Tailoring innovation policies to technology-specific learning patterns: An analysis of the locus of learning and knowledge feedbacks in industry value chains of three clean energy technologies

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Keywords: Locus of learning, knowledge feedbacks, industry value chains, wind, solar PV, lithium ion batteries

Abstract: Policies aiming to address societal challenges for which technology is a relevant factor, often intend to influence the speed and direction of technological change. Neo-Schumpeterian innovation literature demonstrates that technological learning can differ strongly between technologies. Therefore, fostering innovation may require technology-specific interventions. This study intends to address the question of how the locus of learning and learning feedbacks within industry value chains differ across technologies. To this end, we focus on three different technologies (solar photovoltaics, wind turbines, and lithium-ion batteries), and proceed in two steps. First, we analyze the content of the key patents over the life cycle of the technologies in order to identify (i) the locus of innovation in the industry value chain, (ii) the type of innovation (process or product). Second, we carry out semi-structured interviews with actors involved in the innovation system in order to identify where in the innovation system learning through interactions and feedback takes place, and what kind of knowledge (process or product) is involved.

We find that the pattern of innovation and learning feedbacks varies substantially across the industry value chains of the three analyzed technologies. The solar PV industry shows a higher degree of interaction between the original equipment manufacturers, production equipment suppliers and material suppliers during manufacturing. Learning in the wind industry is driven by a higher degree of interaction and knowledge feedbacks between the original equipment manufacturers and power producers during the use phase. The lithium-ion battery industry shows a high degree of interaction between the mentioned actors during both the manufacturing and use of the technology. Finally we discuss implications for policy makers.

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1. **INTRODUCTION**

Addressing societal challenges for which technology is a relevant factor often requires significant technological change. While public policies can play a significant role in changing the speed and direction of technological change in order to meet societal goals (Freeman, 1996; Mowery et al., 2010), there has been significant debate regarding how public policies should be designed to achieve this.

In neoclassical economics, the key principle for policy intervention is to internalize the externality that underlies the societal challenge. Hence, the key distinction between technologies in a neoclassical sense is based on whether and to what extent technologies contribute to the problem or help address it. For example, in the debates around climate change, technologies are often characterized on the basis of their carbon emissions and their costs. This often results in a distinction between “clean” and “dirty” technologies and the argument that clean technologies (which are often more expensive than existent dirty technologies) should be supported by putting a price on the carbon emissions and providing incentives for R&D (to address positive externalities involved in R&D).

However, from an innovation perspective, when designing policies to address societal challenges (e.g., climate change) through technological change, distinguishing between technologies solely on the basis on their environmental impact can be too simplistic (Mowery et al., 2010; Azar and Sandén, 2011). Evolutionary approaches to innovation policy intend to provide a more nuanced view by opening the “black box” of innovation (Rosenberg, 1982). Several studies have highlighted the complex nature of the processes underlying technological innovation (e.g., Arthur, 2009). On one hand, there has been a shift away from the linear model of innovation, to a model that recognizes the importance of interaction and knowledge feedbacks in technological innovation systems (Kline and Rosenberg, 1986; Lundvall, 2010). There is a need for a better understanding of these mechanisms, in order to better inform technology policy aiming to address issues such as climate change (Gallagher et al., 2012). On the other hand, the neo-Schumpeterian innovation literature demonstrates that patterns of innovation can differ strongly between technologies (Malerba and Orsenigo, 1996). This has been demonstrated to an important consideration for policy design in order to prevent technological lock-in (Arthur, 1989), lack of technological diversity (Stirling et al., 2007) and potential long term inefficiency (del Río González, 2008). As a result, fostering innovation in technologies may require technology-specific interventions.

However, there is a relative lack of attention to how technology differences might influence learning and innovation processes in different technological innovation systems. This study analyzes how the patterns in locus of learning and knowledge feedbacks differ across technologies. Specifically, draw from the literature on technological life cycles, and from the literature on tacit or “sticky” information as the theoretical basis for our analysis of innovation processes for three technologies – solar photovoltaic systems, wind turbines, and lithium-ion batteries. We use the concept of global value chains as the analytical framework for our analysis.
of these technologies. In doing so, we aim to address the research question: How do the locus of learning and knowledge feedbacks within industry value chains differ across technologies? We adopt a mixed-method approach in which we: (i) analyze patent data to identify differences in the type and location of innovative activity in the industry value chains, and (ii) collect information from semi-structured interviews and existing literature to identify the interactions and knowledge feedbacks required for innovation in the industry value chains of the three technologies.

