Interactive learning and technology life-cycles – Explaining the patterns of innovation and learning in three clean energy technological innovation systems

1. Introduction

Innovation in clean energy technologies and resulting cost reductions in recent decades (IRENA, 2017; Schmidt et al., 2017; Trancik et al., 2015) have created opportunities for economic growth and societal welfare in the form of green industrialization, job creation and more widespread access to clean and affordable energy (Alstone et al., 2015; Rodrik, 2014; Schmidt and Sewerin, 2017). To seize this opportunity, several countries have set ambitious targets for deployment of clean energy technologies combined with industrial and innovation policies in the form of technology-push, demand-pull and coordination measures, with varying degrees of success (Lewis and Wiser, 2007; Nemet, 2009; Peters et al., 2012; Taylor, 2008).

Studies in technological innovation systems have made significant progress in explaining these outcomes, recognizing that "learning is predominantly an interactive, and therefore, a socially embedded process" (Lundvall, 2010, p. 1), taking place in networks of actors involved in the process of technological change (Binz et al., 2014; Gallagher et al., 2012; Lewis, 2007; Lundvall, 1985; von Hippel, 1994).[1] There is increasing recognition that policies need to account for different technology life-cycles and the resulting differences in the relative importance of learning-by-searching, learning-by-producing and learning-by-using (Binz and Truffer, 2017; Huenteler et al., 2016b; Quitzow et al., 2017). However, empirical studies indicate that the addressal of 'network failures' or failures in learning-by-interacting have also played a role in determining the success or failure of the establishment of innovation systems around these technologies (Choi and Anadón, 2014; Garud and Karnøe, 2003; Kamp et al., 2004; Keller and Negoita, 2013; Musiolik et al., 2012; Shum and Watanabe, 2008; Stephan et al., 2017). Relatively few studies have investigated if there are systematic differences in patterns of learning-by-interacting across technologies, and how industrial and innovation policies can be designed to account for these differences.

To address this gap, we examine how the importance of interactive learning varies across three energy-related TISs – solar photovoltaic systems, wind turbines, and lithium-ion batteries. We build on Stephan et al. (2017), and we link the observed differences in patterns of learning-by-interacting to the characteristics of different sectors involved in the value chain of the TIS, i.e. the sectoral configuration of the TIS. As a result, we make two primary contributions. First, by comparing the micro-level interactive learning processes in multi-sector industry value chains for technologies with different sectoral configurations, we help explain the differences in empirical literature regarding importance of learning-by-interacting between actors in clean energy TISs, and the role of policy in facilitating it. Second, we demonstrate how different sectoral configurations result in different modes of knowledge production and diffusion both within and across TISs. By doing so, we demonstrate the value of explicitly analyzing the sectoral configuration in future TIS analyses, and hence contribute to more closely integrating the literatures on TIS and sectoral systems of innovation.

The remainder of this paper is structured as follows: Section 2 presents the theoretical background on learning processes in technological innovation systems (2.1), how their importance differs across technologies (2.2), and how we integrate the existing literature to answer our research question (2.3).

[1] Other frameworks differing from TIS in terms of their unit of analysis and boundary conditions include national innovation systems (Lundvall, 1992), regional innovation systems (Cooke et al., 1997), and sectoral innovation systems (Malerba, 2002).

Section 3 describes the research case for this study – the industry value chains of solar photovoltaic systems, wind turbines, and lithium-ion batteries. Section 4 describes the mixed-method approach used to answer the research question, in which we analyze qualitative data from semi-structured interviews and from patent documents. Section 5 presents the main findings of the study. The contributions to existing literature, implications for policy makers, limitations for the current analysis, and avenues for further research are discussed in Section 6.

2. Literature review

Sectors have been the focus of analysis in several traditions of research, each with slightly different conceptions of what constitutes a sector. In this study, we follow the literature on sectoral systems of innovation (which itself draws on concepts from evolutionary theory and systems of innovation approaches) to define a sector as a set of activities that are unified by some linked product groups for a given or emerging demand and which share some common knowledge (Breschi and Malerba, 1997; Malerba, 2006, 2002; Stephan et al., 2017).

2.1. Sectoral characteristics and learning processes

Empirical analyses have shown that specific sectors exhibit common features across a wide range of institutional and geographical contexts. In addition, comparative studies have shown that sectors differ in terms of their patterns of innovation (e.g. technological trajectory, balance between product and process innovation), nature of knowledge base (e.g. appropriability, cumulativeness, technological content), industrial organization (e.g. position in the vertical chain, size of firm, degree of vertical integration, market shares, geographic concentration) (Breschi and Malerba, 1997; Castellacci, 2008; Klepper, 1996; Malerba, 2005; Pavitt, 1984). In particular, sectors can differ significantly in terms of the relative importance of different learning processes[2] underlying knowledge development and diffusion. For example, learning in sectors with large-scale assembly (like automobiles) takes place through interaction with "specialized suppliers which provide parts, components, and equipment specifically tailored to the system's features" (Breschi and Malerba, 1997, p. 146). In contrast, in performance-sensitive, high technology sectors such as machine tools, knowledge about applications is very important, and therefore firms rely on close user-producer relationships as well as partnerships with customers (Malerba, 2006; Wengel and Shapira, 2004).

Several scholars have proposed that the patterns of innovation of a particular sector are related to the specific "technological regime" (Dosi, 1982; Malerba and Orsenigo, 1997, 1996; Nelson and Winter, 1982). The technological regime influences the incentives and constraints facing an innovating firm, and thus affects the basic evolutionary processes of variety generation and firm-internal selection (Levin et al., n.d.). Most importantly for our research question, the technological regime determines the nature and locus of problem-solving undertaken for innovation, and the type of technological learning (Malerba, 2002). The technological regime itself is determined by the particular combination of four fundamental factors, namely, opportunity conditions, characteristics of the relevant knowledge base, appropriability conditions, and the cumulativeness of knowledge (Breschi and Malerba, 1997). Each of these fundamental factors can be specified along certain dimensions. These fundamental factors and their respective dimensions, which together characterize a technological regime are summarized in Table 1.

[2] Learning processes can be categorized as learning-by-searching, learning-by-producing, learning-by-using, and learning-by-interacting (Kamp et al., 2004; Malerba, 1992; Sagar and van der Zwaan, 2006; Schaeffer et al., 2004).

Table 1: Factors constituting technological regimes and their dimensions. Adapted from Breschi and Malerba (1997) **and** Malerba and Orsenigo (1996)**.**

Factor	Dimension	Description
Opportunity conditions	Level	The likelihood of innovating for any given amount of money invested in research.
	Sources	The sources of knowledge necessary for innovation, e.g. endogenous learning, advancements in R&D, equipment, instrumentation, knowledge from suppliers, users.
	Variety	The range of options available to a firm in terms of direction of search to find technological solutions.
	Pervasiveness	The range of potential applications of new knowledge (in terms of products and markets).
Knowledge base	Generic vs. specific	The degree to which knowledge is specific to certain domains or applications.
	Complexity	The number of different knowledge components in a system and the degree to which they are interdependent.
	Tacitness	The degree to which knowledge is non-codifiable. This correlates with the complexity and specificity of knowledge.
	Degree of independence	The degree to which knowledge is embedded as part of a larger system. This is correlated with the complexity of the system.
Appropriability conditions	Levels of appropriability	The ease with which innovations can be protected from imitation.
	Means of appropriability	The ways in which innovations can be protected from imitation.
Cumulativeness	N/A	The degree of serial correlation among innovations, i.e. the probability of innovating conditional on innovations in previous periods.

Here we summarize the characteristics of the technological regime that are relevant determinants of the extent of learning-by-interacting required for innovation. First, specific opportunity conditions can act as prerequisites for innovative activity and hence the need for learning-by-interacting. In particular, the *level of opportunity* determines the potential for innovative activity in a particular sector. Thus, it determines the role of learning processes in general, including learning-by-interacting. Second, the *sources of opportunity* determine the extent of reliance on certain sources for learning and innovation. Technological knowledge external to the firm can be in form of knowledge spillovers from advances in science and technology, inter-industry spillovers and learning-by-interacting (Cohen and Levinthal, 1989; Malerba, 1992). The existence of sources of opportunity external to the firm thus represents a second prerequisite for learning-by-interacting. Third, given a certain level of opportunity from firm-external sources, the characteristics of the knowledge base determine the need for learning-by-interacting. The *specificity of the knowledge base* determines the degree on dependence on specific actors and application domains as knowledge sources. For instance, sectors catering to highly specialized user demand often rely on user-producer interaction to develop specialized knowledge related to the application domain and desirable attributes in new products or services (Thomke and Von Hippel, 2002; von Hippel, 1994). Fourth, the *degree of complexity* of the knowledge base determines the need for trial-and-error experimentation or learning-by-doing. Several studies have demonstrated that it can be difficult to anticipate technological performance of innovations, and thus knowledge generated during the development, production and diffusion of the technology (i.e. learning-by-using, -producing and –interacting) feeds back into further innovation (Frenken, 2006; Nightingale, 2004; Rosenberg, 1982). Finally, the appropriability and cumulativeness conditions primarily determine the geographic and market concentration of innovators. While they may be correlated with each other and some of the sectoral characteristics discussed above (such as complexity and specificity) (Levin et al., 1987), they do not directly influence the need for learning-by-interacting.

