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The Sectoral Configuration of Technological Innovation Systems: Patterns of Knowledge Development and Diffusion in the Lithium-ion Battery Technology in Japan

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Abstract

Technological innovation systems (TISs) have found favor for analyzing a technology's innovation dynamics. Complementary to TISs, the sectoral innovation systems approach focuses on sectoral peculiarities regarding innovation. This paper represents a first step towards integrating the sectoral dimension into TIS analysis. This seems particularly relevant for multi-component technologies, since their underlying innovation dynamics involve multiple sectors. We introduce the "sectoral configuration" of a TIS, which relates to the number and types of sectors linked via a TIS's value chain, and elaborate how the sectoral configuration plays out for a TIS's functional dynamics. We apply our theoretical framework to the *knowledge development and diffusion* function. Based on a quantitative analysis of patent data for lithium-ion batteries in Japan (1985–2005), we find that different sectors vary in importance for knowledge development and diffusion, especially with regard to the technology's evolution over time. Our findings suggest that the sectoral configuration deserves more attention in future TIS analyses. This would support a better understanding of functional mechanisms, and therefore offer the potential to derive enhanced TIS-based policy recommendations regarding the nature and balance between demand-pull, technology-push and interface improvement policies.

Keywords Technological innovation system, sector, system functions, knowledge development and diffusion, patents, lithium-ion battery technology

JEL classification: L64, O33, O38, Q28, Q42, Q48

1. Introduction

Technological change is a critical driver for economic growth and a key lever to address societal and environmental problems. Change in individual technologies occurs along trajectories shaped by technological paradigms (Dosi, 1982) and requires the interplay of organizations, material artifacts, and institutions (Hughes, 1987). Reflecting this systemic nature, one approach for analyzing innovation dynamics in individual technologies is the *technological innovation system* (TIS) (Carlsson et al., 2002). TIS scholars aim at understanding the socio-technical mechanisms underlying the innovation dynamics of new technologies[1]. They typically use this approach to pinpoint innovation system weaknesses, and derive policy recommendations on where and how to intervene to boost a specific technology (Hekkert et al., 2007; Hekkert and Negro, 2009; Jacobsson and Bergek, 2011).

TISs are related to two other dimensions, *geography* and *sectors* (Bergek et al., 2015, 2008; Binz et al., 2014; Markard and Truffer, 2008), since “technological progress […] is influenced by various national innovation systems and sectoral innovation systems” (Hekkert et al., 2007, p. 417 ff.). Particularly when aiming for policy recommendations, TIS scholars consider that system weaknesses or possible levers can also be found at the national—i.e. geographical—or sectoral level of a system (Jacobsson and Bergek, 2011). While recent research has started to integrate the geographical dimension into the TIS conceptualization (Binz et al., 2014; Coenen et al., 2012; Coenen and Truffer, 2012), the sectoral dimension has received less attention. At the same time, TIS analyses often focus on technologies that consist of various technological components and subsystems (Tushman and Rosenkopf, 1992) produced in different sectors. We term these technologies “multi-component technologies” (“MCTs”).

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[1] TIS offers a complementary perspective to other innovation system approaches such as national (e.g., Freeman, 1988; Lundvall, 1992; Nelson, 1988), regional (e.g., Cooke et al., 1997), and sectoral innovation systems (e.g., Breschi & Malerba 1997; Malerba 2002, 2004).

As literature has shown significant contrasts between sectors in terms of innovation behavior (e.g., Archibugi, 1988; Dumont and Tsakanikas, 2002; Iammarino and McCann, 2006; Malerba, 2002; Patel and Pavitt, 1994; Pavitt, 1984), this paper represents a first attempt to investigate a sectoral perspective on multi-component TISs. To understand the individual dynamics and interplay of different sectors active in a particular TIS, we introduce the term "sectoral configuration", which refers to the number and types of sectors linked via the value chain of a TIS. This can help to pinpoint sector-related bottlenecks and provide enhanced policy recommendations. More specifically, the sectoral configuration will affect the processes underlying the development of TISs—the so-called TIS functions (Bergek et al., 2008; Edquist, 2005; Hekkert et al., 2007).

We illustrate our theoretical argument with a sectoral analysis of the knowledge development and diffusion function in the Lithium-ion battery ("LIB") TIS in Japan. Sector-specific dynamics such as new LIB applications in transportation and energy sectors have probably affected LIB development substantially, and the knowledge development and diffusion function has a dominant role in early formation processes (Bergek et al., 2008; cf. Binz et al., 2014). Our quantitative analysis of LIB patent data in Japan in the period 1985–2005 shows how patterns of knowledge development and diffusion differ between the sectors involved in LIB technology. Those sectors integrating LIBs into larger systems have particularly contributed to knowledge creation in areas outside their production activities, thereby fostering knowledge diffusion across sectors. Our findings furthermore indicate that the importance of different sectors for knowledge development and diffusion varies over time.

Our analysis illustrates that our approach can yield not only a more detailed understanding of a TIS's functional dynamics, but also more informed policy recommendations. This suggests that the sectoral configuration deserves more attention in future TIS analyses, especially when TISs center around MCTs. By extending our conceptual framework to all TIS functions, we argue that our analytical approach might prove useful for future TIS (functional) analyses.

The paper is structured as follows: Section 2 presents a brief overview of the TIS concept, introduces the sectoral configuration of a TIS and discusses how the sectoral configuration might affect the knowledge development and diffusion function. Our research case, data, and methodology are outlined in Section 3. Section 4 presents and synthesizes the results. We extend our argument to the other TIS functions in section 5. Finally, we derive implications for TIS scholars and policymakers in our conclusion in Section 6.

2. Theoretical perspectives on the sectoral dimension of TISs

The concept of TISs is a key approach for studying the dynamics of (new) technologies. TISs evolved as a variant of innovation systems, focusing on the mechanisms underlying the evolution of individual technologies. Innovation systems are composed of a certain set of structural elements, which consist of "actors, networks, institutions (…) and, in some approaches (…), technology" (Jacobsson and Bergek, 2011, p. 45). Specifically, a *technological* innovation system encompasses all the actors that interact "in a specific economic/industrial area under a particular institutional infrastructure and [are] involved in the generation, diffusion, and utilization of [a] technology" (Carlsson and Stankiewicz, 1991, p. 111).

TIS scholars have emphasized that TIS evolution might be affected by other dimensions, such as geographies (Binz et al., 2014; Coenen et al., 2012; Coenen and Truffer, 2012) and sectors (Bergek et al., 2015, 2008; Hekkert et al., 2007; Markard and Truffer, 2008). While TIS scholars have recently started to analyze the geographical dimension (Binz et al., 2014), the sectoral dimension has received much less attention.

2.1 A sectoral perspective on TISs

Many TISs are related to different sectors (Bergek et al., 2015; Hekkert et al., 2007; Markard and Truffer, 2008) because modern technologies are typically assembled systems encompassing different technological components and subsystems, i.e., MCTs (e.g., Tushman and Rosenkopf, 1992). The way in which these are integrated and linked is determined by technology architectures (Henderson and Clark, 1990; Murmann and Frenken, 2006). Therefore, technology architecture is closely related to the way production activities are organized (Murmann and Frenken, 2006), i.e., the technology architecture determines upstream and downstream positions as well as supplier-customer relationships, and is thus reflected in the technology's value chain. When different process-specific capabilities are required, the technology's value chain links actors from different sectors (Malerba, 2002; Pavitt, 1984)[2]. Therefore, we apply a value-chain perspective to TISs[3]. We~~.~~ hence include all (vertically and horizontally) related parts of the value chain into our conceptionalization of a TIS, which represents a relatively integrated approach[4]. We suggest this integrated approach especially for the analysis of multi-component TISs, as all the different parts of the value chain are mostly highly relevant (and also interrelated) for the entire TIS's development.

Adapted from Porter (1985), a technology's value chain can be described as a collection of activities spanning across different firms that develop, produce, and use a technology[5]. Activities in a value chain are typically organized sequentially and can span different sectors (Sturgeon, 2001). The literature has shown that positions and relations in the value chain can affect innovation. For example, buyer innovation can spur supplier innovation (Isaksson et al., 2016), users are innovation sources for producers (Hippel, 1976), and innovation activities in upstream

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[2] Note that the value chain of a technology might be located within one or more countries, or distributed globally.

[3] Similarly, other scholars, such as Los and Verspagen (2002) have applied an input-output perspective to innovation systems.

[4] Different to our approach, a TIS can also concentrate on parts of the value chain (Bergek et al. (2015)). While in our approach, the different parts of the value chain can typically be attributed to different (larger) sectors, they would represent different TISs in an approach as suggested by Bergek et al. (2015). Note that Bergek et al. (2015) do not relate the different sectors to different parts of the value chain, but talk about broad sectors encompassing different technologies that fulfil similar functions for users.

[5] Note that this understanding, which goes beyond individual firms, relates to Porter's description of value systems (Porter, 1985).

fields can have predictive power on future downstream innovations (Acemoglu et al., 2016). While few TIS studies have applied a value chain perspective on TISs (Hellsmark, 2010; Musiolik and Markard, 2011), the linkages of different sectors can be further explored.