The remainder of this paper is structured as follows: Section 2 presents the theoretical background on technology life-cycles and on “sticky information”. Section 3 describes the research case for this study – the industry value chains of solar PV systems, wind turbines, and lithium-ion batteries. Section 4 describes the methodology used, and Section 5 presents the main findings of the study. The implications for policy makers, limitations for the current analysis, and avenues for further research are discussed in Section 6.

2. Theory

This section discusses the existing literature concerned with technology life-cycles, concepts related to sticky information and the locus of learning, and finally describes how we use these concepts together in order to analyze the locus of learning and knowledge feedbacks in industry value chains.

In this study, we follow Murmann and Frenken (2006, p. 936) in defining a technological system as “a man-made system that is constructed from components that function collectively to produce a number of functions for users”, which can be distinguished on the basis of a shared operational principle.

2.1. Technology life-cycles and patterns of technological innovation

Several studies (especially in the literature on innovation management) have described the patterns of innovation over the life cycle of a technology, linking them to the architecture of the product, and its evolution over the life cycle (Abernathy and Utterback, 1978; Clark, 1985; Anderson and Tushman, 1990; Klepper, 1996; Davies, 1997; Hobday, 1998; Murmann and Frenken, 2006).

The life cycle of a technology can be considered to consist of distinct phases (Abernathy, 1978; Abernathy and Utterback, 1978). Major technological breakthroughs can trigger a period of technological ferment, in which alternate product forms compete for dominance. This phase continues until a dominant design emerges, which outperforms alternate product forms along functional dimensions of merit. Once a dominant design emerges, technological progress consists of incremental innovations aimed at improving the dimensions of merit of the dominant design (Anderson and Tushman, 1990).
Abernathy and Utterback (1978) proposed that the initial ‘era of ferment’ is characterized by many competitors engaging in product innovation in order to develop and acquire knowledge pertaining to the eventual dominant design, thus establishing a competitive advantage. After the emergence of a dominant design, the surviving firms have a greater incentive to gain a competitive advantage through cost reduction, shifting the focus towards process innovation.

However, studies such as that by Miller et al. (1995) have indicated that this model of innovation over the technology life cycle applies may not be applicable to technologies described as ‘complex systems’: complex, high cost, engineering-intensive, and often customized technologies. Davies (1997) characterizes the life-cycle of such technologies, showing that their life cycle is predominantly characterized by product innovation. The focus of innovative activity progresses from fundamental innovations in the system architecture during the ‘era of ferment’ to innovations in the sub-components of the technology once a dominant system architecture emerges. Hobday (1998) juxtaposes these two life-cycle models, highlighting the differences between them in terms of patterns of innovation, modes of learning, and industrial organization.

Huenteler et al. (2015), in a study comparing solar PV systems with wind turbines, integrate these perspectives in a framework that characterizes the two technologies based on these two contrasting life-cycle models proposed in the literature. In doing so, they demonstrate that technology-inherent factors, or technological characteristics, such as complexity of the product architecture can influence the types and sequences of learning processes over the life cycle of a technology. Based on this framework and an underlying patent citation analysis they draw implications on how to design technology policies that consider the differences in the learning patterns.

In general, the literature in technology life-cycles places technology characteristics at the center of the analysis, seeing it as a major determinant of innovation processes. The different actors in the industry value chains of these technologies, who are involved in the processes of learning and innovation receive little attention. Schmidt and Huenteler (2016) address this to some extent by analyzing the differences in capabilities required for technology transfer through localization of steps in the industry value chains of technologies with different characteristics. However, they do not analyze the effect of differences in technology characteristics on innovation and the need for knowledge feedbacks in industry value chains.

2.2. “Sticky information” and the locus of innovation

Von Hippel (1994) provides a different perspective by focusing on the “stickiness” of information, which is defined as the cost incurred in transferring a unit of information from the information seeker to the provider in a usable form. Learning processes in the transfer of information involves such high costs may require shifting of the locus learning towards the site of sticky information (Ogawa, 1998). For example, if a certain
innovation requires adaptation of the technology to conditions in the use environment which cannot be replicated in an experimental environment, then one site of problem solving is at the product design (or manufacturing) facilities, and the other is in the use environment. In such a situation, if the producers and users of the technology are two different actors, learning and innovation will require user-producer interaction or learning by using. By focusing only on the consequences of stickiness, it leaves open the possible reasons that necessitate interactive learning such as tacitness of knowledge (Polanyi, 1967), complexity and non-modularity of technologies (Pil and Cohen, 2006), uncertainty in use environment (Lundvall, 1985), or lack of absorptive capacity (Cohen and Levinthal, 1990). Indeed, such reasons are often interrelated and even impossible to disentangle. This perspective is important in networks involving several actors, since depending on the location of sticky information, innovative activity can require repeated interaction between different actors (Tsai, 2001).