2.2. Sectoral configuration of energy technology innovation systems

While concepts from the literature on sectoral systems of innovation can be useful to answer our research question, recently scholars such as Markard and Truffer (2008) and Binz et al. (2014) have pointed out that there is increasing criticism of setting territorial or sectorial boundaries due to the globalized nature of industry value chains (Gereffi et al., 2005). Thus to analyze a single technology as the unit of analysis (especially as is often the case on studies focusing on clean technologies), TIS can be a particularly useful analytical framework (Bergek et al., 2008). In this study, we follow Carlsson and Stankiewicz (1991) to define technological innovation systems (TISs) as a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of a technology. However, recent studies have highlighted that even though a single TIS can be comprised of activities pertaining to multiple sectors organized in an industry value chain (Bergek et al., 2015; Markard and Truffer, 2008; Stephan et al., 2017), applications of the TIS framework can often neglect the sector-specific patterns of innovation (Binz and Truffer, 2017). Thus, following Stephan et al. (2017) we resolve different TISs into their constituent value chain steps and corresponding sectors to provide deeper insight into the differences in importance of interactive learning across TISs with different technology life-cycles. Figure 1 illustrates the generic sectoral configuration of a clean energy technology.

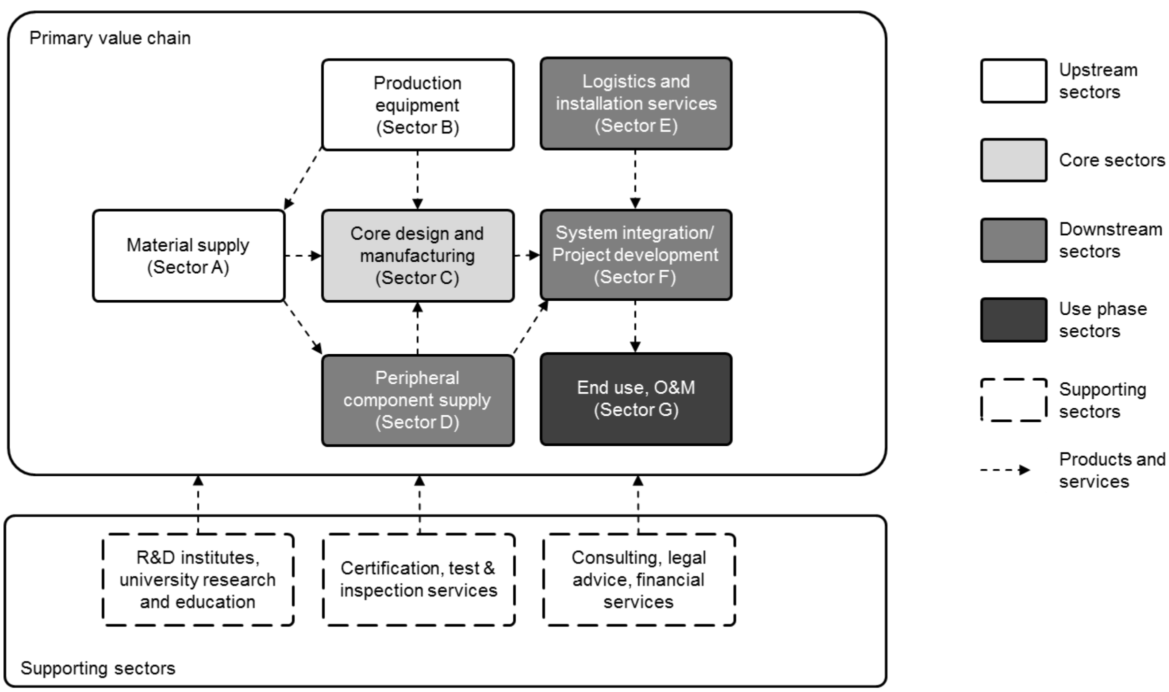

Figure 1: Typical industry value chain for a clean energy technology

We extend this approach by analyzing the sectors involved in different parts of three TIS value chains, and characterizing their patterns of innovation in terms of their level and sources of opportunity, as well as the specificity and complexity of their knowledge bases. We show that differences in these sectoral characteristics lead to differences in patterns of learning-by-interacting in the value chain.

3. Case selection and unit of analysis

To address the research question, we focus on the industry value chains of three technologies – wind turbine systems, solar photovoltaic systems, and lithium-ion batteries – for two reasons. First, we use the diverse case selection strategy (Seawright and Gerring, 2008) and choose technologies with varying levels of complexity in their product architecture (Battke et al., 2016; Huenteler et al., 2016b), as well as production processes (Schmidt and Huenteler, 2016), leading to potentially different technological life-cycles (see Section 3.1). Second, the technologies' industry value chains involve several activities performed by different sectors (see Section 5.2), which enables us to observe differences in sector-specific patterns of innovation and interactive learning.

3.1. Characterization of the case technologies

Here we characterize the three case technologies in terms of the complexity of their product architectures and production processes for the dominant design. We understand complex systems to have a large number of constituent elements that interact with each other in a non-simple way (Simon, 1962; Davies, 1997).

Wind turbines are electro-mechanical machines that convert kinetic energy of wind into electric power. The early phases of the wind industry were marked by competition between the 'light-weight turbine' and the 'Danish design' (Garud and Karnøe, 2003). Since the early 1980s, the market for wind turbines has come to be dominated by the 'Danish design', which features a three-blade upwind rotor (Menzel and Kammer, 2012). The overall system can be divided into four major sub-systems: the rotor, which converts the kinetic energy of wind to shaft power; the powertrain, which transmits the shaft power and converts it to electrical power; the mounting and encapsulation subsystem, which encases the other subsystems and provides mechanical support to them; and the system integration subsystem, which acts as the interface between the wind turbine and the larger power system (Hau, 2010; Huenteler et al., 2016). Each of these subsystems consists of components which can altogether number in the several thousands. In particular, the rotor and powertrain have a high number of moving key components, with their design and performance closely interdependent on other components in the wind turbine system (Hau, 2010). Manufacturing processes for most wind turbine components are standard industrial processes such as casting, forging, welding, milling etc., while more specialized processes and equipment are required for blade manufacture (Veers et al., 2003). Thus, the design of wind turbines is highly complex, while manufacturing processes for wind turbines are not very complex (Huenteler et al., 2016a, 2016b).

Solar photovoltaic (PV) systems use the photovoltaic effect to convert solar radiation into electrical power. The major mature sub-technologies are wafer-based crystalline silicon (c-Si) cells and thin-film (TF) cells, which were developed in the 1950s and 1970s respectively (Hoppmann et al., 2013). As a result, c-Si has had a head start is still the dominant design with a total market share of >90% (Fraunhofer ISE, 2017; Polman et al., 2016). A solar PV system consists of solar cells assembled, connected and encapsulated into a module, which is used with appropriate mounting structures for end-use along with balance of system (BOS) components such as cabling, inverter and control system (IEA-

ETSAP and IRENA, 2013). Manufacturing of c-Si modules involves casting of polysilicon (the material required to manufacture the cells) into ingots; slicing the ingots into thin wafers; etching, polishing, printing contacts, and coating the wafers to form cells; and finally interconnecting the cells, encapsulating them, and fixing them onto a frame to form a module (Zhang and Gallagher, 2016). Many of these processes have sensitive and mutually interdependent parameters, making them complex in nature (Huenteler et al., 2016b).

Lithium-ion batteries (LIBs) use the electrochemical effect to store electrical energy, in which Li+ is an active material. Several design variants such as lithium-metal, lithium-alloy, and lithium-intercalation batteries were being developed for commercial application in the 1970s and 1980s (Tarascon and Armand, 2001). However, the rocking chair design commercialized by the Sony Corporation in June 1991 has emerged as the dominant deign (Nitta et al., 2015; Yoshio et al., 2009). They consist of individual cells (themselves made up of a cathode, an anode, electrolyte, and separator), connected and assembled in a casing with electronics for control and protection to form a battery pack, which may then be used with BOS components such as inverters and control systems. There are large number of possible combinations of elements such as cell materials, battery pack design, and control algorithms and they are mutually interdependent (Santee et al., 2014). Manufacturing of LIBs involves several steps which can be summarized as: mixing of the active material of each electrode with carbon black and polymer binders to form a slurry; coating of the slurry onto the electrode, calendaring, slitting and drying to form the electrodes; winding or stacking the electrodes, filling it with the electrolyte and sealing it, and performing a charge cycle to 'form' the cell; and finally testing, assembling and connecting them into a module with a casing and charge control system to form a battery pack (Tagawa and Brodd, 2009). The parameters for different steps in the manufacturing process are highly dependent on each other, and also on the product design parameters, making the manufacturing process very complex.