We assume that the existence of different sectors and their interaction affects TIS development, since sectors differ in their innovation behavior (see Dosi, 1988; Malerba and Nelson, 2011; Malerba, 2004, 2002; OECD/Eurostat, 2005; Pavitt, 1984)[6]. However, the term "sector" itself is used in several ways in these literature streams, particularly regarding the aggregation level and/or attribute that serves to group organizations into a "sector." Sector-defining factors can include similarity in output/products (Archibugi, 2001; Malerba, 2002), fulfilling a particular function for users (Bergek et al., 2015), processes of interaction (Breschi and Malerba, 1997), or similarities in production techniques and (process) knowledge (Malerba, 2002). To delineate different sectors within one TIS, we understand a "sector"[7] as an *aggregation of actors having similar production competences and outputs*. While actors within one sector that produce a particular component/subsystem are typically in competition with each other, actors from different sectors are often vertically—and sometimes horizontally[8]—linked in the technology's value chain, i.e., TIS. Individual organizations—such as conglomerates—may be active in various different sectors (e.g., vertically integrated firms).

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[6] These differences result from differences in certain dimensions, such as the composition of actors and their networks; technological diversification; knowledge base, research intensity and learning processes; production processes; complementarities among technology artifacts and activities; demand; and prevailing institutions (e.g., Dosi, 1988; Malerba, 2002).

[7] In literature, the terms "sector" and "industry" are mostly used as exact synonyms (e.g., Pavitt, 1984), but their definitions are occasionally debated (Hawawini et al., 2003). To avoid confusion, we use the term "sector" exclusively.

[8] For example, in the case that different sectors supply the components for one (sub)-system, or use the technology in an integrated system.

TISs and sectors have the same types of structural elements (Bergek et al., 2015): knowledge and technologies; actors and their networks; and prevalent institutions (Malerba, 2004). However, they differ in the boundaries that group these structural elements. TIS's actors can be attributed to different larger sectors, i.e., "structural coupling" (Bergek et al., 2015). This results in sectoral subgroups within a TIS, representing the overlaps between the TIS and various sectors.

Technological artifacts (outputs) are different for different sectors by our definition. In one specific multi-component TIS, all these artifacts serve the same technology. However, the various sectors' artifacts can also serve different technologies. The *knowledge bases* of the sectors center on, and emerge from, different scientific fields—such as the chemicals sector from chemistry. *Actors and their networks* relate to the sectors' structures with some sectors being dominated by a few large and powerful actors, whereas others have market power more evenly distributed among smaller and less endowed actors. Sector-specific networks, such as associations, establish linkages between actors of one sector. Finally, different *institutions,* such as standardization bodies and processes, labor markets, and financial institutions, govern different sectors.

2.2 The sectoral configuration of a TIS

The technology architecture determines the way production activities are organized in different sectors. The different components and subsystems of a technology require different process capabilities and therefore are produced/assembled in different sectors. Each TIS therefore has a *sectoral configuration*, a term that we introduce to refer to the number and types of sectors involved in a TIS. The different types (e.g., chemicals, transportation) determine the difference of the sectors involved[9]. Sectors can be more or less different in terms of their knowledge bases,

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[9] Note that we refer to the kind of sectors here, and not to the clustering of sectors into higher level types (see Breschi and Malerba, 1997; Iammarino and McCann, 2006; Pavitt, 1984).

processes, institutions, etc. This is, for example, shown in differences in their industry classification (OECD/Eurostat, 2005). In this view, while sectors such as transportation and electronics might differ substantially in their practices and knowledge, they might still be rather similar if compared to sectors such as finance or trade. Aspects related to the sectoral configuration but not determined by the technology's architecture are the sectors' maturities, relative power in the TIS, duration of activity in the TIS, and geographical location (local vs. global distribution of the TIS's value chain).

The sectoral configuration differs between TISs with different technology architectures. It seems reasonable to assume that this affects TIS development. A TIS related to a high number of sectors might naturally develop less smoothly than one related to one or two sectors, as there are fewer sectoral boundaries to overcome. These sectoral boundaries might be more severe the more different the sectors are. The more numerous and different the sectors, the more cross-sectoral interaction might therefore be required in a TIS.

Like any TIS, multi-component TISs are also embedded in specific policy contexts. Policy might relate to one or several sectors, or target the development of the entire TIS. The sectoral configuration can help policymakers achieve the appropriate policy mix and balance of policy measures to foster a TIS's development (Borrás and Edquist, 2013; Costantini et al., 2015b), which must reflect the factors hampering TIS development; in a multi-component TIS, these can include problems at individual sector level as well as in their interplay (TIS level)[10].

A multi-component TIS furthermore relates to different infrastructure contexts (Bergek et al., 2015). The different sectors active in a TIS typically have sector-specific infrastructures such as transmission and distribution lines in the power sector. The existence and the quality of these

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[10] Note that literature discusses how the policy mix affects exploitation/exploration activities (Costantini et al., 2015b; Hoppmann et al., 2013) or the development of non-radical innovations (Nemet, 2009).

infrastructures can therefore be a source of opportunities or constrains for the individual sectors' and thereby TIS development.

Figure 1 shows how a technology architecture (Figure 1a) relates to the sectoral configuration of a TIS via the value chain (Figure 1b) and with regard to actors and their networks (Figure 1c). In Figure 1b, *Component*$_1$ is produced by actors from *Sector*$_A$ (light blue), whereas *Component*$_2$ is produced by *Sector*$_B$ (dark blue). *Sector*$_C$ integrates those components into a *Subsystem* (light green), which is then integrated into a larger *Assembled System* by actors from *Sector*$_D$ (dark green). Finally, the assembled system is used in different integrated systems in *Sector*$_E$ (red) and *Sector*$_F$ (dark red). There might be further sectors supporting TIS that are not directly linked to the producing sectors, e.g., research or finance (*Sector*$_G$, grey). The sectoral configuration of the illustrated TIS consequently consists of seven sectors that can be more or less different. While more than one sector can be active in a single value-chain stage, one sector might also encompass different value-chain stages (not depicted in Figure 1). Furthermore, some actors might be active in more than one sector (e.g., vertically integrated firms; see the actor at the intersection of *Sector*$_C$ and *Sector*$_D$). While some sectors are more concentrated on the focal TIS (*Sector*$_A$, *Sector*$_D$), others might be more active in other TISs (e.g., *Sector*$_B$, *Sector*$_C$ *Sector*$_D$). Note that these actors are typically linked by factors beyond the production of technological artifacts, such as knowledge and information flows or vertical integration (Pavitt, 1984), typically in a less linear way.

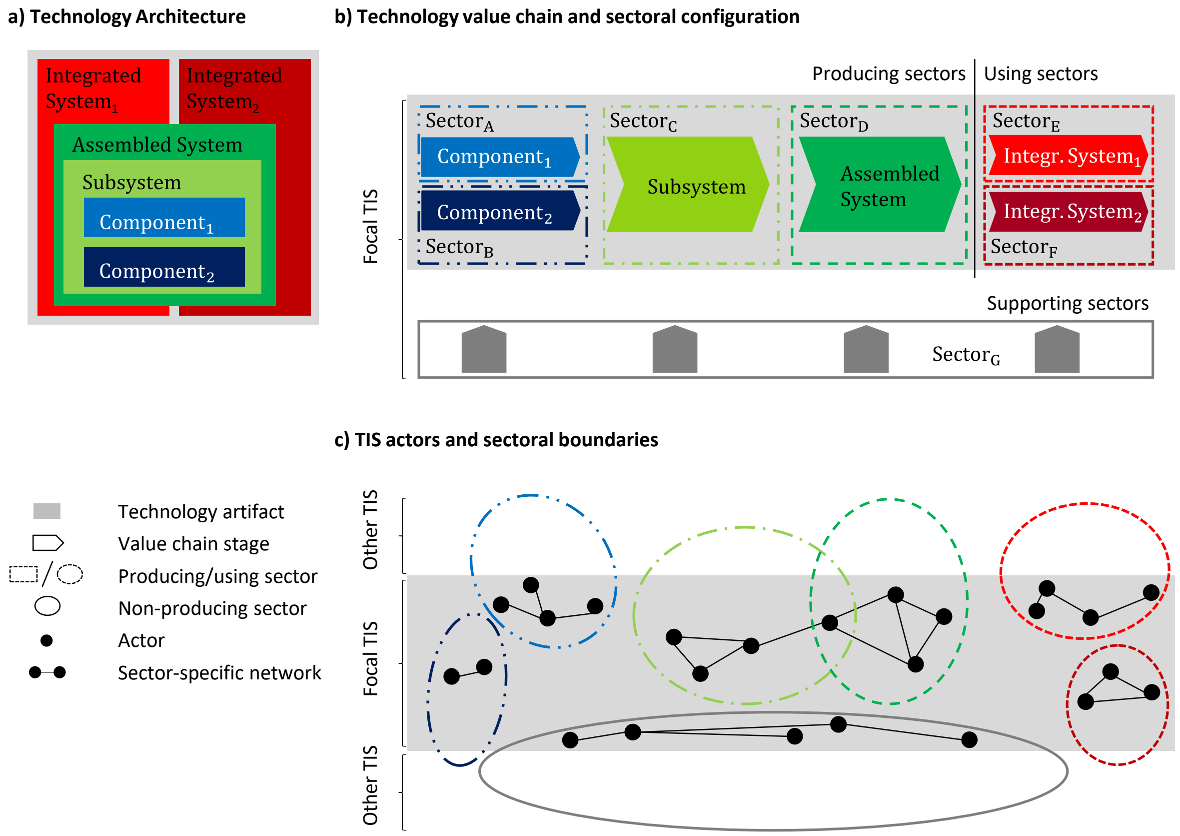

Figure 1 The relationship between technology architecture, the value chain, and the sectoral configuration of a TIS. a) Technology architecture describes how different technology artifacts such as components and subsystems are combined in an assembled system, which then can be integrated into one (or more) systems. b) The different components and subsystems can be ordered according to their sequence in production and use—i.e., further up- or downstream in the technology's value chain. The sectoral configuration describes the number and types of the different sectors that are active in the respective TIS. c) Each sector encompasses the actors producing similar outputs; these actors share similar institutions and production techniques, and are linked through sector-specific networks. One actor might be active in different sectors. The sectors are active in other technologies to varying degrees.

