recent ones, could complement the picture and lead to additional data points further supporting the importance of the mechanisms and enablers. While the elite interviews allow for first-hand participant observations related to the innovations we study, our results are limited to the understanding and framing of a few, albeit prominent, individual interviewees and the literature available. However, we observe a strong consensus in many aspects when contrasting and triangulating across the responses from the different interviewees and the literature. In spite of the high convergence across the data sources, some particular aspects, such as specific enablers or mechanisms, might be subject to the interviewees' individual interpretation. The spillovers identified should hence be viewed as important exemplars of mechanisms at play, rather than as an exhaustive compendium of all the factors that may have played a role in a particular spillover. While we cover different innovations in terms of their occurrence in the technology life cycle, type (product and process innovation), or origin (academia and industry), the small number of spillover events we explore makes it impossible to disentangle the extent to which different enablers and mechanisms may be more important or prevalent in spillovers of these characteristics. In addition, a better understanding of inefficient spillovers or time lags or an analysis of creating synthetic counterfactuals as more research becomes available could improve the level of evidence and allow for more detailed policy and R&D management recommendations.

Resource availability

Lead contact

Further information and requests should be directed to and will be fulfilled by the Lead Contact, Annegret Stephan (astephan@ethz.ch).

Materials availability

This study did not generate new unique reagents.

Data and code availability

There are restrictions to the availability of original interview data beyond the quotes due to confidentiality reasons.

METHODS

All methods can be found in the accompanying Transparent Methods supplemental file.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2020.101995.

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AUTHOR CONTRIBUTIONS

Conceptualization: A.S., L.D.A., and V.H.H.; Formal analysis: A.S.; Investigation: A.S., L.D.A., and V.H.H.; Writing – Original Draft: A.S.; Writing – Review & Editing: A.S., L.D.A., and V.H.H.; Funding acquisition: L.D.A. and V.H.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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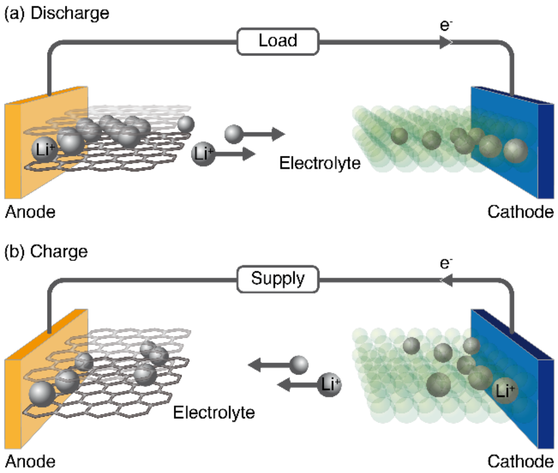
Supplemental Information

How has external knowledge contributed to lithium-ion batteries for the energy transition?

Annegret Stephan, Laura Diaz Anadon, and Volker H. Hoffmann

Figure S1. Functioning of secondary LIBs (own illustration), Related to LIB history and key breakthroughs, and to Table 1



Since 1991, when Sony produced the first Carbon-LCO LIB (Nishi, 2001), most LIB cells follow the same general concept (Berg, 2015; Crabtree et al., 2015; Whittingham, 2012; Winter et al., 2018). Each cell consists of a negative and a positive electrode. During discharge, lithium-ions are transported via an electrolyte from the negative electrode to the positive electrode, while electrons pass via the external circuit. Current collectors enable the transport of the electrons to the external circuit. During charging, the reverse process takes place. The more electropositive electrode in the charged state is typically called the anode, while the other electrode is called the cathode. The terms for anode and cathode are typically used this way regardless of whether the cell is being charged or discharged. A porous separator between the two electrodes isolates the two electrodes from each other and holds the (typically liquid) electrolyte. A number of different materials can be used for the different components. These materials have different reaction mechanisms, which have to be well understood in order to choose the best combination. Furthermore, specific requirements—such as energy versus power applications, or lifetime issues—render some material combinations more attractive than others. Depending on the application, different cells can be connected in a single LIB.

Table S1. Sources, mechanisms, and enablers of spillovers in LIB innovations, Related to Figure 1.