3.2. Sectoral configurations of the case technologies

Figure 1 illustrates the concept of a generic TIS industry value chain for our case technologies. Activities within the value chain can broadly be classified into 7 categories: capital equipment supply, material supply, design and manufacturing, balance of systems (BOS) components supply, project development (or system integration), logistics and installation services, and operation and maintenance. Each of these activities is carried out in one or more sectors. We describe each of the value chain activities and the associated sectors for the three technologies in Section 5.1. While these 'primary value chain activities' are essential for the industry value chain, there are a number of sectors which influence or facilitate these functions, which we classify as 'supporting sectors': research and development, testing and certification services, and consulting and financial services.

4. Data and Methodology

To investigate our research question, we used an embedded mixed-method design. Specifically, we used a qualitative case study design with a quantitative strand (Creswell and Clark, 2011). In this design, we carried out semi-structured interviews with actors involved in different activities in the industry value chains of the case technologies to understand the opportunity level for innovation, the sources of opportunity, and the need for interactive learning in different parts of the value chain. We enhanced and triangulated our qualitative findings by analyzing the content of highly cited patents to quantitatively estimate the relative level and type of innovation over the life-cycles of the technologies as measures of the level and sources of opportunity.

4.1. Qualitative analysis of interview data

We used qualitative methods to address our research question, since qualitative analysis allows for studying of the underlying mechanisms of a phenomenon in greater depth as compared to quantitative methods (Eisenhardt and Graebner, 2007). A list of potential interview partners including entrepreneurs, executives, R&D scientists, and industry experts was compiled based on a literature research as well as personal contacts. In preparation for the interviews, we 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 interview (see Table A1 in Appendix A for a typical interview guide). We conducted 38 semi-structured interviews covering the entire value chain of the case technologies.[3] Each interview lasted between 45 and 60 minutes, and helped to deepen our understanding of innovation and interactive learning (for a full list of interviews, please refer to Table 3). The interviews were recorded or documented using hand-written notes. Subsequently, we coded the interview transcripts for the locus of innovation in the industry value chain, the type of innovation, and associated learning interactions, if any. We used the software MAXQDA for coding and analyzing the interview data.

[3] In addition, we had informal consultations with industry experts during visits to a wind farm, a renewable energy technology professional training center, a PV manufacturing plant, and a lithium-ion battery material production testing facility.

Table 2: List of interviewees

Interview number	Actor	Value chain position	Designation
1	Wind turbine OEM	Core	Chief Technology Officer
2	Wind turbine OEM		Head of wind turbine engineering
3	Wind turbine OEM		Sales director
4	Wind turbine OEM		Project manager, project development
5	Wind turbine OEM		Regional Product Strategy Manager
6	Wind turbine blade manufacturer		Plant Director
7	Wind turbine gearbox manufacturer		Head of Electrical Systems
8	Wind turbine electrical drivetrain		Manager for Medium-Voltage Converters
9	Utility	Downstream	Project manager, offshore wind
10	Installation and construction		Director of Field Services
11	University, wind R&D organization	Support	Professor of technology and innovation
12	University R&D		Professor of technology and innovation
13	University R&D		Professor of science, technology and policy
14	Industry expert		Analyst, renewable energy industry
15	Solar PV production equipment	Upstream	Ex-CEO
16	Solar PV production equipment		President and CEO
17	Solar PV cell manufacturer	Core	Group leader
18	Solar PV system manufacturer		Project manager
19	Solar PV project developer	Downstream	Director Strategy & Business Development
20	Research and consulting firm		Senior project manager, energy industry
21	Solar PV project developer		Business Development Manager
22	Solar PV inverter manufacturer		Vice President of Products
23	Solar PV inverter manufacturer		Managing Director
24	Solar PV research and consulting firm	Support	Director
25	Solar PV R&D institution		Professor
26	Management consulting firm		Project manager, renewables business
27	LIB material manufacturer	Upstream	President, Process & Chemical Engineering
28	LIB material manufacturer		Director, Research & Development
29	LIB production equipment		Chief executive officer
30	LIB production equipment		Head of Market Segment Battery Solutions
31	LIB cell manufacturer	Core	Senior Manager
32	LIB cell manufacturer		Executive Director, Product Planning Strategy & Innovation
33	LIB cell manufacturer		General Manager Automotive Systems
34	System integrator	Downstream	Senior scientist
35	System integrator & EV manufacturer		Systems Engineer
36	University R&D	Support	Professor, lithium-ion batteries
37	LIB R&D institute		Head of Electrochemical Materials Research
38	Grid R&D organization	Downstream	Head of business development

4.2. Patent content analysis

We used patent data to quantitatively describe the patterns of innovation in the industry value chains of the case technologies (Archibugi and Planta, 1996; Basberg, 1987; Jaffe and de Rassenfosse, 2016). However, the use of patents for studying innovation raises the conceptual problem of using "a legal title protecting an *invention* [emphasis added]" (Giovannini, 2008) to measure *innovation*. We address this problem by identifying a subset of highly cited patents. It has been demonstrated that the number of forward citations of a patent have a statistically significant positive correlation with its economic value (Hall, 2005; Harhoff et al., 2006; Trajtenberg, 1990), and its technological impact (Albert et al., 1991), making highly cited patents more likely to embody *innovations*. Pavitt (1984), in his seminal study on sectoral patterns of innovation, showed that the sources of opportunity of a sector are highly correlated with the relative emphasis on product versus process innovation. Specifically, sectors with relatively high emphasis on process innovation have production equipment suppliers and in-house production engineering departments (upstream and core sectors) as primary sources of opportunity, while sectors with relatively high emphasis on product innovation have in-house R&D, design and development departments and users (core and downstream sectors) as primary sources of opportunity. Thus, we measure the number of patents as a proxy for the level of opportunity, and the relative share of product versus process innovation to triangulate the sources of opportunity observed in the interview data.

As a first step for the patent analysis, we compiled a database of patent applications pertaining to the three technologies filed globally from 1960-2015[4], obtained from the Spring 2016 version of the European Patent Office (EPO) Patstat Database (for details, see de Rassenfosse et al., 2014). To extract patents related to the case technologies, we iteratively developed search criteria based on relevant International Patent Classification (IPC) and Cooperative Patent Classification (CPC) codes[5] and keywords[6]. The additional classification codes assigned to the 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, individual patents were grouped into patent families to avoid double-counting of citations to different patents in the same patent family. The resulting database contains 230,246 patent families for solar PV, 92,990 patent families for wind turbines, and 131,374 patent families for LIBs. Third, the number of citations for each patent family within a 5-year window after the date of application was calculated and the patent families with the highest number of citations were identified[7]. Finally, the subset of patent data thus obtained was manually coded to locate the knowledge embodied in the patent to its corresponding position in the industry value chain, and the type of innovation (process or product), using the coding scheme shown in Tables D1 to D3 in Appendix D. The codes were verified and refined over the course of the patent analysis and interviews. Two coders independently classified each patent based on its title, abstract and claims into these coding categories.

[4] 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

[5] The codes H02S (generation of electric power by conversion of infrared 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. For the list of used codes, please refer to Appendix B.

[6] The presence of keywords in patent titles and abstracts was used as an additional search criterion.

[7] The sampling strategy and sensitivities are described in more detail in Appendix C.

In case of disagreements regarding the classification, consensus was reached following a discussion between the coders.

5. Results

We present the sectoral configuration for each of the three technologies in Section 5.1, followed by the observed patterns of interactive learning for the three case technologies in sections 5.2, 5.3 and 5.4,. For each technology, we organize the results by dividing the industry value chain into three major parts: upstream, core, and downstream sectors (c.f. Figure 1). For each part of the value chain, we describe the learning interactions required for innovation, the opportunity level for innovation, and the type of innovation (product or process). We support these results using a three-panel figure for each technology.

5.1. Sectoral configuration of the three TISs

Table 2 describes the main features and sectors involved in the primary value chain activities for the three case technologies. It is based on analyses of industry value chains in existing literature and industry reports (see, for example, Rasmussen, 2010; Gallagher, 2014; Chung et al., 2016; Zhang and Gallagher, 2016).

Table 3: Description of the value chains and sectoral configurations for the three case technologies. The Standard Industrial Classification (SIC) codes for each sector are indicated in brackets.