2.3 The sectoral configuration and the knowledge development and diffusion function

The evolution of a TIS is shaped by certain core processes, known as TIS *functions*: knowledge development and diffusion, influence on the direction of search, entrepreneurial experimentation, market formation, legitimation, resource mobilization, and the development of positive externalities (Bergek et al., 2008; Hekkert et al., 2007). For a TIS to evolve, its functions must be sustained by actors, and positive interactions between functions must be enabled, while negative interactions blocking innovation dynamics must be prevented (Negro and Hekkert, 2008). The functions might depend on the sectoral configuration, since interaction across different sectors is required to fulfill the functions on the technology (i.e., TIS) level. One might assume that the more sectors are involved, and the more different they are, the harder it is for them to interact—i.e. for the TIS to develop. We expect the sectoral configuration to play a particularly important role in knowledge development and diffusion due to its dominant role in early formation processes (Bergek et al., 2008; Binz et al., 2014) and the differences in knowledge-bases that characterize a sector.

Generally, both greater numbers and more different in terms of a TIS's sectors can represent opportunities for knowledge development and diffusion. As knowledge base and learning processes differ between sectors (Malerba, 2002), a large number of different sectors would imply a large and diverse knowledge base available to TIS actors[11]. Due to the cumulative and combinatory characteristics of knowledge (Arthur, 2009; Battke et al., 2016; Nemet and Johnson, 2012), one can expect a TIS that embodies diversified knowledge from different sectors to produce more breakthrough innovations (Schoenmakers and Duysters, 2010). New knowledge arises when old ideas are newly reconfigured or when novel knowledge is combined with existing knowledge (Fleming, 2001; Schilling and Green, 2011), engendering abundant "hybridization of ideas" (Weitzman, 1998, p. 334). New technologies can therefore be described as a combination of existing knowledge (Arthur, 2009). Especially in complex technologies, knowledge creation can be "viewed as a collective process made possible by the development of continuous accumulation of highly differentiated but complementary competences and technological knowledge" (Costantini et al., 2015a, p. 300). However, the bottleneck typically lies less in generating new ideas than in processing them into a usable form (Weitzman, 1998).

Knowledge flows between different sectors are therefore a precondition for successful knowledge combination, since the mere existence of many different sectors is not necessarily

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[11] Note that the existence of different sectors is beneficial not only for technologies, but also economies (Saviotti and Frenken, 2008) or regions (Frenken et al., 2007).

sufficient. Moreover, while knowledge flows across sectors "have become a central feature" (Mowery and Rosenberg, 1998, p. 170) for modern technologies, and their existence is shown in early works from Schmookler (1966) and Scherer (1982a, 1982b), they do not necessarily work smoothly[12][13]. Knowledge might rather accumulate within sectors than flow between them due to a combination of factors: similarities between the knowledge bases of organizations in a sector, the cumulativeness of knowledge, and the likelihood that specialized knowledge will flow to technically proximate new knowledge (Battke et al., 2016). The resulting sector-specific dynamics (as opposed to interactions between sectors) might be reinforced if the sectors differ sharply, resulting in a barrier for (natural) cross-sectoral interaction.

A large number of highly diverse sectors in a TIS can therefore act as a driver of non-incremental innovation—but may also constitute a constraint, if the diverse knowledge base cannot be exploited. In the following, we analyze how knowledge bases develop for a particular sectoral configuration.

3. Case, data, and methodology

3.1 Research case

We investigate the LIB TIS in Japan, for two main reasons. First, LIB technology consists of multiple components and subsystems produced in different sectors. Second, in the period of our analysis, substantial technological change has taken place in Japan during which LIBs have replaced other established battery technologies in various applications. In addition, LIBs are expected to play an important future role in the energy and transportation sectors (Battke et al., 2013; IEA, 2014; Lowe et al., 2010) and hence catch the interest of policymakers, practitioners,

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[12] Note that numerous studies investigate knowledge spillovers, specifically the role of knowledge diversity and specialization for a technology's development (e.g., Battke et al., 2016; Nemet and Johnson, 2012; Nemet, 2012).

[13] For example, Pan et al. (2012) find that knowledge diffuses more readily within sectors than between them.

and academics alike. As the use of LIBs in those sectors require further LIB development (Crabtree et al., 2015), investigating the role of different sectors can yield important insights.

Figure 2 transposes our theoretical argument to LIBs. The LIB's technology architecture consists of multiple components and subsystems (Figure 2a). The smallest unit includes the main components (cathode, anode, separator, and electrolyte), which are synthesized from raw materials. The main components enable the key functions of the battery: the electrochemical redox-reactions converting electrical into chemical energy (charging) and vice versa (discharging). Single cells assemble the main components—enhanced through peripheral components (e.g., wiring, casing, cooling system, balance of system)—and might be stacked into a battery pack. LIBs can be integrated into various larger technical systems, as in mobile applications (e.g., laptops, electric vehicles) or stationary applications (e.g., integration of intermittent renewables into electricity grids).

These different subsystems and applications require different production processes and specific knowledge, provided by different sectors (Figure 2b). For instance, raw materials from the mining sector are processed into main and peripheral components by the chemicals, metals, and electronic and electric sectors. The electronic and electric sector assembles components into the battery cell or pack, and several sectors integrate the battery into their final application. Individual sector dynamics have probably affected LIB TIS innovation processes. While consumer electronics pioneered the use of LIBs, automotive firms have entered the TIS in their quest to attain national targets for electric transport.

The sectoral configuration of the LIB TIS therefore consists of many and different sectors. Their (process) knowledge and practices differ substantially, e.g., since they are based upon different scientific disciplines. Note that the technology architecture and sectoral configuration illustrated in Figure 2 indicate the complexity of knowledge creation in LIBs.

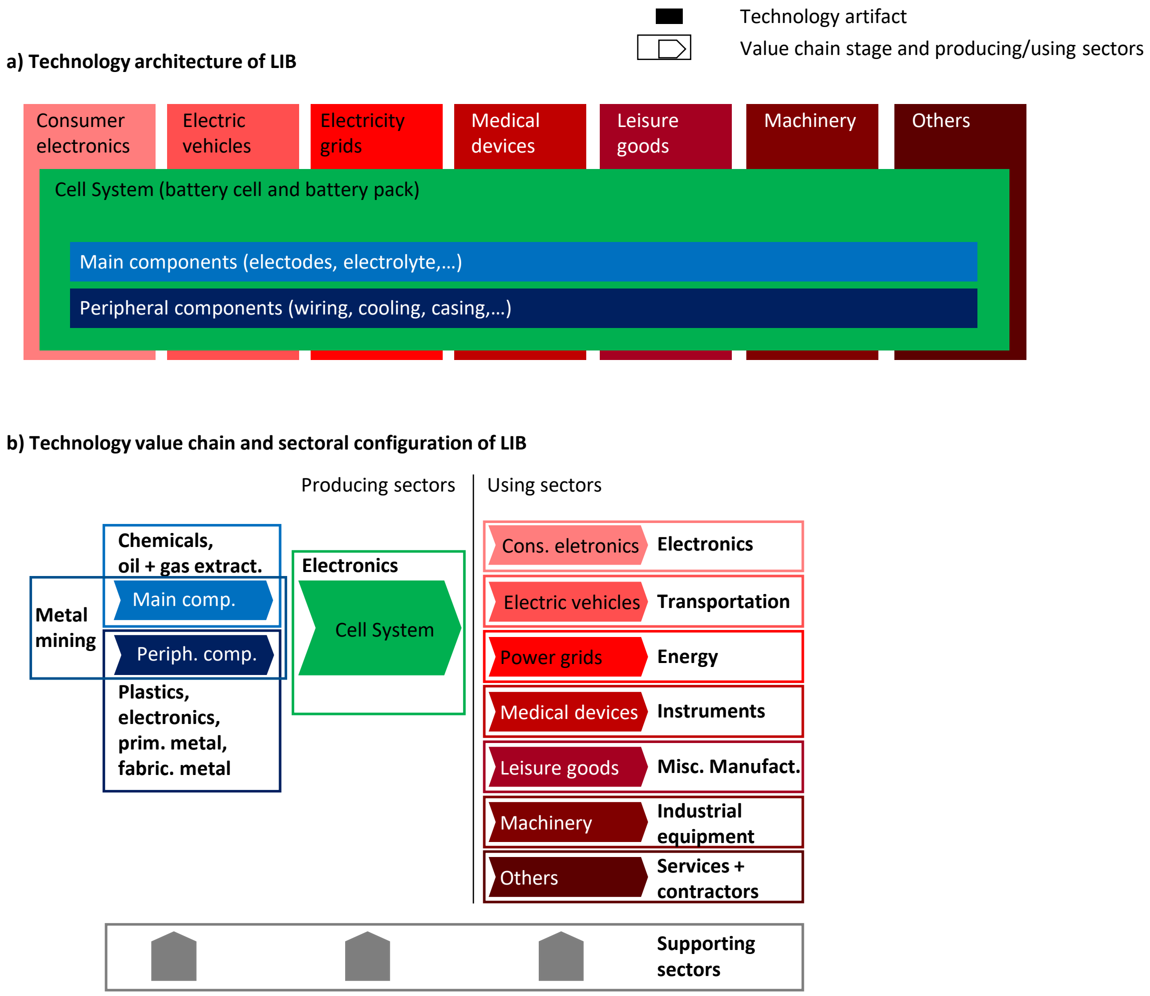

Figure 2 Transposing the sectoral configuration presented in Figure 1 to LIBs. a) The LIBs' technology architecture of different components and subsystems, including different applications. b) Different sectors are involved in the value chain of producing and using LIBs. (The main and peripheral components could be broken down further into more sectors, but are aggregated for clarity.)