It is important here to distinguish between the locus of innovation and the source of innovation in such a network. While the locus of innovation depends on the where the sticky information is located, the source of innovation, i.e. which actor is the innovator, depends on the temporary profits expected by the potential innovators (von Hippel, 1988).

In this study, we analyze the locus of innovation, which we define as activities which exhibit a relatively high occurrence of innovation. We perform this analysis using the concept of industry value chain as the analytical framework. We adapt Porter’s (1985) definition in defining an industry value chain as a collection of activities spanning across different firms that are performed to develop, produce, market, deliver and support a technology. We further analyze the knowledge feedbacks within the industry value chain, which are conceptualized as interactive knowledge flows between activities in the industry value chain (for a more detailed description, see the “chain-linked model” technology innovation system, as described by Gallagher et al., 2012). Thus we use the concept of industry value chain for a technological system as the unit of analysis.

3. Research Case
To address the research question, we focus on the industry value chains of three different technologies - solar PV systems, wind turbines, and lithium-ion batteries - because of three reasons. First, the technologies have varying levels of complexity in their architecture (Huenteler et al., 2015; Battke et al., 2016), potentially leading to different types of technological life-cycles. Second, all three technologies’ industry value chain are relatively complex, involving a number of activities in phases such as material supply, manufacturing, installation, and operation phases, requiring multiple interactions between different steps in the supply chain and allowing for the possibility of an iterative process of problem solving at the different loci of innovation. Third, understanding the innovation process for these technologies is highly relevant for policy makers aiming at accelerating innovation to mitigate climate change.
4. DATA AND METHODOLOGY

This study uses a mixed methods approach, proceeding in two major steps. First, we analyzed the content of the most important patents over the life cycle of the technologies in order to identify the locus of innovation over the life-cycle of the technologies. Second, we carried out semi-structured interviews with actors at different steps in the industry value chain in order to identify which activities in the value chain exhibit a relatively high level of innovation, where learning through interactions and feedback takes place, and what kind of innovation (process or product) is involved.

Patent data has been used extensively in order to analyze innovative activity and technological change (Basberg, 1987; Archibugi and Planta, 1996; Jaffe and de Rassenfosse, 2016). However, the use of patents for studying the nature of innovative activity for a technology raises two problems: first, the conceptual problem of using patents, “a legal title protecting an invention [emphasis added]” (Giovannini, 2008) to measure innovation; and second, the practical problem of qualitatively analyzing all the patents pertaining to a technology. Both problems can potentially be addressed by identifying a subset of patents for a technology which are significant for the industry. Indeed, several studies have examined the suitability other indicators as a proxy for the importance of a patent. It has been demonstrated that the number of citations received by a patent is correlated with its economic value (Trajtenberg, 1990; Hall, 2005; Harhoff et al., 2006), and its technological impact (Albert et al., 1991), making highly cited patents more likely to embody innovations with significant technological or commercial value. Thus, analysis of the content of the most important patents over the life cycle of a technology (as indicated by the count of forward citations) can help identify the locus of innovative activity over the different stages of evolution of the technology.

As a first step for the patent analysis, we compiled a database containing data on patent applications pertaining to the three technologies filed globally from 1960-2010, obtained from the Autumn 2015 version of the European Patent Office (EPO) Patstat Database (de Rassenfosse et al., 2014). The EPO Patstat database contains information about 74 million patent families from more than 90 patent offices. In order to extract patents related to the three technologies of interest, we iteratively developed search criteria based on keywords, and IPC and CPC patent classification schemes relevant to the technologies. The keywords were adapted from Huenteler et al. (2015) and Battke et al. (2016) and applied to the patent classification codes H02S (generation of electric power by conversion of infra-red radiation, visible light or ultraviolet light, e.g. using photovoltaic modules), Y02E 10/50 (photovoltaic technologies), F03D (wind motors), Y02E 10/70 (wind energy), H01M (processes or means, e.g. batteries, for the direct conversion of chemical into electrical energy), and Y02 E60/122 (lithium-ion batteries) as a starting point. The additional classification codes assigned to the

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1 Patents after 2010 are not included since they have not yet had sufficient time to be cited by subsequent patents in a 5 year window.
resulting patents were used to update the search strings in subsequent iterations to identify sub-classification codes (to refine the search within these codes) and additional codes (to broaden the search to include patents relevant to other steps in the value chain).

In the second step, the dataset was cleaned by grouping the individual patents into patent families and excluding ‘virtual applications’. This was done to avoid double-counting of citations to different publications in the same patent family. This resulted in a database containing 239,782 patent families for solar PV, 123,924 patent families for wind turbines, and 138,758 patent families for lithium-ion batteries. The number of forward citations for each patent family within a 5 year window after the date of application was calculated. Some key indicators of the dataset thus obtained are shown in Figure 1. The most important patent families for the three technologies were obtained by identifying the patent families with the highest number of forward citations.