		Wind turbines	Solar photovoltaic systems	Lithium-ion batteries
Production equipment	**Description**	Specialized equipment from the composites sector such as lay-up machines and large molds are required for blade manufacture. Most other processes use multi-purpose equipment from the metalworking machinery sector, such as casting, forging, welding, milling, and drilling machines.	Specialized equipment is required for the manufacture of the cells and modules, similar to the semiconductor sector. This includes equipment for cutting wafers, encapsulation of cells, assembly of modules, and process monitoring and measurement.	Specialized equipment is required for the manufacture of cell components, cells, and modules. This includes equipment for slurry mixing, electrode coating, calendaring, electrolyte filling and cell sealing in dry-room conditions, cell formation cycling and testing, and module and pack assembly.
	Sectors involved	Metalworking machinery and equipment (354)	Special Industry Machinery, Not Elsewhere Classified (3559); Industrial Instruments for Measurement, Display, and Control of Process Variables (3823)	Special Industry Machinery, Not Elsewhere Classified (3559); Industrial Instruments for Measurement, Display, and Control of Process Variables (3823)
Material supply	**Description**	Key materials for wind turbine systems are from the metallurgy sector, such as cast iron for the hub and frame, and high-tensile steel for bearings and drivetrain components. In addition, glass or carbon fiber reinforced polymers from the composite sector are used for the blades.	The key material required for solar PV cells is specialized polycrystalline solar grade silicon, which is made by purifying metallurgical-grade silicon using specialized processes and equipment, similar to the semiconductor sector.	The key materials for lithium-ion batteries are specialized intercalated lithium compounds for the positive electrode, graphite for the anode, organic polymers for the separators, and lithium salt solutions for the electrolyte, produced by firms in the chemical sector.
	Sectors involved	Primary metal industries (33), Iron and Steel Forgings (3462), Plastics Materials, Synthetic	Semiconductors and related devices (3674)	Industrial Inorganic Chemicals, Not Elsewhere Classified (2819)

		Resins, and Nonvulcanizable Elastomers (2821)		
Core design and manufacturing	**Description**	Several components are manufactured separately and assembled together. This includes molding, assembly and finishing of blades, manufacture of the drive shafts, gearbox, hydraulic systems, bearings, motors and control systems for the drivetrain and rotor, manufacture of the generator and power electronics, and manufacture of the chassis and composite panels of the nacelle.	Solar PV module manufacturing involves several sequential steps. The silicon material is cast or drawn into ingots or ribbons, sliced into wafers. The wafers are doped, cleaned, coated with antireflective material, and screen-printed with metallic contacts to form cells. The cells are interconnected, laminated and framed to form modules.	Manufacture involves several parallel and sequential steps. The electrodes are produced by mixing a material slurry, coating and calendaring it on a metallic foil, drying and slitting it. The electrodes and separators are wound or stacked, and sealed with the electrolyte in a can with connectors, terminals and safety features to form the cell. The cells are interconnected to form modules.
	Sectors involved	Steam, Gas, and Hydraulic Turbines, and Turbine Generator Set Units (3511), Speed Changers, Industrial High-Speed Drives, and Gears (3566), Ball and Roller Bearings (3562), Motors and Generators (3621)	Semiconductors and related devices (3674)	Storage batteries (3691)
Peripheral component supply	**Description**	The peripheral components or balance of system (BOS) consists of all components apart from the wind turbine and generator. This includes the tower and foundation (infrastructure sector), transformer, power cables, power electronics (power sector) and wind-farm control systems.	Consists of all components apart from the solar modules. This includes the mechanical support structure, tracking system, control unit and inverter, electric cabling, and protection devices such as fuses, grounding rods, and disconnect switches.	Consists of all components apart from the cell modules. This includes electronics for monitoring, charge control, cell balancing and protection. It also includes the inverter, battery casing, interconnections, electric cabling, thermal management systems and protection devices such as fuses, and disconnect switches.
	Sectors involved	Power, Distribution, and Specialty Transformers (3612), Electrical Industrial Apparatus, Not Elsewhere Classified (3629); Fabricated Structural Metal (3441)	Power, Distribution, and Specialty Transformers (3612)	Power, Distribution, and Specialty Transformers (3612), Electrical Industrial Apparatus, Not Elsewhere Classified (3629)
Project development/ System integration	**Description**	Includes resource assessment, site acquisition, contracting, permitting, system design and financial closure.	For large scale, grid connected systems, includes resource assessment, site acquisition, contracting, permitting, system design and financial closure. For distributed systems this includes system design and integration.	For large scale, grid connected systems, includes resource assessment, site acquisition, contracting, permitting, system design and financial closure. For mobile applications (electric vehicles and consumer electronics), includes system design and integration.
	Sectors involved	Engineering Services (8711) , Electric Services (4911)	Engineering Services (8711), Electric Services (4911)	Radio and Television Broadcasting and Communications Equipment (3663), Electronic Computers (3571), Power-Driven Handtools

				(3546), Motor Vehicles and Passenger Car Bodies (3711), Engineering Services (8711), Electric Services (4911)
Logistics and installation services	**Description**	Includes transport of components to the deployment site and on-site system assembly and installation.		
	Sectors involved	Marine cargo handling (4491); Trucking (4213); Construction Machinery and Equipment (3531)	Marine cargo handling (4491); Trucking (4213); Construction Machinery and Equipment (3531)	Marine cargo handling (4491); Trucking (4213); Construction Machinery and Equipment (3531)
End use, operation and maintenance	**Description**	Includes activities carried out in the use phase of the technology, including operation, monitoring and maintenance of the system.		
	Sectors involved	Electric services (4911)	Electric services (4911)	Radio and Television Broadcasting and Communications Equipment (3663), Electronic Computers (3571), Power-Driven Handtools (3546), Motor Vehicles and Passenger Car Bodies (3711), Electric Services (4911)

5.2. Learning-by-interacting in wind turbine systems

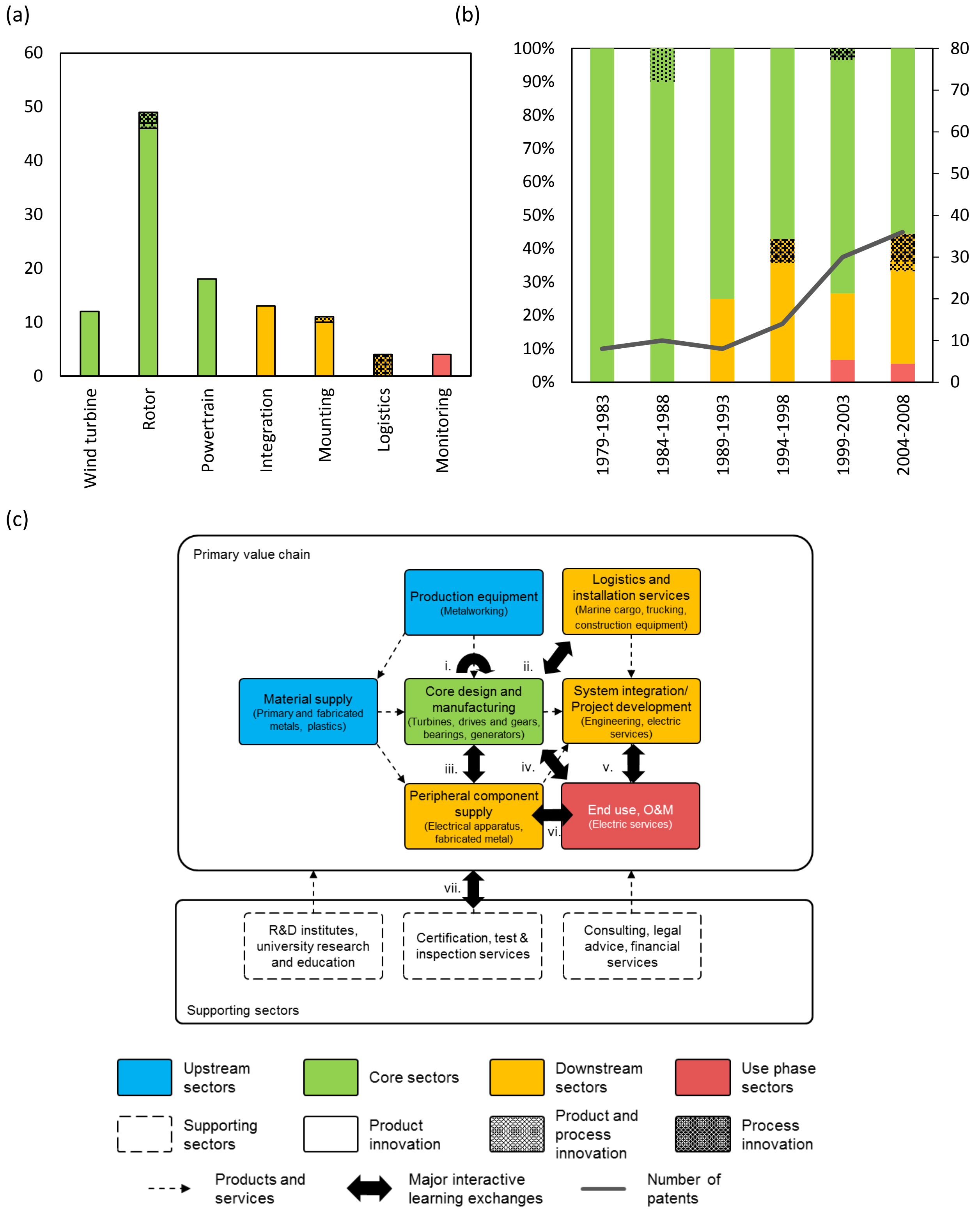

Figure 2: (a) Number of patents pertaining to each wind turbine industry value chain activity (b) Relative shares of patents pertaining to value chain activities, indicating type of innovation over time (c) Interactions involved in innovation in wind turbine systems

