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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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A B S T R A C T

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.

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; pp. 416-417). Particularly when aiming for

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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 and Malerba 1997; Malerba 2002, 2004).

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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").

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; 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 include all (vertically and horizontally) related parts of the value chain into our conceptualization of a TIS, which represents an integrated approach.[4] We suggest this integrated approach especially for the analysis of multi-component TISs, as all parts of the value chain are interrelated and thus relevant for the entire TIS's development. This approach proposes a clear definition of the boundaries of a TIS that considers the fact that many technologies are developed, produced and used across sectors, and allows TIS to be delineated from sectoral systems of innovation.

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 fields can have predictive power on future downstream innovations (Acemoglu et al., 2016). While few TIS studies have applied a value chain perspective on

[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 fulfill similar functions for users.

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

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