![Graph](image)

**Figure 1:** Number of patents, number of cited patents, and total number of citations received (in a 5 year window) for patent databases for (a) solar PV systems, (b) wind turbines, and (c) lithium ion batteries, for the period 1960-2015

Third, the subset of patent data thus obtained was manually coded in order to identify the locus of innovation in the industry value chains of the respective technologies. The coding was done in order to (i) locate the knowledge embodied in the patent to its corresponding position in the industry value chain, (ii) the type of innovation (process or product), using the coding scheme shown in Table 1, Table 2, and Table 3. The coding schemes are based on analyses industry value chains in existing literature and industry reports (see, for example, Rasmussen, 2010 for wind industry in Denmark; Chung et al., 2016 for lithium ion battery industry; Zhang and Gallagher, 2016 for solar PV industry in China). The codes were verified and refined over the course of the patent analysis and interviews. For example, the code for ‘system monitoring’ was included in the coding scheme due to its recurrence in the patent analysis. Two coders independently classified each patent on the basis of its title, abstract and claims into these coding categories. In the rare case of disagreements regarding the classification, consensus was reached following a discussion between the two coders.
### Table 1: Coding scheme for solar PV patents

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel material for solar PV system.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel production process for material for solar PV system.</td>
</tr>
<tr>
<td><strong>Cell</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of cell.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel manufacturing process for cell.</td>
</tr>
<tr>
<td><strong>Module</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design or arrangement of cell encapsulation, interconnection, and cells within the module.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or assembly of cell encapsulation, interconnection, and cells within the module.</td>
</tr>
<tr>
<td><strong>Grid integration</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of inverter, connection, or power control system for solar PV system integration.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or installation of inverter, connection, or power control system for solar PV system integration.</td>
</tr>
<tr>
<td><strong>Mounting system</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of mounting system or tracking system.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or installation of mounting system or tracking system.</td>
</tr>
<tr>
<td><strong>System monitoring</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of monitoring systems for solar PV system.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or installation of monitoring systems for solar PV system.</td>
</tr>
</tbody>
</table>

### Table 2: Coding scheme for wind turbine patents

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel material for wind turbine system.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel production process for material for wind turbine system.</td>
</tr>
<tr>
<td><strong>Rotor</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of rotor, or any of its components (blades, hub, rotor control).</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or assembly of rotor, or any of its components (blades, hub, rotor control).</td>
</tr>
<tr>
<td><strong>Powertrain</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of powertrain, or any of its components (transmission, generator, electronics and control).</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or assembly of powertrain, or any of its components (transmission, generator, electronics and control).</td>
</tr>
<tr>
<td><strong>Grid integration</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of transformer, substation, cabling, or power control system for wind turbine system integration.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or installation of transformer, substation, cabling, or power control system for wind turbine system integration.</td>
</tr>
<tr>
<td><strong>Mounting system</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of nacelle, tower, or foundation.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or assembly of nacelle, tower, or foundation.</td>
</tr>
<tr>
<td><strong>System monitoring</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of monitoring systems for wind turbines.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or installation of monitoring systems for wind turbines.</td>
</tr>
</tbody>
</table>
Table 3: Coding scheme for lithium-ion battery patents

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel material or combination of materials for lithium-ion batteries.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel production process for materials for lithium-ion batteries.</td>
</tr>
<tr>
<td><strong>Cell</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of the cell, or any of its components (anode, cathode, separator, electrolyte).</td>
</tr>
<tr>
<td>Process</td>
<td>Novel manufacturing process for the cell, or for its components (anode, cathode, separator, electrolyte).</td>
</tr>
<tr>
<td><strong>Battery pack</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design or arrangement of battery management system, thermal management system, or cells within the battery pack.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or assembly of battery management system, thermal management system, or cells within the battery pack.</td>
</tr>
<tr>
<td><strong>Grid integration</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of inverter, connection, or power control system for battery system integration.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or installation of inverter, connection, or power control system for battery system integration.</td>
</tr>
<tr>
<td><strong>Mounting system</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of battery casing or mounting system.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or installation of battery casing or mounting system.</td>
</tr>
<tr>
<td><strong>System monitoring</strong></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Novel design of monitoring systems for lithium-ion batteries.</td>
</tr>
<tr>
<td>Process</td>
<td>Novel process for manufacture or installation of monitoring systems for lithium-ion batteries.</td>
</tr>
</tbody>
</table>

Patents and patent citations by definition represent knowledge and knowledge flows that are codifiable. As discussed in Section 2.2, there is a large body of literature devoted to tacit knowledge which cannot be codified in the form of patents or manuals (Polanyi, 1967; von Hippel, 1994; Howells, 1995), manifesting itself as human skills, experience, organizational routines etc. Knowledge of this form can be costly to acquire (von Hippel 1994), requiring interaction and feedbacks, which can be an essential learning process in a technological innovation system. Thus we used qualitative methods in order better understand the locus of innovation, as well as interactions and feedback between the various stages in the industry chain, since qualitative analysis allows for studying of the underlying mechanisms of a phenomenon (“how” and “why” questions) in greater depth as compared to quantitative methods (Yin, 2003; Eisenhardt and Graebner, 2007).