Innovation			**Spillover sources**			**Mechanisms**					**Enablers**											
			Other tech-nology	Other sector	Other scientific discipline	People/firms switch field	Inter-disciplinary education / interest	Commu-nication / contact		Publica-tions	Structure and availability of public research funding programs and innovation policies					Existing of interdisciplinary education and knowledge exchange programs			Management of R&D groups		Firms working in multiple sectors	Public interest in a problem
								intentional	accidental		Freedom of search	Different funding options	Overseas funding options	Non-storage related funding	Market incentives	Academic-industrial exchange	Conferences	Inter-disciplinary training	Inter-disciplinary hiring	Geographic proximity		
1	a	NaS batteries	x			x					x		x						x			x
	b	Superconductors	x	x		x					x		x						x			x
2	a	Solid-state physics			x	x		x	x	x		x	x	x		x			x	x		x
	b	Digital data storage	x	x		x		x	x	x		x	x	x		x			x	x		x
3	a	Material science			x		x		x	x	x	x		x				x		x		x
	b	Physical chemistry	x	x					x	x	x	x		x					x			x
	c	Heat storage	x	x					x	x	x	x		x					x			x
4	a	Crystallography			x	x		x		x	x			x			x					x
	b	ZEBRA batteries	x			x		x		x	x			x			x					x
	c	Digital data storage	x	x		x		x		x	x			x			x					x
	d	Nature (geology)			x		x	x		x	x			x			x					x
5	a	Cassette/magnetic tape production	x	x		x									(x)						x	
6	a	Printing ink production	x	x		x		x		x					x		x				x	x

TRANSPARENT METHODS

We conduct a qualitative case study based on two data sources: literature research and semi-structured elite interviews with key actors in the LIB field, i.e., R&D and industry authorities/experts and well-known senior-level inventors of LIB innovations. While the insights from literature (academic review articles, press releases, industry reports) help to illuminate the past development of LIBs, to identify potential interviewees and triangulate findings, the elite interviews serve to get an in-depth understanding of the spillovers, their sources, mechanisms and enablers.

We sampled the interviewees (elites) in a purposive, non-probability (i.e., non-random selection) way (Tansey, 2007). In contrast to random sampling, this strategy allows for a real-time and first-hand participant observation of the key actors in the field. We identified an initial subset of interviewees based on literature research, and then initiated a snowballing system whereby the initial interviewees were asked to recommend further experts in that area (Tansey, 2007). Hence, we wanted the relevant actors to be identified by the field and not by us as outsiders. We stopped contacting further experts once we had the sense that the sample was large enough for the main aim of the study (Tansey, 2007), which was the identification of mechanisms and enablers of spillovers based on selected examples. Unfortunately, despite several attempts, we could not reach every expert we wanted to.

We spoke to ten interviewees, half of whom were inventors and half were R&D and industry authorities/experts, including two Nobel laureates. Four of the interviewees were inventors and five were R&D and industry authorities/experts (see below for more details on interviewees and an exemplary interview guide). Each interview lasted 45–60 minutes and was conducted via phone by at least two researchers. While the researchers took notes during all interviews, interviews 1–8 were also recorded for reconstruction purposes, and interview 10 was a written discussion via email on our findings. Data collection and analysis proceeded iteratively in order to inductively develop an understanding of mechanisms and enablers for spillovers. This also allowed us to iterate with the literature, and adapt and specifically target our interview questions. In each interview (interview 10 being an exception here), we first sought an expert view on the LIB field, including the most important innovations. We then asked how those LIB innovations had come about. Inventors were primarily questioned about their own and related innovations, whereas R&D and industry experts were asked about underlying processes in LIB innovations in general, or specific examples they could recall in which spillovers had played a particularly important role. This second phase typically took up most of the interview time, particularly when the inventors provided many details of the innovation process. During each interview, we specifically discussed challenges and enablers that had affected the respective innovation(s) and encouraged spillovers, as well as the role of government. After compiling and analyzing all the information, we asked the interviewees to provide feedback on our results and on the descriptions of the general developments and their specific inventions.

For identifying the key breakthrough innovations, we took the technological advances mentioned most frequently. While mostly, the interviewees directly mentioned the technological advances, i.e., electrochemical intercalation, lithium cobalt oxide, graphite and the ethylene carbonate based electrolyte, some answered more broadly. We linked these replies to the respective technological advances if possible. In particular, (i) interviewee three (I3) stated that it was a breakthrough to make rechargeable LIBs work; we think this refers to all four breakthrough innovations, (2) interviewee nine (I9) mentioned "a high-voltage battery" as a breakthrough innovation, which could be attributed to the combination of LCO, graphite, and the ethylene carbonate based electrolyte, (3) interviewee seven (I7) mentioned a "stable electrolyte" as a breakthrough innovation, which we attributed to ethylene carbonate.

We considered knowledge to be external—i.e., a spillover—if it was developed for application in other technologies (beyond LIBs), sectors (beyond the development, production, and use of electrical energy storage), or scientific disciplines (beyond electrochemistry). We chose this narrow interpretation of what constitutes "internal"—and, hence, a broad interpretation of what constitutes "external"—because it enables us to identify spillover sources from a variety of distances, i.e., the transfer of knowledge ranging from relatively familiar to relatively unfamiliar. We consider the whole spectrum of external knowledge transfers to be relevant as they might require different kinds and levels of support. In addition, extant work applying a similarly narrow understanding has also demonstrated the relevance of spillovers from relatively familiar areas for technology and industry development (Battke et al., 2016; Mowery and Rosenberg, 1998; Stephan et al., 2019). A more conceptual description of our understanding of technology, sector, and scientific discipline can be found below.