Upstream sectors: We find that upstream sectors exhibit low levels of innovation and interactive learning as compared to other activities in the industry value chain for wind turbines (WIN2, 4, 11). The patent data indicates that material supply has been the least important activity in terms of innovation, with no patents related to materials in the analyzed sample (Figure 2a). As seen in Table 2, knowledge related to the material supply is not specific to wind turbines, since they employ mature, general purpose materials from the iron and steel and synthetic polymer sectors, which are also commonly used in other industries (Janssen et al., 2012). Accordingly, the role of interaction and feedback in material supply is also very small (WIN2, 4, 11).

We also find that innovation in production equipment and manufacturing processes for wind turbines is less important as compared to innovation in core and downstream sectors. Processes for manufacturing wind turbines employ mature, general-purpose technologies from the metalworking machinery sector (Table 2). One exception is the rotor blade manufacturing process, which requires *specialized equipment*. "There has been a trend towards automation of blade manufacturing in recent years" (WIN11), and major turbine and blade manufacturers have developed in-house expertise in this area, seeing it as a core competence to be guarded with secrecy. Therefore, "If you visit a factory, for example, they will usually not let you in with your camera into the blade factory facilities" (WIN11). Thus, innovations in rotor blade manufacturing processes have not involved much interaction with other stakeholders, and are likely to be underrepresented in the patent data.

Core sectors: We find that innovative activity in the wind industry largely occurs in the core activity of rotor and powertrain subsystem design. This is reflected in the patent data (Figure 2a), where 44% of the highly cited patents are related to the rotor, and 16% are related to the powertrain. In addition, few patents are related to the overall design of the rotor and powertrain (labeled 'Wind turbine' in Figure 2a, comprising 11% of the total), reflecting the systemic nature of wind turbine design.

The high *complexity* of the rotor and drivetrain design has resulted in a closely integrated structure of the wind turbine industry, where large OEMs design several components in-house (interactions i, iii in Figure 2c) and they source key components from suppliers with specialized knowledge bases. "Whether and how components are self-designed depends on whether core components and competences are involved. The control electronics, the rotor blade production, and the drive train are core competences" (WIN2). Specifically, gearbox design and power converter design use specialized knowledge bases from other sectors (Table 2), and so they are often procured externally by the OEMs. However, product development is enabled by a "very, very close" (WIN6) collaborative and iterative process between the suppliers and the OEM to ensure acceptable system performance (for example, response to vibrations, damping and bending forces). Thus, there is extensive interactive learning among sectors involved in core design and manufacturing (i). Besides in-house component testing, co-development of new concepts by OEMs and suppliers involves testing at the sub-system and system level through extensive use of test rigs and prototypes (vii, WIN4, 7, 8, 12).

Since the early days of the wind industry, feedback from end-use has been very important for innovation in the core sub-assemblies (iv, vi; Karnøe, 1990). This is due to several reasons: First, wind turbines are *complex* systems whose performance is difficult to simulate or test in laboratory conditions. Second, the system design is dependent on continuously varying factors in the use environment such as wind speed, turbulence, temperature etc. According to one wind industry expert, "wind turbines are complex products in which a large number of components from different materials interact with each other to create the overall functionality, and together they are in complex interaction with the highly dynamic environment – the wind – that is very hard to predict" (WIN12). Thus, new turbine platforms are typically deployed at a limited scale to obtain feedback before commercial introduction. OEMs often develop their own projects, or reach special contractual agreements with customers in the power sector in which new turbines are provided at a discounted price to monitor turbine performance (WIN2, 4). Once an innovation is introduced to the market, OEMs continue to collect data from end-use by interacting closely with several wind farm operators, and as a by-product of carrying out O&M. However, as predicted by Karnøe (1990), for incremental improvements in existing turbine designs, the importance of direct interaction with end-use has reduced in recent years (WIN12) since they understand better which data to collect, how to collect it remotely, and since "over the years the ability to simulate the performance of new turbine generations has improved" (WIN5). However, for new turbine generations, early feedback from prototypes and close interaction with wind farm operators is still essential for innovation. For example, manuals for O&M of new turbine generations are often co-developed with farm operators based on their experience (WIN8, 12).

Downstream sectors: We find that the role of innovation in downstream sectors has been less critical as compared to core sectors, but its importance has steadily increased in recent years. Downstream activities represent 25% of all highly cited patents, (Figure 2a) and with time the locus of innovation has spread to downstream sectors (see Figure 2b). Specifically, there has been increased innovation in towers and foundations, processes and equipment for transport and assembly of turbine components, and technologies for grid connection and power output conditioning.

These developments can be attributed to three factors. First, as the literature on technology life-cycle predicts, once the design of the core components has stabilized and as the technology matures, the *locus* of innovative activity shifts to the peripheral components (Murmann and Frenken, 2006). In the case of wind turbine towers and foundations, the knowledge base for materials and fabrication is generic. However, their design is dependent on specific turbine design parameters, and so new designs are introduced by OEMs themselves, or by tower manufacturers through close interaction and testing in collaboration with OEMs (WIN4, 9, 10). Second, product innovations aiming to reduce the specific cost (which have resulted in progressively larger turbines with higher hubs) have necessitated process innovations in logistics and installation to produce the new designs cost effectively (WIN6, 9, 11; see downstream process innovations in Figure 2b). While in the past OEMs had to design components to minimize cost of logistics, with increasing turbine sizes, *specialized* equipment (e.g. trucks) and installation procedures were required for larger components, which were enabled by early interaction between OEMs and firms transporting and assembling the turbines (ii, WIN4, 6, 11). Third, the need for interaction in downstream sectors was further increased due to deployment of turbines in different use environments (vi). For example, the deployment of offshore turbines necessitated innovation in the foundations and towers, resulting in increased need for interactive learning between OEMs, tower manufacturers and foundation construction companies (WIN2, 4, 9).[8]

[8] In recent years, there has also been innovation in wind turbine operation, enabled by the development of condition monitoring systems for automated real-time data collection from multiple wind turbines and farms. The collected data has also led to the development of more accurate simulation models, enabling a shift from reactive to preventive maintenance. It has also led to more sophisticated control systems for wind farm operation, so that depending on the preferences of the end user, parameters such as power output, maintenance cost and turbine lifetime can be optimized by modifying the operation mode of the turbines (WIN5, 8).

To summarize, we find that innovative activity in the wind turbine industry largely focuses on product innovation in the core activities of rotor and powertrain design (see Figure 2a), with increasing focus on downstream product and process innovation in recent years (see Figure 2b). Learning in the wind industry is driven by a high degree of interaction among core sectors (i, iii), and interaction with downstream sectors, particularly by original equipment manufacturers obtaining feedback from the use phase of the technology (iv, v, vi in Figure 2c).