A list of potential interview partners including entrepreneurs and executives in the three industries, R&D scientists, and industry experts was compiled on the basis of a literature research as well as personal contacts. In preparation for the interviews, we systematically scanned news articles, case study reports and online company statements for information related to the company and the interviewee. These were used to tailor the interview guidelines to the interviewee’s organization and experience, which we then used as the basis for a semi-structured discussion during the interviews. We conducted 19 semi-structured interviews, each lasting between 45 and 60 minutes, in order to deepen our understanding of innovation, interactions and feedback for the three technologies (for a full list of interviews, refer to Table 4). At least two interviewers conducted the interviews, with one interviewer taking notes and recording the interview proceedings.
Table 1: List of interviews

<table>
<thead>
<tr>
<th>Interview number</th>
<th>Stakeholder</th>
<th>Interviewee</th>
<th>Interview code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar PV project developer</td>
<td>Director Strategy &amp; Business Development</td>
<td>PV1</td>
</tr>
<tr>
<td>2</td>
<td>Solar PV cell manufacturer</td>
<td>Group leader</td>
<td>PV2</td>
</tr>
<tr>
<td>3</td>
<td>Solar PV system manufacturer</td>
<td>Project manager</td>
<td>PV3</td>
</tr>
<tr>
<td>4</td>
<td>Wind turbine company</td>
<td>Chief Technology Officer</td>
<td>WIN1</td>
</tr>
<tr>
<td>5</td>
<td>Wind turbine company</td>
<td>Head of wind turbine engineering</td>
<td>WIN2</td>
</tr>
<tr>
<td>6</td>
<td>Wind turbine company</td>
<td>Sales director</td>
<td>WIN3</td>
</tr>
<tr>
<td>7</td>
<td>Wind turbine company</td>
<td>Project manager, project development</td>
<td>WIN4</td>
</tr>
<tr>
<td>8</td>
<td>University, wind R&amp;D organization</td>
<td>Professor of technology and innovation</td>
<td>WIN5</td>
</tr>
<tr>
<td>9</td>
<td>University R&amp;D</td>
<td>Professor of technology and innovation</td>
<td>WIN6</td>
</tr>
<tr>
<td>10</td>
<td>Utility</td>
<td>Project manager, offshore wind</td>
<td>WIN7</td>
</tr>
<tr>
<td>11</td>
<td>University R&amp;D</td>
<td>Professor, lithium-ion batteries</td>
<td>LIB1</td>
</tr>
<tr>
<td>12</td>
<td>Lithium ion battery production equipment</td>
<td>Chief executive officer</td>
<td>LIB2</td>
</tr>
<tr>
<td>13</td>
<td>Battery system integrator</td>
<td>Senior scientist</td>
<td>LIB3</td>
</tr>
<tr>
<td>14</td>
<td>Research and consulting firm</td>
<td>Senior project manager, energy industry</td>
<td>IND1</td>
</tr>
<tr>
<td>15</td>
<td>University R&amp;D</td>
<td>Professor of science, technology and policy</td>
<td>IND2</td>
</tr>
<tr>
<td>16</td>
<td>Grid R&amp;D organization</td>
<td>Head of business development</td>
<td>IND3</td>
</tr>
<tr>
<td>17</td>
<td>Management consulting firm</td>
<td>Project manager, renewables business</td>
<td>IND4</td>
</tr>
<tr>
<td>18</td>
<td>Industry expert</td>
<td>Analyst, renewable energy industry</td>
<td>IND5</td>
</tr>
<tr>
<td>19</td>
<td>Research and consulting firm</td>
<td>Director</td>
<td>IND6</td>
</tr>
</tbody>
</table>

5. Results

Following the same order as the two-step methodology described in Section 4, we present the results in two steps. First, we present the results of the patent analysis for the three technologies, highlighting the type of innovative activity (product or process innovation), and locus of innovation in the industry value chains of the three technologies. Second, we present the main findings of the semi-structured interviews, in which we discuss the locus of innovation within the industry value chain, as well as the interactions and feedback required for learning and innovation. The key findings of this analysis are also illustrated in Figure 4, which provides a generic schematic representation of the industry value chain for the three technologies, and highlights the important interactions between the activities in the value chain for the three technologies.