LIB technology has made significant progress within the last 30 years, especially in Japan. Many sectors have successfully collaborated in the realm of LIB development in Japan (Keller and Negoita, 2013), and the country has led the way in LIB development, achieving a dominant market share (57% in 2010 (Lowe et al., 2010)). Furthermore, Japan has the highest share (73.5%) of global LIB patents in the analyzed period (see also Appendix A), indicating the extent and pace of evolution in the underlying knowledge base. Eight of the top 10 firms applying LIB patents are located in Japan (Mueller et al., 2015).

The Japanese government has implemented several policies that have fostered LIB development during the period investigated and continues to do so until now. Different programs have been in place since 1992 (Tatsumi, 2010) and Japan still has ambitious LIB development targets for the future (Energy Storage Council, 2015; IRENA, 2015a; pv magazine, 2014). While general LIB development began in the electronics industry, Japanese policy has specifically targeted electric-vehicle and grid applications, and has successfully fostered cross-sectoral collaboration between utilities, electronics, battery manufacturers, automotive firms, and universities (Keller and Negoita, 2013). By starting the "Development of dispersed-type Battery Energy Storage Technology" and establishing the Lithium Battery Energy Storage Technology Research Association (LIBES)[14] in the early 1990s, the Japanese government has started to support LIB development. This R&D project was already targeted at both stationary and automotive batteries[15] (Åhman, 2006; Koyamada and Ishihara, 1995; Tatsumi, 2010). Since then, further policy measures such as R&D, infrastructure and market support for BPEVs (Åhman, 2006) and—especially in the recent years—several subsidy programs for stationary (lithium-ion) batteries, demonstration programs and standardization efforts have spurred LIB development (pv magazine, 2014; Tomita, 2014). The fact that Japan was so successful in LIB development can also be related to the strong National Innovation System, which is characterized by a high R&D expenditure and strong linkages between industry actors (Freeman, 1995).

3.2 Data and method

To address our research objective, we selected an analysis of patent families (hereafter, simply "patents"). Patent data are suggested in TIS literature as one measure for knowledge development and diffusion (Bergek et al., 2008; Hekkert et al., 2007), and have been widely used as a measure of inventive activity and knowledge flows (e.g., Griliches, 1998; Jaffe and de

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[14] The "dispersed-type battery energy storage program" was run by the LIBES as part of the "new sunshine project" (Koyamada and Ishihara, 1995; Terada et al., 2001).

[15] This program has resulted in the first LIB suitable for electric vehicles (Åhman, 2006).

Rassenfosse, 2016; Jaffe, 1989)[16]. Hence, we use counts of patents and patents' forward citations[17] as proxies for knowledge development and knowledge diffusion (Corrocher et al., 2007; Nemet, 2012; Nemet and Johnson, 2012; Rosenkopf and Almeida, 2003).

We retrieved, processed, and analyzed our patent data in a three-step approach. *First*, we retrieved our data from the *Thomson Innovation* database[18]. Relevant patents were selected using sequential data-retrieval rounds based on a combination of keyword- and classification-based (International Patent Classifications, IPC) searches (Battke et al., 2016)[19]. After each round, we tested data for false positives and false negatives and adapted the search string until low levels (<5%) of shares of false positives and false negatives were reached (for more information see Appendix B). Forward-citation information was linked by a MATLAB-based matching algorithm, which identified all citations created from one LIB patent to another during the period covered. Our analysis spanned the years 1985–2005 to ensure consistent data coverage and quality[20].

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[16] While patents exhibit limitations, they serve as a good index of inventive activity (Griliches, 1998). The use of patent citations for knowledge flows is also not without its limitations (Alcacer and Gittelman, 2006; Criscuolo and Verspagen, 2008); however, it is superior to other measures, such as R&D relationships (Verspagen, 1997). The use of patent citations as a proxy for knowledge flows is discussed in detail in Jaffe and de Rassenfosse (2016).

[17] A forward citation from patent A to patent B is created if patent B builds upon knowledge from patent A, and thus must cite patent A.

[18] The *Thomson Innovation* database covers the most important patent offices worldwide (Battke et al., 2016).

[19] We chose to combine IPC classes and keywords. Note that previous analyses on energy technologies have focused on either classification schemes (e.g., Verspagen, 2007) or keywords (Costantini et al., 2015a; Nemet, 2009). The latter are considered more appropriate, as the IPC classification system might not reflect the economic activity that the researcher wants to cover (Corrocher et al., 2007; Costantini et al., 2015a; Lybbert and Zolas, 2014).

[20] Data were retrieved at the end of 2012. We covered the period until 2005 as we wanted to ensure that all patents had a comparable chance of being cited, and to allow for the duration of the examination process.

Second, to explore patterns in knowledge development and diffusion with regard to the framework presented in Figure 3, we classified each patent into both its technology architecture category and the sector of the patent's assignee in terms of production. We distinguished between four different technology architecture categories within LIB technology: Main Components, Peripheral Components, Cell System, and Battery Integration (based on Battke et al. (2016), industry reports (Lowe et al., 2010), and expert interviews). We then used Derwent Electrical and Chemical Patents Index (EPI and CPI) Manual Codes to identify each patent's technology architecture category. Two researchers independently assigned EPI and CPI manual codes to the technology architecture categories[21]. Patents were unambiguously assigned to one of these categories if at least 50 percent of their manual codes fell into that category[22].

The sector of each patent's assignee was determined either by standard industry classification (four-digit SIC)[23] codes or, if they were unavailable, by manually coding publicly available company information such as industry reports, company websites, and company databases. As SIC codes and our manual classification categorize organizations into sectors depending on their products, both match up with our delineation of a sector based on production knowledge. We restricted our analysis to sectors relevant to LIB production[24], and added the sector Research[25], as this is the sector dedicated to knowledge creation. Classification and coding was also cross-

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[21] A consensus on the categories of all Manual Codes was reached among the researchers.

[22] Otherwise, they were not considered in our analysis.

[23] We used SIC 1–8 of each organization.

[24] Two researchers independently identified the relevant sectors on a four-digit level, but aggregated them into two-digit sectors for the analysis. Furthermore, we aggregated different services and contractors into the Service & Contractors sector, as they are only weakly related to battery production or integration.

[25] This sector encompasses organizations that are solely devoted to research activities, such as universities and pure research companies. Patents filed by the research departments of firms assigned to other sectors are classified into the sectors of the respective firm.

checked by two independent researchers[26]. We covered organizations that assigned at least one patent with at least five forward citations. In doing so, we made sure we covered those organizations that are most relevant for the most important inventive activities in LIB technology. Multiple classifications occur when organizations act in several sectors (e.g., conglomerates).[27] Patents were assigned to a country via their stated priority country. Our final database comprised 15,947 patents from Japan.

We assigned the patents to the technology architecture categories and sectors as shown in Figure 3. The wide spread of SIC codes across different fields—five first-digit differences—indicates how different the LIB TIS's sectors are. Furthermore, Figure 3 illustrates how the technology architecture categories relate to the sectors' production activities (shown in green).

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[26] Inter-coder reliability was calculated on a sub-sample, in which a satisfactory inter-coder reliability of more than 88% could be reached.

[27] Our assignment procedure assumes that knowledge developed in one part of the organization exists within the entire organization.