5.3. Learning-by-interacting in solar PV systems

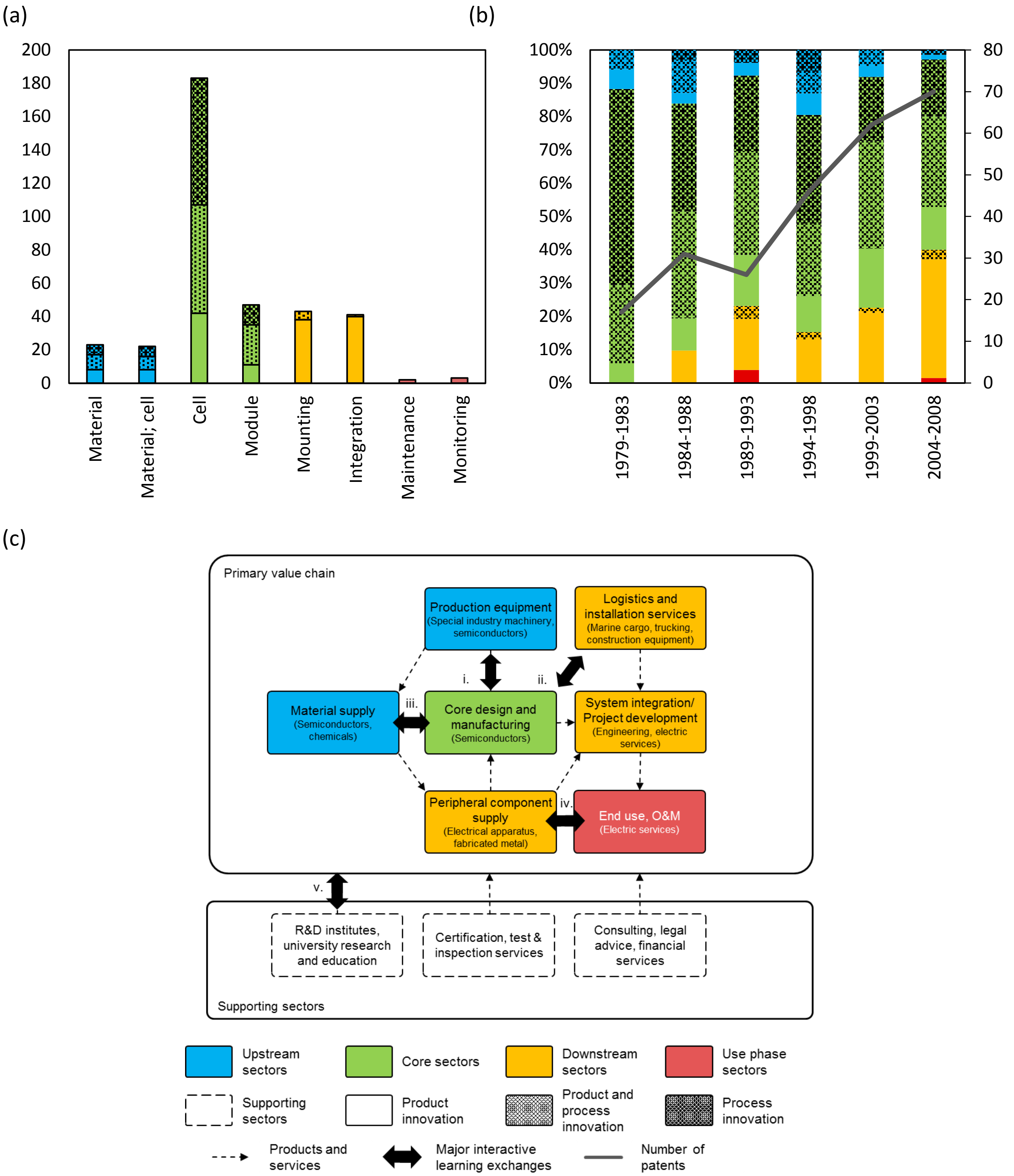

Figure 3: (a) Number of patents pertaining to each solar PV value chain activity (b) Relative shares of patents pertaining to value chain activities, indicating type of innovation over time (c) Interactions involved in innovation in solar PV systems

Upstream sectors: We find that innovation in the solar PV value chain is focused on the upstream activities of production equipment and processes for cell manufacturing. Figure 3a shows that 12% of all highly cited patents for solar PV are related to innovations in materials or related production processes, and 49% of all patents disclose process innovations for cell and module manufacturing. In addition, 88% of process innovation patents are related to innovations in materials and cell manufacturing processes. Another striking feature is the prevalence of patents disclosing both product and process innovations (31% of all patents). The interviews and patent content analysis shows that this is because solar PV materials and core components have *specialized* production processes, meaning that product innovations often also require innovative or specially adapted production processes.

In general, interactive learning is essential for innovation in upstream sectors (i, iii in Figure 3c). “Until the completed cell, the feedback and the interaction are very concentrated, since the actors work relatively close together” (SPV10). Close interaction between material suppliers and cell manufacturers played an important role in introducing cell material innovations during the early phases of development of the PV industry (i). Since *specialized* cell and material production process (e.g. Siemens process or Fluidized Bed Reactor process) are required depending on the material type (chunk or granular polysilicon), material compositions in this early phase were based on detailed specifications from cell manufacturers. Over time, *low complexity* of cell materials enabled standardization, and in turn, reduction in the need for interaction (SPV2, 5). Once cell manufacturer noted, “…one could say that the internal feedback is not necessarily really valuable to the company, so it is not really crucial whether it [the material] is from us or other producers” (SPV5). The interviewees also noted that although the successful introduction of significant material innovations is unlikely, it would require significant interactive learning (SPV5). [9] According to one production equipment manufacturer (PEM) “…when it comes to new concepts like epitaxial growth then you need input [from material suppliers]” (SPV2). Additionally, innovations in other cell materials (often from the chemical sector) such as cell passivation layers, encapsulation material, and metal pastes for contacts have not required sustained interaction between cell manufacturers and material suppliers due to the *low complexity* and science-based knowledge involved in these innovations (SPV1, 3, 4). Rather, the PEMs need to work closely with cell manufacturers to introduce such innovations into production processes.

We find that innovation in manufacturing equipment and production processes requires interaction between PEMs and cell manufacturers (i in Figure 3c). Information related to production processes is sticky, and the locus of problem-solving is at the manufacturing facilities because: First, due to the *complex* nature of the production line from polysilicon wafers to cells, problem-solving is often based on data from full-scale production lines, and may require adaptations in other production line parameters to ensure stability of processes. One interviewee highlighted that “If you manufacture a module there are up to 700 parameters you need to tune” (SPV1). Thus, the cell manufacturers play an important role in suggesting improvements based on their experience with operating the production equipment (SPV1, 5, 12). Second, due to the highly *specialized* knowledge related to the production processes, installation, maintenance and upgrades to the production equipment are often exclusively provided by the PEMs, with employees working on-site at the production facilities (SPV3, 4, 5). These characteristics are very similar to those of production equipment in the semiconductor industry (Hatch and Mowery, 1998). The link between PEMs and cell manufacturers played an especially important role in the early days of the industry, which may explain the initial and continued presence of major PEMs from Japan, Germany,

[9] It should be noted that scale of the production equipment also plays an important role here. Due to the large scale and capital-intensive nature of the production equipment, new processes or materials are introduced into mass production of PV cells only after extensive qualification testing with the cell manufacturer.

Switzerland and the US (Zhang and Gallagher, 2016), which were also the early leaders in cell manufacture (Photon, 2003). As cell manufacturing has evolved to become a global industry, the PEMs have continued to interact closely with cell manufacturers to innovate and maintain their competitive advantage.

Core sectors: We find that problem-solving in the core value chain activities of solar PV had two main objectives. First, product innovations focused on cell materials and designs in order to increase cell efficiency (Kavlak et al., 2016). Second, cost reduction was achieved by scaling up production processes and increasing their efficiency, enabling, for example, reduction in wafer thickness and hence the amount of silicon used (SPV4, 10). About 50% of all highly-cited solar PV patents are related to innovation in cell design and manufacturing, as compared to 13% representing innovation in modules (Figure 3a). Both activities exhibit a continued focus on product and process innovation throughout the observed time period, with a relatively higher focus on process innovation (Figure 3b).

Product innovations in cells were enabled by close collaboration with universities and R&D institutions (SPV1, 2, 4) in countries such as Australia, Germany, Japan, Switzerland, and the US (v in Figure 3c, Gallagher, 2014). Close links to R&D institutions were a significant competitive advantage for cell manufacturers. However, with standardization of cell design, the importance of this linkage reduced, as the focus of innovation shifted more towards process innovations and achieving economies of scale, especially following increasing cell manufacturing in China (Fu and Zhang, 2011; Quitzow, 2015; Zhang and Gallagher, 2016). One interviewee remarked that "In recent years, there has been such a sharp cost reduction, that you could not innovate. Before the influence of a new specification had been understood, the costs of the rest of the value chain had fallen so far that the matter was perhaps no longer worth it" (SPV5). As discussed above, innovations in production processes were enabled by interactive learning between cell manufacturers and PEMs (see section on "Upstream sectors").[10]

According to the interviewees, interaction with downstream sectors is not very significant for innovations in cells (SPV1, 3, 12). The performance and efficiency of solar cells is easily measurable in laboratory conditions. While the industry did encounter unexpected problems in modules which were only detected via feedback from end-use (such as potential-induced degradation and light-induced degradation), they were small in number when compared to the total deployed capacity (SPV4, 5, 10). Further, one requires "no complicated engineering know-how to understand what the problem is" (SPV5) since the defective modules can be transported to the lab, tested, and diagnosed using science-based knowledge. Thus, such information has low stickiness and can easily be obtained, regardless of geographic location.