5.1. Results from patent content analysis

An initial analysis of the top 100 cited patents for the three technologies reveals that there are significant differences in the levels of activity related to product and process innovation across the three technologies (see
Figure 2). It is important to note that the propensity to patent is higher for product innovations as compared to process innovations, since the location of process equipment within the premises of manufacturers provides “natural protection” from reverse-engineering, reducing the need for legal protection in the form of patents. However, we expect this effect to be uniform across all three technologies, making it possible to compare differences between them.

First, while almost all the patents for wind power are related to product innovations (97%), a much smaller proportion of patents for solar PV and lithium-ion batteries relates to product innovations (51% and 44% respectively). In the case of wind power, the only exceptions are patents on a novel method for mounting wind turbine blades (CA2611343), a novel blade design and a method for assembling it (EP1761702), and a novel design for the base of an offshore turbine and a method for transporting and assembling it (US2004262926). Second, the patents for solar PV systems exhibit the highest proportion of process innovation (26%), followed by those of lithium-ion batteries (12%), and wind turbines (1%). Finally, a striking feature of solar PV systems and lithium-ion batteries is the prevalence of patents disclosing both product and process innovations (23% and 45% respectively). A closer inspection of the content of these patents shows that this might be because the production processes for these technologies are specialized, meaning that novel design features in the products necessitate innovative or specially adapted production processes as well.

A more detailed view of the distribution of innovative activity in the industry value chain can be found in Figure 3. Once again, we observe significant differences across the three technologies.
First, we observe that innovation in the solar PV and lithium-ion battery value chains is more focused on the upstream activities of material supply and processing, and principal component design and manufacturing. These activities taken together account for 75% and 79% of the patents for solar PV systems and lithium-ion batteries respectively. On the other hand, for wind power the locus of innovation is further downstream focusing on the design of principle components (the rotor and powertrain), and integration of system into the grid. When taken together, they account for 76% of the patents. Second, almost all of the patents disclosing process innovations are related to material and cell manufacturing for solar PV systems and lithium ion batteries. This observation reflects the fact that the materials and core components of these technologies have complex and specialized production processes showing high levels of innovative activity. Third, it should be noted that we distinguish between patents disclosing novelty in materials in general (which may find application in the research case technologies), and patents disclosing novelty in materials specifically for application in the technologies. This distinction highlights a major difference between innovation in the industry value chains of solar PV and lithium ion batteries. The patents for solar PV show significant innovative activity for materials finding application in the electronics industry in general (32% of all solar PV patents). These are patents related...
to novel processes and compositions for semiconductor and organic materials, which may find application in solar PV cells as well. The patents for lithium ion batteries, on the other hand, show significant levels of product and process innovation in materials with specific application in the core components (anode, cathode, electrolyte, and separator) of lithium-ion batteries (55% of all lithium-ion battery patents). There are no patents at all for novel materials for wind turbine technologies. Finally, another small but important difference is the relatively higher number of patents related to system monitoring for wind power, as compared to solar PV and lithium-ion batteries. In the case of wind power, these include sensors to detect and monitor blade ice formation (DK200500492), fatigue assessment (US2006070435), load measurement (EP1674724) etc.

To summarize, we observe that patents for wind turbines are mostly related to product innovation, and to downstream activities in the industry value chain. In comparison, solar PV and lithium-ion batteries show a higher number of patents related to process innovation, further upstream in the industry value chain. Lithium-ion batteries have a high number of patents which disclose both product and process innovations.

5.2. Results from semi-structured interviews

We find that the patterns of innovation and learning feedbacks in technological innovation systems vary substantially across the three analyzed technologies. We observe some differences between the locus of innovation as indicated by the patent data, and that observed from the interview data, with a more detailed account of learning and feedbacks involving tacit knowledge during manufacturing and use phases obtained from the interviews. The results from the conducted interviews for solar PV, wind turbines and lithium-ion batteries are presented in Section 5.1.1, Section 5.1.2, and Section 5.1.3, respectively. Figure 4 summarizes the results presented in these sections, highlighting the important interactions between different steps in the industry value chains for each of the three technologies.
Figure 4: Schematic diagram of a generic industry value chain for a clean energy technology

5.2.1. Solar PV systems

The interview results indicate that learning and innovation in the solar PV industry requires a high degree of interaction between the original equipment manufacturers, production equipment suppliers and material suppliers.