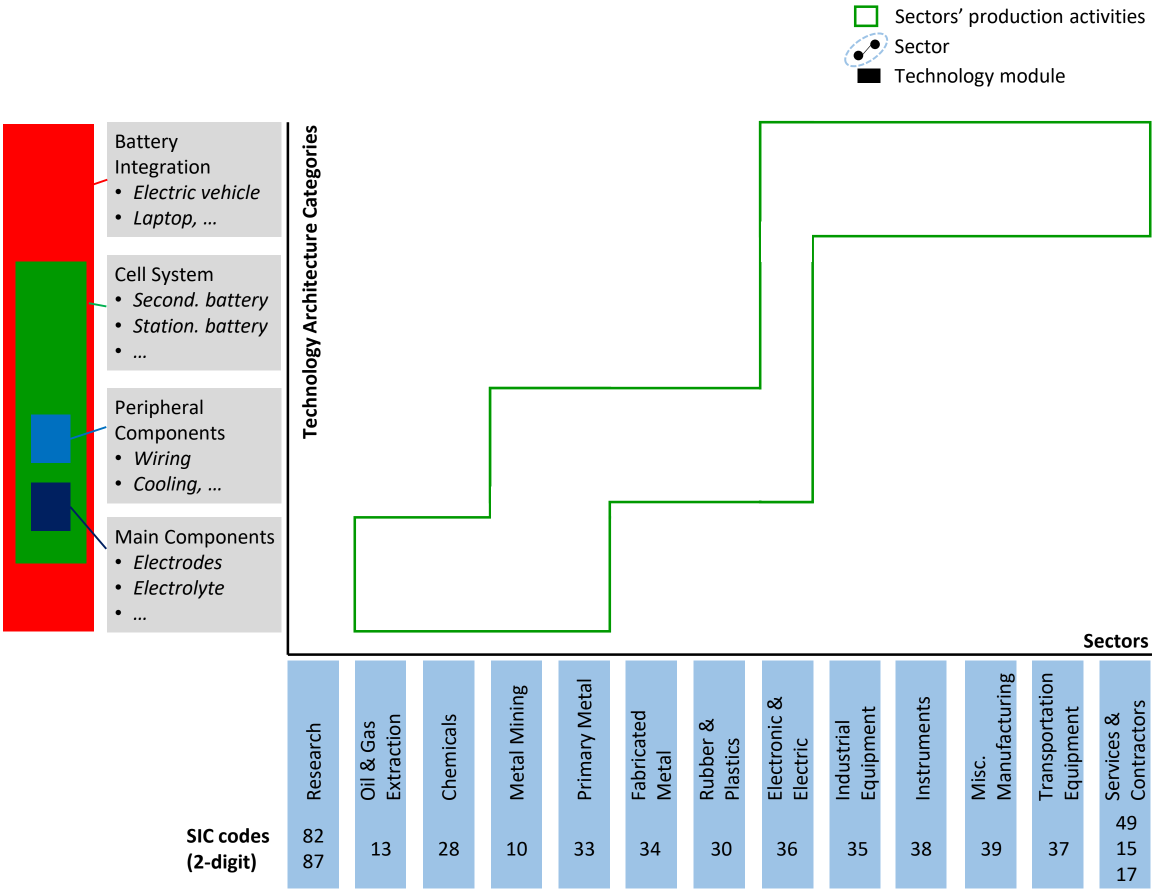

Figure 3 Illustrative sketch of the relationship between the sectoral configuration and the knowledge development and diffusion function in LIB technology. Different sectors are distinguished via SIC codes. We aggregated some SIC codes to increase reader friendliness.

Third, we analyzed our data with a longitudinal network approach, clustering patents into nodes and forward citations (hereafter simply "citations") into arcs. Sizes of nodes and arcs reflect the number of patents or citations they contain, respectively. We used the social-network analysis software *Pajek*; see e.g., Huenteler et al. (2016b).

4. Results

4.1 Static analysis of sectoral knowledge development and diffusion in the LIB TIS in Japan

Figure 4 shows the number of patents assigned by each sector in each technology architecture category and the number of citations between them over the entire period.

We elaborate on four striking aspects. First, sectors differ in their total numbers of patents (columns in Figure 4), which range from 12 (*Misc. Manufacturing*) to 11,474 (*Electronic & Electric*) (horizontal axis labels Figure 3a). *Electronic & Electric* is most prolific*,* followed by *Industrial Equipment, Chemicals,* and *Instruments*. Despite its designated role as knowledge generator, the patent activity of *Research* is negligible.

Second, sectors have the same preferences regarding the order of technology architecture categories. However, since they differ in their production activities (shown by the green area in Figure 4), the respective overlap of production and patent activity differs between sectors. Most patent activity occurs in *Main Components*, followed in descending order by *Cell System*[28], *Peripheral Components,* and *Battery Integration* (vertical axis labels in Figure 4). Therefore, a substantial number of patents in all technology architecture categories are developed in sectors that are not responsible for the respective components' production. For instance, the *Electronic & Electric* sector holds twice as many patents in areas outside its own production activities as within it. In *Main Components* especially, *Chemicals*, the sector "responsible" for production, develops only the third-largest number of patents, being outperformed in this respect by *Electronic & Electric* and *Industrial Equipment*, neither of which produces *Main Components.*

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[28] Misc. Manufacturing being an exception here.

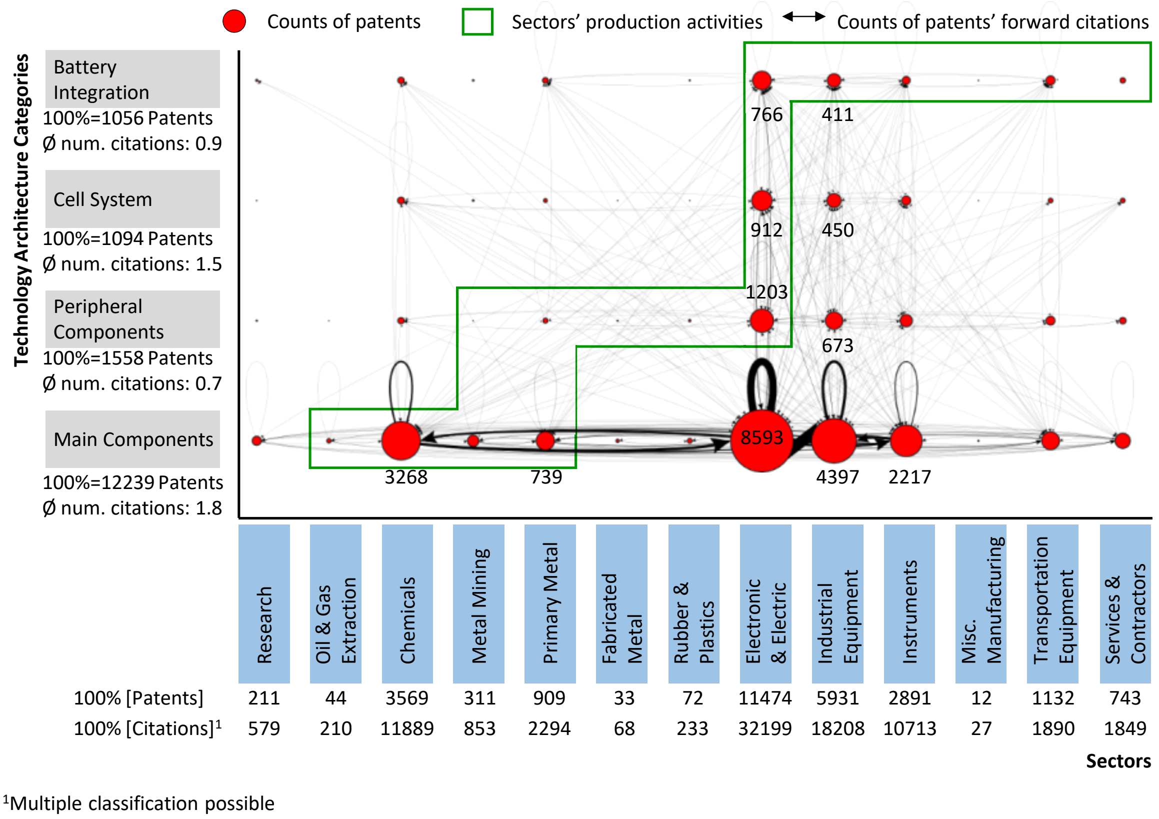

Figure 4 Distribution of patents and citations across sectors for each technology architecture category in the LIB TIS in Japan, 1985–2005.

Third, the total number of citations varies substantially[29]. In line with its importance in patenting activity, *Electronic & Electric* has the most citations, followed by *Industrial Equipment, Chemicals,* and *Instruments*. This might result from the large number of patents this sector develops compared to others. Patents in *Main Components* and *Cell System* are, on average, more likely to be cited than those in *Peripheral Components* and *Battery Integration.* As the sectors mentioned obtain large numbers of patents in the first two technology architecture categories, this might even reinforce the effect that their high totals have on their citations.

Fourth, citations occur within sectors (vertical arcs and loops) and between them (horizontal and diagonal arcs). However, the latter predominate, due to the many citations that occur across

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[29] The total number of forward citations per sector varies between 27 (Misc. Manufacturing) and 32,199 (Electronic & Electric).

sectors and within technological architecture categories (horizontal arcs)[30]. Cross-sectoral citations are especially prevalent between *Electronic & Electric*, *Industrial Equipment, Chemicals,* and *Instruments* in the technology architecture category *Main Components*. However, these four sectors also dominate in terms of citations within sectors (vertical arcs and loops). Citations within sectors and technology architecture categories (loops) are most striking for *Electronic & Electric* in the technology architecture category *Main Components*. Citations across sectors and technology architecture categories (diagonal arcs) are most striking between the sectors mentioned and the technology architecture categories *Cell System* and *Main Components*.

4.2 The evolution of sectoral knowledge development and knowledge diffusion in the LIB TIS

Figure 5 shows the results in five-year steps, mapped cumulatively, while Figure 6 depicts the patent activity of the most active sectors[31]. We emphasize four observations.

First, sectors start their patent activity in the same technology architecture categories, spreading to others over time. Patent activity and citations typically start in *Main Components* and *Cell System* and later spread to *Battery Integration* and *Peripheral Components* (Figure 5).