Downstream sectors: With falling module costs, BOS components comprise an increasingly larger share of the total system cost (IRENA, 2016), shifting the locus of innovation to downstream sectors, resulting in product innovation in mounting and system integration subsystems. The patent data reflects this trend (Figure 3b).[11] Additionally, even though BOS components are mature and have relatively *low complexity*, innovation is also driven by increased diffusion and deployment of the system in different *use environments.* For example, the installation system needs to be designed for specific applications

[10] In recent years, the role of strong linkages between PEMs and R&D institutes in developing and bringing to the market new cell concepts for thin-film and heterojunction cells is becoming more important in counteracting the trend of reduced product innovation. ("When it comes to latest ideas for solar production, Europe is still at the leading edge. This helps a lot to get ideas from R&D institutes and we work closely with all of them.")

[11] This is in agreement with the literature on technology life-cycles (Murmann and Frenken, 2006).

such as off-grid, grid-connected open field, rooftop, or building-integrated systems (SPV7; Shum and Watanabe, 2008), and the inverter performance is sensitive to different grid codes and climatic conditions (SPV8, 9). However, the adaptations required in inverter design are incremental and the associated knowledge is well understood and codified due to extensive deployment and data collection across different contexts (SPV8, 9).

To summarize, we find that innovative activity in the solar PV industry focuses on product and process innovation in the core value chain activity of cell design and manufacturing, and the upstream activity of material supply (see Figure 3a), with gradually increasing focus on downstream product innovation in recent years (see Figure 3b). Learning in the solar PV industry is driven by a high degree of interaction and knowledge feedbacks in the upstream value chain activities, particularly between the original equipment manufacturers and production equipment suppliers during the manufacturing of the technology (see i in Figure 3c).

5.4. Learning-by-interacting in lithium-ion batteries

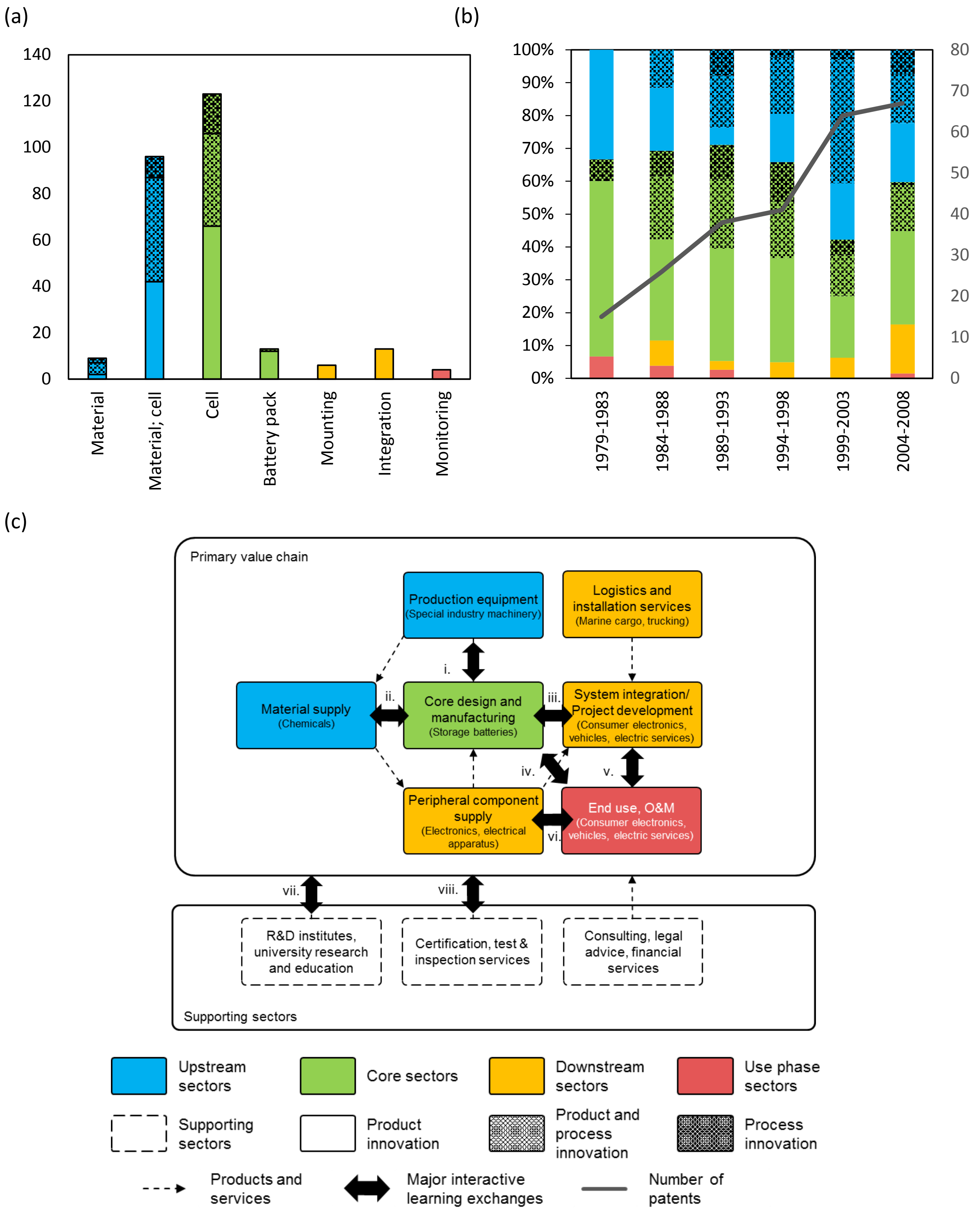

Figure 4: (a) Number of patents pertaining to each LIB industry value chain activity (b) Relative shares of patents pertaining to value chain activities, indicating type of innovation over time (c) Interactions involved in innovation in LIB systems

Upstream sectors: We find that innovation in LIB value chains is focused on the upstream sectors involved in material supply, and core component design and manufacturing. These activities taken together account for 86% of the patents for LIBs (Figure 4a). Further, we observe high levels of innovation in materials developed specifically for cell components (anode, cathode, electrolyte, and separator - 36% of all LIB patents). We also observe a high prevalence of patents disclosing a combination of product and process innovation (35% of all LIB patents), which is indicative of the specialized production processes for lithium-ion cells.

We find that innovation in cell materials is strongly dependent on close interaction between material suppliers and cell manufacturers (ii in Figure 4c). Collaboration with R&D institutions enables material suppliers to obtained science-based expertise in individual material chemistries (LIB1, 10) and underlying processes such as "the root causes of degradation and how to customize the material through additives, dopants and morphology" (LIB1). However, this is not sufficient due to the *complex and specialized* nature of the cell manufacturing processes and of the cell materials. Thus material suppliers (especially cathode) require feedback from cell manufacturers on material performance and characteristics inside the cell and in the context of industrial production processes (LIB1, 4, 7), since up to "200 properties of a cell can be varied such as densities, porosities, areas of active material" (LIB3). From a material supplier's perspective, "understanding of the interactions within the cell can be understood through interactions with the cell manufacturer" and "ideally you would like to have measurements in [the] lab adapted to the technical set up used by the customers" (LIB1). As a result, long-term collaborations between firms from the chemical sector and cell manufacturers are quite common in the LIB industry, with several large cell manufacturers (such as Hitachi, LG Chemicals, BYD and Samsung SDI) even benefiting from in-house chemical production divisions. Similarly, European chemical companies such as Umicore and BASF have R&D centers or collaborations with Japanese and Korean chemical companies to have close proximity with leading cell manufacturers.

Innovation in production equipment and manufacturing processes also involves close interactive learning with cell manufacturers (i in Figure 4c). This is because production equipment for lithium-ion cell manufacturing needs to fulfil *specialized requirements* for processes such as electrode slurry mixing, electrode coating, calendaring, and slitting, meaning that installation, maintenance and upgrades are done exclusively by PEMs (LIB4, 10). In addition, cell manufacturing process parameters, material composition, and cell performance are all interdependent, leading to high *complexity* (LIB1, 4, 7, 10, 11). As a result, the major PEMs for electrode and cell manufacturing are concentrated in Japan and South Korea, benefitting from knowledge base developed through extensive experience from producing equipment for similar processes (for example, equipment for slot coating or clean room technology) in the electronics sector[12], and from close interaction with large cell manufacturers such as Panasonic, LG, Samsung, Sanyo and Sony. Thus, the sectors involved in material supply, production equipment manufacturing and cell manufacturing are closely interlinked, requiring a high degree of information exchange which is mediated by the cell manufacturer.