Production equipment required for the manufacture of PV cells from polysilicon is highly specialized, complex, and capital intensive. As a result, new processes or materials are introduced into mass production of PV cells only after long and complicated qualification testing. Due to the knowledge intensive nature of the production processes, the interviewees reported that there is intensive interaction between production equipment manufacturers (PEMs) and solar PV cell manufacturers. Concurrently, R&D and production engineering divisions in cell manufacturing firms often work extremely closely. The interaction between PEMs and cell manufacturers is necessary for several reasons. First, maintenance and capacity upgrades to the production equipment are often exclusively provided by the PEMs. Second, in case of improvements in the production processes, the equipment suppliers approach the cell manufacturers with new upgrades. Additionally, due to the integrated nature of the production line from polysilicon wafers to cells, such upgrades
often also require adaptations in other parameters of the production line. Third, the cell manufacturers have also played an important role in suggesting improvements in the production processes based on their experience with operating the production equipment. Thus, while the initiative for process innovation may come from either step in the value chain, the innovation itself requires extensive interaction between the two steps. This appears to have played an especially important role in the early days of the industry, which may explain the initial and continued presence of major PEMs in the US, Germany, Switzerland, and Japan (Zhang and Gallagher, 2016), which were also among the early leaders in PV cell manufacture (Photon, 2003). As solar PV cell manufacturing has evolved to become a global industry, the PEMs have continued to interact closely with cell manufacturers and maintain their market presence.

The process for production of polysilicon is similarly intensive in terms of technological know-how, capital expenditure, and energy consumption. The interviewees indicate that learning feedbacks between material supply and cell manufacture has reduced significantly since the early phase of development of the PV industry. First, prior to the current level of standardization of polysilicon material, the material compositions and corresponding production processes were based on specifications from cell manufacturers. Second, the choice of material production process (e.g. Siemens process or Fluidized Bed Reactor process) has a significant impact on the material characteristics (chunk or granular polysilicon) and subsequent cell manufacturing processes as well. With the standardization of cell production processes specific to these materials, the degree of interaction and feedbacks has also reduced.

According to the interviewees, feedback for solar PV from the use phase is not very significant. First, the lifetime performance of solar PV in terms of efficiency and degradation is measurable in laboratory conditions. Second, feedback from the use phase is limited to detection of issues with quality control, an activity that can also be largely transferred to the laboratory. Due to the standardized, modular, and portable nature of the technology, the information regarding problems with quality has very low stickiness. According to one interviewee, one requires “no complicated engineering know-how to understand what the problem is” since the defective modules can be easily transported to the lab, tested, and diagnosed, meaning that feedback from the use phase can easily be obtained, regardless of geographic location. A much larger consideration is quality assurance measures undertaken internally by the manufacturers, as well as in partnership with external testing agencies such as International Electrotechnical Commission (IEC) and UL.

### 5.2.2. Wind turbines

In comparison to solar PV systems, learning in the wind industry is driven by a higher degree of interaction and knowledge feedbacks between the original equipment manufacturers and power producers during the use of the technology.
The interviewees indicate that the role of interaction and feedback in material supply and manufacturing of wind turbines is very small. The knowledge related to the material supply and production equipment is not very specific to wind turbines, since it employs mature, general purpose materials and manufacturing processes also commonly used in other industries. One exception to this is knowledge related to glass fiber composites required for rotor blades, which was developed specifically for wind turbines. However, the major turbine manufacturers have developed their own expertise in this area, minimizing the need for interactions with other material suppliers. Interaction and knowledge feedbacks play a bigger role in the logistics and on-site assembly of the sub-assemblies and components. This is largely due to the high cost and site-specific nature of the transportation and project development processes, which may necessitate adaptation in the technology.

The feedback from the end use to the product design and manufacturing is much more important for wind turbines. This is due to several reasons: first, wind turbines are complex and dynamic systems whose performance is impossible to simulate in laboratory conditions; second, their performance and lifetime is highly dependent on factors in the use environment such as wind speed, turbulence, and even temperature. Due to the complex and non-modular nature of sub-assemblies and components of wind turbines, wind turbine companies are often highly integrated, from design and manufacture of wind turbines, to developing projects and often operating their own wind farms. It is also very common for turbine manufacturers to have O&M contracts with several wind farm operators, which enables them to get direct feedback from the field. For large wind turbine companies with mature turbine models based on extensive knowledge and experience from decades of wind turbine operation, feedback from end use is reducing in importance. However at the same time this, along with the high risks involved in developing and testing new turbines, poses great an enormous barrier to entry of new firms into new and existing markets.