Overview of interviewees

Number	Function	Reference
1	R&D and industry authority (director of research centre)	I1
2	Inventor	I2
3	R&D and industry authority (university professor)	I3
4	Inventor	I4
5	Inventor	I5
6	Inventor	I6
7	R&D and industry expert (manager)	I7
8	R&D and industry authority (manager)	I8
9	R&D and industry authority (scientific director of research centre)	I9
10	R&D and industry authority (university professor)	I10

Exemplary interview guide for an interview with an inventor

1. Introduction (5min)

- Thank for participation, and emphasize once again that it is an honor for us to have the opportunity to talk to them
- Introductions for the team (in general, and participants in the interview): «A», «B», «C»
- Introduction to the project
- Formalities (duration, consent to make a recording, confidentiality, etc.)
- Introduction to topic/what we have done/stimulus
- Structure interview as follows:
    1. Briefly discuss your expert view on past innovations in the field of LIBs
    2. Talk about your breakthrough innovation(s) and how they came about
       Better understand what sources of information and knowledge you use, and how you access them (this includes to what extent do they include (or have included) other industries, or fields of research beyond Li-ion research). [Target: How do you get new ideas? What information do you access?]
    3. Talk about future LIBs and innovation processes

2. Expert interview on the field (10 min)

- Identifying breakthrough LIB innovations (typically, they may have happened outside their own firm or organization)
    - What do you consider to be the *top three* [or more, if they can name more] important/breakthrough LIB innovations since its first conceptualization in the 1970s? How do they relate to challenges that LIBs were facing at that time (e.g., substantial cost reduction in terms of less materials, solved bottleneck xy which increased cycle efficiency, etc.)?
- [If not mentioned before] Specifically ask for the two inventions Material X, Material Y

3. Elaborating their research and innovation processes (30 min)

- Bridge to their inventions:
    - We think the inventions that you made have been crucial for the development of LIBs. [If not explained differently in the previous section] One of your major breakthroughs was the development of Material X. Starting with this [potentially coming back later on to other breakthroughs they mentioned or that we know of], we would like to understand how this happened.
- Understand innovation processes of their inventions [identify possible areas of, and avenues for, spillovers]

- Can you describe the research processes in general and with regard to the kind of knowledge that was involved?
- Why do you think it was you and your team and nobody else who came up with the ideas?
- Where do you see the biggest intellectual leap?
- Where did you get ideas from?
- Who was involved (researchers from different fields) in the research process?
- Which knowledge from other technologies/fields was relevant for your research?

- Challenges and enablers for knowledge exchange
  - How did/do you access these knowledge sources?
  - Which role did your own academic background play?
  - What have been challenges for your research regarding the access to different knowledge sources beyond your organization and industry? Strategies?
  - Can you think of measures that helped to obtain new knowledge from other sources beyond your organization and industry (e.g., government)?
- [If time] Also talk about other inventions that they suggested earlier on

4. Possible future developments (5–10 min)

- What will be the future bottlenecks and breakthroughs for LIBs?
- In what way, if any, will research in LIBs change over the next 5–10 years? E.g., organizations involved, knowledge exchange, technical parts of the battery in focus…?
  - Where do you think future breakthroughs [long-term] could come from?
  - How would you utilize these knowledge sources?
  - To what extent does industry structure play a role?
- Which role can/should the government play? Knowledge broker, papers, breakthroughs, information, networks, developing broader science

5. Opening up (5 min)

- Are there any other points regarding the aspects that we have touched upon that you want to add?
- Are there any other people you think we should talk to? With either a broad knowledge of battery innovations, or particular detailed insights about previous breakthroughs?

6. Closing (max. 5 min)

- Thanks, process for feedback on our results, any further issues

Our understanding of technology, sector, and scientific discipline

We understand a *technology* as an assembled physical artefact, which consists of different components and subsystems and is itself embedded in a broader social context (Tushman and Rosenkopf, 1992). In contrast to some studies that use the notions of technology and sector interchangeably (Nemet, 2012; Nemet and Johnson, 2012; Schoenmakers and Duysters, 2010; Verspagen, 1997), we understand a sector as a broader construct, which can encompass more than one technology. A *sector* consists of a group of organizations centered around certain outputs and characterized by similar knowledge bases, specifically with regard to production knowledge (Stephan et al., 2017). A sector can therefore develop, produce, or apply different technologies, and the value chain of individual technologies can cut across different sectors. We understand a *scientific discipline* as an academic field of education and specialization as typically developed at universities. Material science, electrochemistry, solid-state physics, etc. are examples. In particular, we identified a spillover if the transferred knowledge was not developed for LIBs (technology); if it was not related to the development, production, and use of electrical energy storage (sector); or if it originated from a scientific discipline other than “electrochemistry”.

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