Second, Figures 5 and 6 show that each sector began patenting at a different time. Some sectors, such as *Electronic & Electric*, *Chemicals,* and *Instruments,* were active from the outset, while others, such as *Transportation Equipment,* entered later. The former sectors are also those that patented in the technology architecture categories *Battery Integration* and *Peripheral Components* first (from 1990 on), while other sectors began no earlier than 1995 (e.g. *Transportation Equipment*).

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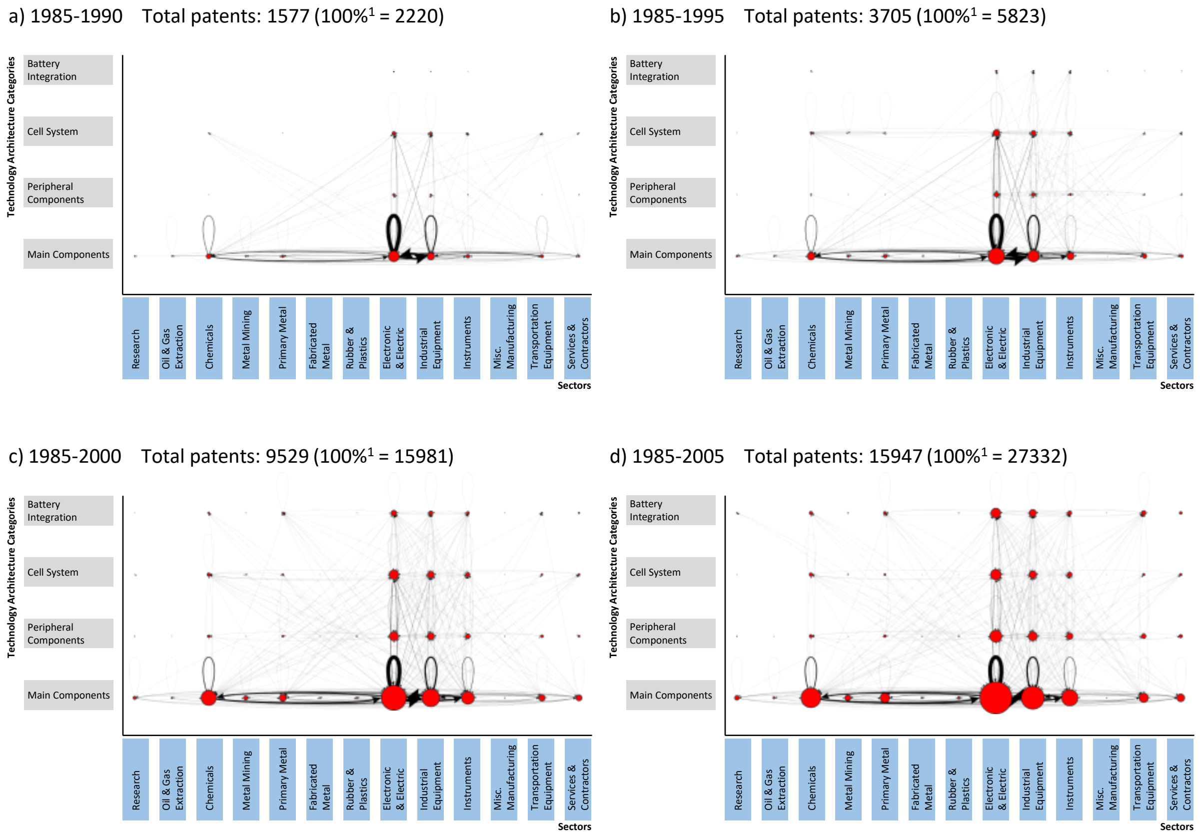
[30] The exact counts of citations are: horizontal arcs (47,069), loops (20,664), diagonal arcs (9,015), vertical arcs (4,264).

[31] Sectors depicted have a share of at least 4% on all patents in at least one year.

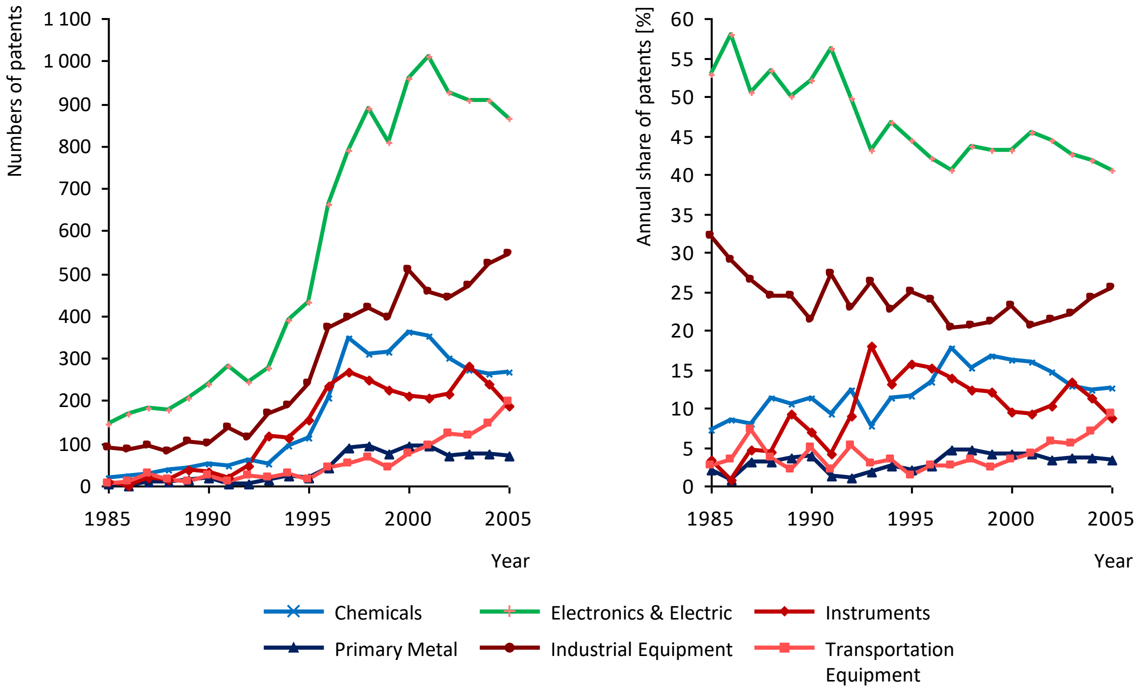
Third, the timing of peak patent activity varies between sectors (Figure 5a). For example, by the mid-1990s, *Chemicals* is at its zenith, *Electronics & Electric* and *Industrial Equipment* seem to be on a plateau, and *Transportation Equipment* has yet to reach its peak.

Fourth, sectors vary in their shares of the total number of patents over time (Figure 5b)—a fact that results from the previous two aspects. While *Transportation Equipment, Instruments,* and *Primary Metal* have almost identical (low) shares at the beginning, by 2005 their shares vary greatly. Thus, the role or importance of the different sectors for knowledge development changes over time.



¹Multiple classification possible

Figure 5 Evolution of patents and citations across sectors for each technology architecture category in the LIB TIS in Japan over different periods. Arcs' thickness represents their relative importance over the specific period; arcs may therefore narrow or even vanish over time as their relative importance decreases



a) Total patents assigned per sector over time

b) Annual share of patents assigned per sector over time

Figure 6 Annual patents of selected sectors: a) total patents per sector over time; b) annual share of patents per sector over time

4.3 Synthesis of the identified knowledge development and diffusion patterns in the LIB TIS in Japan

In a nutshell, our results demonstrate three aspects: knowledge development and diffusion differs substantially between the sectors active in the LIB TIS in Japan; knowledge diffuses widely across sectors; and the role of the different sectors changes over time. The large number of different sectors in the LIB TIS in Japan therefore exhibits both sector-specific dynamics and cross-sectoral interaction.

We find that sectors differ in the numbers of patents (indicating the amount of relevant knowledge developed), especially as some develop knowledge in areas outside their production activities (indicating the kinds of relevant knowledge developed). Both the individual sectors’ amount of knowledge creation and the diversification patterns seem to be LIB-specific[32]. The effect of knowledge diversification is remarkably strong for sectors located downstream in the LIB value chain. This might result from the sectoral configuration of the LIB TIS. While firms, especially those active in cumulative technologies (Stuart and Podolny, 1996), develop their "technological activities in an area close to [their] own production activity" (Bergeron et al., 1998, p. 741), system integrators of complex technologies[33] seem to diversify their knowledge rather than specialize in what they produce (Brusoni et al., 2001; Lee and Veloso, 2008; Takeishi, 2002). An organization/sector's knowledge-creation patterns can hence relate to its position in the LIB value chain. Furthermore, multiple new LIB applications (Stephan et al., 2016) and the LIB performance required (Crabtree et al., 2015) cause high technology uncertainty, which can intensify this effect (Brusoni et al., 2001).

These diversification patterns can explain the unexpectedly high number of cross-sectoral citations. Downstream sectors develop knowledge in upstream sectors' production areas as the knowledge bases of these sectors partly overlap. In this case, technological proximity (Battke et al., 2016)[34]—which can explain knowledge flows within one sector—could also explain

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[32] Other studies such as the analysis of US patents from different French sectors (many technologies) (Bergeron et al., 1998) indicate that the ranking of the sectors according to their patent activity we identified in the LIB TIS does not necessarily reflect overall dynamics. Moreover, especially the diversification of the sectors located downstream in the value chain into the area of *main components* seems to be particular to the LIB TIS. Diversification patterns might be less pronounced or occur in other areas in other technologies.