5.2.3. Lithium-ion batteries

The interviews indicate that innovation in lithium-ion battery industry involves a high degree of interaction between battery manufacturers, production equipment suppliers, and material suppliers on the production side, as well as between battery manufacturers, system integrators, and users during end use of the technology. Lithium-ion batteries require highly specialized materials for the manufacture of their core components, especially the anode and cathode. Due to the specialized nature of the materials, innovation in materials is often accompanied by innovation in material production equipment as well. Furthermore, collaborations between material suppliers and cell manufacturers are quite common in the lithium ion industry, with firms such as Hitachi even having both chemical and battery manufacturing divisions.

Lithium-ion cell manufacturing requires highly complex, knowledge intensive, and capital intensive production equipment for processes such as electrode slurry mixing, electrode coating, calendaring, and
slitting. The major PEMs for electrode coating are concentrated in Japan and South Korea, benefitting from extensive experience from producing equipment for similar processes in the electronics industry, and from close interaction and feedback from large customers manufacturing lithium-ion cells in the consumer electronic industry. Due to the high interdependence of cell manufacturing process parameters, material composition, and cell performance, these three steps are closely interlinked, requiring a high degree of coordination and associated costs for the involved actors.

Knowledge feedbacks during end use are important for cell manufacturers. According to one interviewee, “even the cell suppliers do not know how their cells age because their tests are different from the real applications”. However, feedbacks take place only in applications with significantly large markets such as consumer electronics and battery electric vehicles (BEVs), even though the cell performance is highly application-specific and sensitive to parameters such as discharge duration, cycle frequency, temperature, and weight requirements. This is because adaptation of the technology and related production processes for applications with smaller markets (such as household renewable power systems) is often too costly to be interesting for cell manufacturers.

However, system integrators catering to these smaller markets still have an incentive to get good feedback in order to optimize system design and choice among existing cell chemistries and suppliers. This is often enabled by the use of sensors to monitor battery performance, temperature and lifetime. Furthermore, peripheral components such as thermal control systems and control electronics are mostly designed in-house by system integrators (for example, for household renewable power systems and BEV manufacturers) since they are application specific, and their design and combination benefits from feedback from technology users.

6. POLICY IMPLICATIONS AND CONCLUSIONS

Our results show that the locus of innovation and the need for long-term intense interaction to transfer sticky but valuable information across the industry value chain differs between the three analyzed technologies. Correspondingly, the potential for learning by producing and using differ between technologies. These results have implications for policy makers, since they highlight the need for technology-specific policy measures in order to foster innovation in different technologies. In the case of climate change, just installing one carbon price and some broad R&D support policies does not take into account the many complexities involved in innovation. Governments that want to support low-carbon energy technologies - or other technologies that address societal challenges - rather should tailor technology-specific policies that help foster innovation throughout the industry value chain. Three more specific recommendations can be drawn from our results:
First, deployment policies play an important role as they help to foster value chains for niche technologies in the first place. These could be complemented by targeted measures that increase interaction and long-term networks which help sticky information to travel in the value chain where it is most relevant. Japan’s industry policy around lithium-ion batteries seems to be a good example of how industry network formation across different activities in the industry value chain can be supported (Keller and Negoita, 2013).

Second, as sticky information travels more easily between (geographically and institutionally) close actors, our results also highlight the varying role of home markets: depending on the importance of interaction and feedback in different parts of the value chain, different early home markets might be important for innovation in different technologies. In wind, home markets for the end product might be more relevant whereas in PV home markets for manufacturing equipment might be more relevant. This has implications for industry localization and the success of industry policy. Simply creating demand for the end product might not be the best way to support new technologies.

Third, our results highlight that the need for long-term and intensive feedbacks to transfer sticky knowledge differs strongly between technologies. It is thus likely that those parts of the value chain where interactions are most important are performed by the same firms in order to reduce the cost of transferring information. In other words, based on our analysis and the framework provided by Huenteler et al. (2015), policy makers that aim to foster a new industry can anticipate the degree and locus of vertical integration in that industry’s value chain. High degrees of vertical integration typically result in market power. Managing market power within emerging industries is challenging but can be dealt with if well anticipated. Also, vertical integration and market power often results in more political power, which might result in more sticky policies in those countries that host the vertically integrated parts of the value chain.

To conclude, our paper provides micro-level insights into three technologies’ innovation processes across their industry value chains. We show that the locus of innovation and feedback needs across the value chain differ significantly between these technologies. These empirical micro-level findings support earlier claims made based on higher-level analysis (Schmidt and Huenteler, 2016). We thereby contribute to an emerging literature that analyses the role of technology differences and their implications for policy design (Murmann and Frenken, 2006; Huenteler et al., 2015; Schmidt and Huenteler, 2016). In line with this literature we argue that policies need to be tailored to specific technologies in order to trigger innovation cost-effectively. Based on our analysis we are able to derive recommendations on the design of such technology-specific policies.
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