[33] Both interviews with LIB research experts and the heterogeneity of our data sample demonstrate that LIB exhibits complexity (Battke et al., 2016; Huenteler et al., 2016b). Our patent sample spreads across 381 IPC classes (first classification code of the families, IPC differentiation on a four-digit level), demonstrating the complexity of knowledge involved (Costantini et al., 2015a).

[34] Battke et al. (2015) refer to different technologies, whereas we refer to different technology architecture categories within one technology. We therefore transfer the concept from different technologies to different components of one technology.

knowledge flows across sectors. Note that literature has not previously analyzed knowledge diffusion across sectors and technology architecture categories at the same time (diagonal arcs). While explanations are subject to further analyses, these flows might engender generic knowledge, or build on extant knowledge from other sectors or technology architecture categories.

Our findings further indicate that different sectors' input might be more important at certain times due to different knowledge being required at different points[35]. Sectors active towards the upstream end of the value chain seem to be more important earlier on, while downstream sectors become more important later. One explanation might be the (relatively new) multiple mobile and stationary (Battke and Schmidt, 2015) applications that LIBs can serve. While some applications have been in widespread use for over a decade (mobile phones, hearing aids), others (electric vehicles, grid applications) have just emerged and will be important in the future. The role of different integrating sectors therefore changes with the importance of different battery applications. The Japanese government's efforts hence seem to have shifted knowledge creation in the LIB TIS towards grid and transportation applications during the period analyzed[36].

5. Discussion

Our empirical analysis of the knowledge development and diffusion function of the LIB TIS demonstrates that a sectoral perspective generates useful new findings that can be of theoretical and practical relevance. It is very likely that the same effects also play out for other functions. We briefly illustrate this on two further functions, guidance of the search and market formation in the LIB TIS before we extend our argument more general to all TIS functions.

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[35] See Huenteler et al. (2016a) for similar effects in wind-power technology.

[36] Note that determining the detailed effect of the different policy instruments and their interplay on knowledge creation is subject to further research.

Influence on the direction of the search, for example, illustrates how sector-specific dynamics might have affected TIS functions and thereby the TIS's innovation dynamics. Policy has directed LIB search towards power and transportation applications in Japan (and elsewhere) responding to landscape changes such as the oil crisis, the Fukushima disaster, and climate-change mitigation efforts. LIBs can help integrate renewable energy technologies in the power sector, and power electric vehicles in the transportation sector. Policy measures such as demand-pull instruments that support electric vehicle uptake (IEA, 2016) or stationary battery deployment, or technology-push instruments such as specifically targeted R&D programs (Borden and Schill, 2013; IRENA, 2015a) have created incentives for research in these sectors and for organizations to enter the LIB TIS. Japan is one of many countries that clearly shows how LIB development began in electronics, later moving to transportation and power (IRENA, 2015a; Keller and Negoita, 2013). These policy efforts have stimulated deployment and resulted in substantial technological learning (Nykvist and Nilsson, 2015), benefitting all sectors in the LIB value chain.

We can observe similar patterns for market formation. While the first LIB was commercialized and used within one firm (Sony[37]) and therefore also one sector in 1991, new markets have formed since then. Policy has started to foster markets in the energy and transportation sectors with typical demand-pull instruments, e.g. via electric vehicle tax regimes (IEA, 2016) or grid storage procurement targets (IRENA, 2015b), or by supporting demonstration projects (IRENA, 2015a). Deployment has thus increased, and the relative market shares of different using sectors on LIB deployment has shifted from consumer electronics to power and transportation sectors (Chung et al., 2015).[38] These market dynamics in new sectors have substantially increased TIS development, accompanied by changes in the organization of production activities in the TIS's

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[37] The first commercially successful LIB was used in Sony's own camcorder (Sony Corporation, 2016).

[38] Note that these shifts required specific infrastructures as these sectors relate to different infrastructures: consumer electronics to mobile communication infrastructure, power sectors to the electricity grid, transportation to charging infrastructure for electric vehicles.

value chain (e.g., joint ventures or vertical integration efforts across different sectors). The Gigafactory—a Tesla-Panasonic joint venture—is one example.

Our empirical analysis shows that certain sectors in the LIB TIS in Japan predominantly drive knowledge development and diffusion, and that their importance varies over time. Based on the discussion of the direction of the search and market formation in the LIB TIS, we hypothesize that the sectoral configuration also plays out in other LIB TIS functions. Table 1 illustrates how sectoral differences and their interplay in the TIS's value chain might affect TIS functions. The more "extreme" the sectoral configuration—i.e., the more numerous and different the sectors in the value chain—the more severe the potential outcome. We therefore propose to extend our conceptual argument to the other TIS functions as well. Empirical evidence of sectors' role in other functions would further strengthen our argument; our analytical approach might prove useful here.

Table 1 How sectoral differences and the cross-sectoral interplay in a multi-component TIS might affect TIS functions

TIS function[39]	**Examples of sectoral differences**	**Examples of the cross-sectoral interaction effect in a single TIS**
Knowledge development and diffusion	• Differences in knowledge bases and learning processes (Malerba, 2002), e.g., due to different scientific fields	• A large and diverse knowledge base might be available for the recombination of knowledge into new ideas • Knowledge might not diffuse smoothly between different sectors
Entrepreneurial experimentation	• Differences in industry structures (Iammarino and McCann, 2006) • Differences in R&D behavior (Patel and Pavitt, 1994) • Differences in technical opportunities and appropriability conditions (Pavitt, 1984) determine R&D incentives and productivity of innovative effort (Levin et al., 1985)	• Sectors might not interact (firms are less likely to collaborate and experiment across sectors than within (Mowery et al., 1998)) in order to consider the other sectors' technical requirements and R&D appropriabilities

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[39] See Bergek et al. (2008), Hekkert et al. (2007), Lundvall (1992), Negro et al. (2007) for descriptions.

TIS function[39]	Examples of sectoral differences	Examples of the cross-sectoral interaction effect in a single TIS
Influence on the direction of search	• Different sector-specific technological opportunities and limitations (e.g., production processes) (Malerba, 2002) set boundaries for the respective sectors' direction of search • Different applications in different sectors might offer multiple potential search directions	• Sectors might not develop a common vision of the technology easily, as sector-level requirements have to be coordinated • If one sector has greater relevance for policymakers (e.g., public interest in one application), the TIS will benefit from guiding search in this direction, but might also lock in a single technological design
Market formation	• Sectors' products serve different technologies (Malerba, 2004) and are included in different markets • The typical policy instruments stimulating market formation, such as tax regimes and minimal consumption quotas (Hekkert et al., 2007; Negro et al., 2007), might only stimulate some sectors' markets—with an emphasis on end-products' market formation • Differences in characteristics that influence market formation (e.g., pricing mechanisms, contracting procedures)	• Creating markets between sectors for product exchange might be complicated due to sectors' differing institutions/ characteristics • Other technologies' market dynamics might also impact a TIS (e.g., increased demand or increased prices)
Resource mobilization	• Different resource requirements and access to resources (e.g., different market risks leading to different financing risks and hence financing costs; access to human resources might differ between sectors)	• Sectors might not coordinate their individual resource requirements for the focal technology (or others)
Legitimation	• Different levels of legitimacy due to the sectors' products (e.g., tobacco products) or production techniques (e.g., sectors using carbon- or resource-intensive production techniques) • Idiosyncratic legitimation processes • Legitimacy differences due to different relevance of sectors in certain geographies	• Not all sectors might contribute (equally) to an increased legitimation of the technology • It might be difficult to align individual processes of legitimation
Development of positive externalities	• Likelihood of creating positive externalities differs between sectors	• Positive externalities within a TIS might not occur between different sectors • Positive externalities might flow more easily from/to other TISs if sectors are involved in different TIS

6. Conclusion and implications

This paper represents a first step towards integrating the sectoral configuration into TIS analysis. Our empirical illustration indicates that mapping the TISs' functional dynamics with regard to the sectoral configuration helps to identify the roles that different sectors play in a function's performance over time. We therefore suggest that the sectoral configuration deserves more attention in future TIS analyses and hope that our paper may spark future research on the sectoral configuration in the TIS community.

Three additional aspects might prove useful as starting points. First, scholars could elaborate on how different sectoral configurations might affect functional dynamics in a TIS. We assume that different sectoral configurations, e.g., more similar sectors linked in a technology's value chain than in the LIB TIS, might result in a different relevance of the sectoral dimension as well as different functional dynamics. The knowledge diversification of downstream sectors that we find in the LIB TIS indicates that the functional dynamics also relate to the positions of the sectors in the value chain. Second, the role of larger types of sectors[40] and their interaction might be interesting. Both aspects would expand the predominant scope of analysis towards a comparative analysis of multiple TISs, and serve as a starting point for a taxonomy of sectoral configurations in the realm of TIS development and policy intervention. Third, integrating spatial and sectoral dimensions at the same time might heighten the conceptual rigor and practical relevance of TIS analyses. Other than in the LIB TIS, many technology's value chains are globally distributed—and institutional contexts at system and organization level, in particular, typically relate to spatial dimensions such as countries or regions (Binz et al., 2014).

We argue that policymakers can make good use of information on the TIS's sectoral configuration and the interaction of different sectors in its functions. Sectors need support and coordination, especially when new ones need to be built up or those lagging behind need to be encouraged to catch up. The LIB TIS being a technology that has to improve for new applications

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[40] For instance, Pavitt (1984) distinguishes between supplier-dominated, production-intensive, and science-based sectors, whereas Iammarino & McCann (2006) develop a knowledge-based taxonomy that distinguishes between pure agglomeration, industrial complex, and social network. Breschi & Malerba (1997) characterize sectors by opportunity conditions, appropriability, cumulativeness of technological knowledge, and the nature of the relevant knowledge base.

in different sectors serves as a good example. We emphasize three important aspects for policymakers.

First, understanding the roles of the sectors involved in a TIS (and its functions), and the sectoral configuration with potential (power) changes over time[41], can help policymakers pinpoint potential bottlenecks and deploy specific inter-or intra-sectoral policies that favor TIS development or avoid unintended lock-in. Sometimes, specific established sectors, such as the electronics, automotive and power sectors for LIBs, might be a key driving force for the new technology. Policymakers might want to consider whether these sectors exist within their region or country, and if so, whether they are relevant. Sometimes, individual sectors might be more or less focused on a particular technology; policymakers could guide their focus towards it, or try to promote externalities that link to other technologies, such as knowledge bases, networks, and market creation.

Second, policymakers should consider the sectoral configuration in the balance of technology-push-and demand-pull policies (Borrás and Edquist, 2013; Costantini et al., 2015b) [42] over the different stages of TIS development. For example, technology-push policies typically relate to a particular sector (Mowery, 1998), whereas demand-pull policies are technology (TIS) specific (Schmidt et al., 2016). Furthermore, the different policy types furthermore result in different innovation behavior such as exploration and exploitation (Costantini et al., 2015b; Hoppmann et al., 2013).

Third, we assume that the sectoral configuration determines the balance between technology-push, demand-pull and interface improvement policies. A TIS with a sectoral configuration consisting of a variety of very different sectors might require more policy coordination

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[41] Innovation policies typically also develop over time (Hoppmann et al., 2014; Nill and Kemp, 2009).

[42] The location of technology-push and demand-pull policies might also be relevant for innovation activities (Peters et al., 2012), e.g., in case of globally distributed TISs.

stimulating interaction than one that overlaps with less or more similar sectors in order to prevent system failures (Jacobsson and Bergek, 2011; Negro et al., 2012). Coordination could cover various aspects such as knowledge exchange, network formation, and division of labor in the value chain[43]. Policy coordination might furthermore relate to the different sectors' infrastructures, e.g. in cases the required infrastructure is not available or standards need to be defined. Policymakers could therefore strengthen the role of intermediaries that act as (knowledge) brokers between sectors (Taylor, 2008) or provide platforms (e.g., associations) to foster technology-specific networks (Musiolik et al., 2012). The advanced development of the Japanese LIB TIS compared to other countries indicates that the applied policy mix—targeting different sectors and their interplay via technology-push, demand-pull, and interface improvement policies—has been successful in the analyzed period. For example, the Japanese government successfully supported the formation of actor networks across sectors of the entire value chain, whereas establishing such networks in other countries, such as the US, has proved harder (Keller and Negoita, 2013).

However, our investigation has its limitations. We only cover the illustrative case of LIB technology in Japan; similar studies in other technological fields or countries might help to validate and improve our conceptual approach. Furthermore, we use patent data as a proxy for knowledge development and diffusion, which yields two caveats. First, by using patents, we neglect both tacit knowledge and unpatented explicit knowledge. Not all patent citations represent knowledge flows, since they might be added by the examiner rather than the inventor themselves (Alcacer and Gittelman, 2006; Criscuolo and Verspagen, 2008). Therefore, further research could use other data sources, such as innovation databases or R&D projects, or additional expert interviews, to extend our study. Second, the propensity to patent varies

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[43] Thereby, we complement the attention that TIS scholars already pay to various dimensions of interactions such as interaction between actors, functions, TIS and context, and different levels (Bergek et al., 2015; Hekkert et al., 2007; Markard et al., 2012; Negro et al., 2012, 2007) with the sectoral configuration.

between countries, (Bergeron et al., 1998), firms (Arundel and Kabla, 1998), and sectors (Fontana et al., 2013; Griliches, 1998). We address country differences by focusing on one country, Japan, which exhibits relatively high propensities to patent compared to other countries (Cohen et al., 2002; Fontana et al., 2013). While differences in sectors' propensity to patent might have affected our results, they cannot explain magnitude or direction of our findings[44]. Further research might investigate other countries or even global TISs. Lastly, our methodological approach requires data truncation to 1985–2005. While our data underpins our general argument, we can draw only preliminary conclusions about more recent findings. Investigating more recent data is a subject for further research.

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[44] The differences in propensities to patent between individual sectors in Asia (which are dominated by Japan) (Fontana et al., 2013) are much smaller than the differences we found in the patenting activity across sectors in our study. The results of Fontana et al. (2013) would furthermore indicate other rankings between sectors. For example, the instruments sector has a higher general/overall propensity to patent than the chemicals sector (Fontana et al., 2013), in the case of LIB, we find a higher absolute amount of patent in the chemicals sector than in the instrument sector.

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Appendix

Appendix A: Annual number of LIB patents

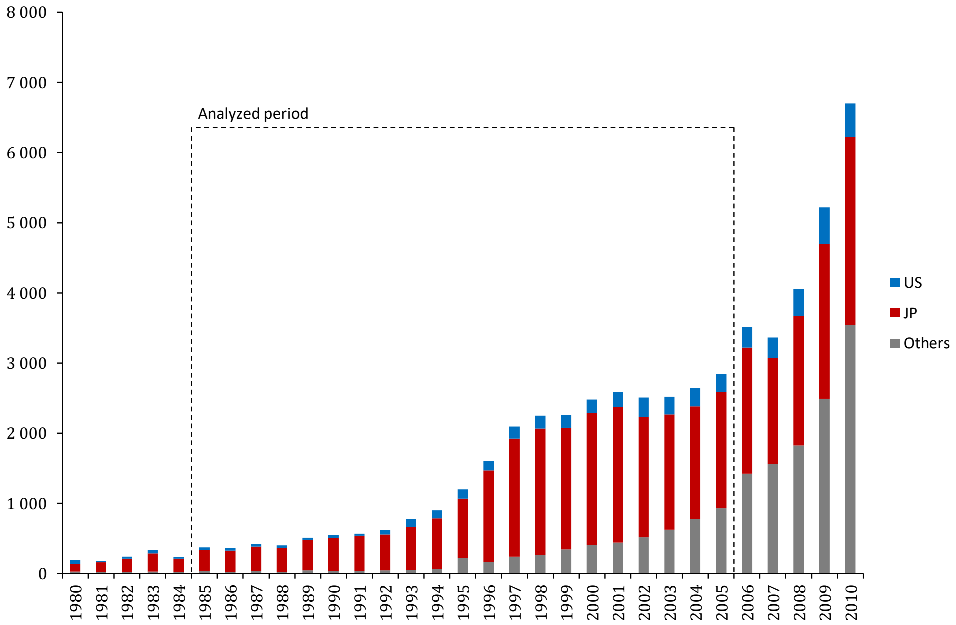

Figure A.1 Highest shares of patents: JP: 73.5%, US: 9.3%, South Korea: 8.8%

Appendix B: LIB search string and validity

Search string: (IC=(H01M 4/13 or H01M 10/052 or H01M 10/0525)) or (EC=(Y02E006012B or Y02T001070B2)) or (TI=((batter* or accumulator*2 or (stor* and device*2) or cell*2) and (li?ion or lithium)))

Scheme	**Class**	**Description**
IPC	H01M-04/13	Electrodes for accumulators with non-aqueous electrolyte, e.g. for lithium-accumulators; Processes of manufacture thereof
IPC	H01M-10/052	Lithium accumulators
IPC	H01M-10/0525	Rocking-chair batteries, i.e. batteries with lithium insertion or intercalation in both electrodes; lithium-ion batteries
ECLA	Y02E006012B	Lithium batteries
ECLA	Y02T001070B2	Lithium ion battery in transportation

Sample validity:

Identification of false positives and false negatives

- False positives: We checked a randomly selected subsample of the data set (100 patent families) for relevance with regard to LIBs. 5% of these families were considered to be another battery type or not assignable.
- False negatives: We retrieved control samples of patents. These control samples encompass LIB patents from manufacturers that produce materials,/components, cells or integrate the LIBs. The search string for the control sample uses DWPI manual codes (X16-E03A1 or X16-A02A or X16-B01F1 or X16-E08A) (instead of IPC codes used for the original search sting) in combination with the organizations' names. We checked the patent families that were included in the control sample but not in the database for being false negatives (LIB patents).

Table B.1 Characteristics of control samples for false negatives

Control sample	**Number of patents**	**Number of patent families**	**Number of patent families existing in control sample that do not exist in the data sample and are considered to be LIB patents**
Materials/ components	1002	370	28
Cell producers	7376	2379	135
Integrators/users	3261	1454	42
All	11639	4203	205

False negatives: 205/4203=4.9%