Core sectors: We find that problem-solving in core activities for the LIB industry has focused both on product innovation to improve service characteristics such as energy and power density, and on process innovation to increase the efficiency and scale of production processes. The patent data shows that the shares of product and process innovation for LIB (55% and 11% respectively, Figure 6a) lie in between

[12] Firms particularly benefitted from experience with equipment for the manufacture of thin and flexible displays for electronic devices.

those observed for the core value chain activities for wind turbine systems (93% and 5%, Figure 4a) and solar PV systems (42% and 27%, Figure 5a). Furthermore, there is significantly higher focus on innovation in cells and cell components than on modules.

According to the interviews, product innovations have been enabled by cell manufacturers interacting closely with material suppliers (ii), while also receiving extensive feedback on cell lifetime and performance from end use in different contexts and applications, often through the system integrators (iii, iv). Process innovation is often required to bring such product innovations to the market, or to produce existing products more efficiently, and is enabled by close interaction with PEMs (as described in the section on "Upstream sectors").

Cell manufacturers maintain close ties with R&D institutions to maintain an overview of global developments (vii). At the same time, specialized knowledge related to cell concepts and design is considered a core competence and related research is done in-house. Lithium-ion active material compositions are at a mature stage with a well-defined technological trajectory, focusing on incremental product innovation in cell chemistries, e.g. optimizing the dopant (typically manganese or aluminium) level or increasing the amount of nickel in high-nickel chemistries on the cathode side (LIB1, 10); or introducing and increasing the amount of silicon in graphite on the anode side (LIB1, 2, 10). The successful introduction of such innovations at a commercial scale is largely dependent on close interaction with PEMs (as described in the section on "Upstream sectors"). Consequently, the amount of knowledge transfer involved in collaboration with external R&D for the introduction of such innovations is perceived as a threat to cell manufacturers' core competences in a highly competitive industry (LIB5).

Feedback from end use is also important for cell manufacturers (iv). However, with the exception of application in consumer electronics, the industry so far has been described as an "open loop" (LIB5). Cell chemistries today are largely dictated by requirements of the consumer electronics industry, historically the largest market segment for LIBs, and have benefitted from more than 20 years of experience. This is beginning to change since prospects of increasing and sustained demand for electric vehicles is driving the adaptation of cells and related production processes to suit the requirements of the automotive industry. Modifying cell chemistries for other applications with small market sizes and specialized requirements is often too costly for leading cell manufacturers, but these applications are exploited as niches by smaller players (LIB7, 11). Due to dynamic and varying conditions in the use environment, electric vehicles have been described as "the most challenging application to develop cells, compared to stationary applications or consumer electronics" (LIB11). Cell manufacturers still rely on extensive in-house testing to ensure reliability since the "nascent state of the industry makes feedback more difficult" (LIB5). It is also acknowledged that for newer applications, even the cell suppliers "do not know how their cells age because their tests are different from the real applications" (LIB8), and since simulation models are calibrated using real-life data. Thus cells for new applications are developed in close collaboration with end users, e.g. automobile manufacturers (LIB9).

Downstream sectors: We find that the extent of learning required in downstream sectors is highly dependent on the application (LIB 7, 8, 9). We observe a much smaller number of patents in downstream activities in the value chain (7% of all LIB patents), and no significant change in their number over time, although there is an increase in the last three years of the sample (Figure 6b). This is because consumer electronic applications generally do not involve extreme or highly variable discharge profiles or use environments, thus requiring no sophisticated thermal management and control systems (LIB5). However, for more demanding industrial, power sector and especially automobile applications with specialized requirements, learning is enabled by extensive feedback from technology users in different *use environments* (LIB9). System integrators obtain user feedback in order to optimize BOS components and system design (v, vi) since “they have to sell to end customers and so they need to know their requirements to build a bridge between the cell and the application” (LIB7). While collection of data related to usage profiles, environmental conditions, and battery performance is facilitated by the use of sensors, such information can still be sticky in early stages of the market since it is often unclear what data needs to be collected and how it can be used, i.e. “the more data you have the better you get and the more you know about what you need to focus on and what you can ignore” (LIB9).

To summarize, we find that innovative activity in the LIB industry focuses on product and process innovation in the core value chain activity of cell design and manufacturing, and the upstream activity of material supply (see Figure 2a), with increasing emphasis on material innovations in the second half of the observed time period (see Figure 2b). Learning in the LIB industry is driven by a high degree of interaction and knowledge feedbacks among the upstream activities of cell design and manufacturing, production equipment supply, and material supply on the production side, as well as among the downstream activities of battery design and manufacture, system integration, and end use (see Figure 2c).

6. Discussion and conclusion

6.1. Implications for theory: The role of the sectoral configuration and learning-by-interacting in TIS studies

This study builds on the work by Stephan et al. (2017) to further integrate the sectoral configuration into TIS analysis. While the TIS literature emphasizes the importance of interactive learning in networks of actors, (Lundvall, 2010; Musiolik et al., 2012) our results demonstrate that different sectoral configurations can result in distinct patterns of interactive learning and hence knowledge production and diffusion in different TISs. We find that the role of interactive learning for innovation is strongly dependent on specific characteristics of the key characteristics of a sector – the level and sources of opportunity, technological complexity, and specificity of knowledge base – which we discuss in detail here.

The degree of *technological complexity* is a strong determinant of the need for trial-and-error experimentation. Technological complexity makes it difficult to predict or simulate the performance of new designs – especially in capital-intensive technologies, where the cost associated with building and operating a full-scale prototype becomes prohibitive. Depending on the incidence of technological complexity in the industry value chain, the trial-and-error experimentation can take different forms. For instance, as highlighted by the literature on technology life cycles, learning in mass-produced technologies with complex production processes (i.e. complexity in upstream sectors) takes place through trial-and-error experimentation in production processes or learning-by-producing. In contrast, learning in complex product systems (i.e. complexity in core sectors) takes place through learning-by-using.

However, to understand how technologies with different life cycles differ in terms of interactive learning, we follow Stephan et al. (2017) in demonstrating that it is useful to disaggregate the actors in the TIS value chain and characterize them in terms of their respective sectors. Specifically, we find that in cases where the different components of a complex sub-system of a technology are reliant on *specialized, cumulative (and thus appropriable) knowledge bases* from different sectors, interactive learning is necessary for knowledge (co-)production, with the firm manufacturing the core component in the sub-system acting as a mediator of learning interactions with the suppliers. For example, cells for lithium-ion batteries require inputs from the chemicals sector and electronics sector, in addition to knowledge specific to lithium-ion batteries possessed by the cell manufacturers and PEMs. In contrast, in cases where the different components are reliant on similar knowledge bases from the same sector, there is a greater tendency to vertically integrate, reducing the importance of interactive learning. For example, the rotor, drivetrain, and related control systems for wind turbines are complex but all require specialized knowledge in mechanical engineering, and are generally designed in-house by OEMs. Additionally, *specialized demand* for a sector's outputs can also lead to the need for user-producer interaction in a value chain activity. Even for innovations in non-complex technologies with specialized user requirements, an initial phase of user-producer interaction is required, since understanding and codifying user specifications, or standardization of interfaces between sub-systems or components requires the acquisition sticky information through close interaction with the user (von Hippel, 1976). New forms of specialized demand for a sector's outputs can arise even in an established value chain because of innovations in other parts of the value chain, or because of use of the technology in a new sector or use environment.

Further, by analyzing the sectoral configuration and patterns of interactive learning of lithium-ion batteries, we find that the patterns of innovation do not conform to either of the two technology life-cycle models discussed by Huenteler et al. (2015). Instead, they can be considered a case of dually complex, mass-produced technologies. Huenteler et al. (2015) hypothesized about technologies that have not been described by the two traditional life-cycle models, and could involve continued product and process innovation over the entire life-cycle. Our findings confirm that in terms of their continued emphasis on closely interlinked product and process innovation, lithium-ion batteries exhibit characteristics of both design-intensive and process-intensive technologies. We find that there is high complexity in both product architecture and production processes for lithium-ion batteries, as well as strong interdependencies between process parameters and product characteristics (dual complexity). Innovation in this case is a multi-optimization problem drawing on specialized knowledge bases of multiple sectors (chemical sector, electronics sector, machinery and automotive/power sector) simultaneously. Thus, it requires close interactive learning among material suppliers, production equipment manufacturers, cell manufacturers, system integrators and end users in the value chain, with cell manufacturers acting as the central node for interactive linkages.

6.2. Implications for policy: Learning-by-interacting in energy technologies

By examining the micro-level interactive learning processes in multi-sector industry value chains (rather than comparing the differences in the user-producer interaction dyads for the complex artifact as a whole), we help explain the differences in empirical literature regarding importance of interactive learning between actors in clean energy TISs.

In a study analyzing the wind industry in Denmark, Keller and Negoita (2013) found that government measures to promote collaborations between researchers, manufacturers, and end-user fostered innovation. They further find that Japanese policies were effective in promoting collaboration between firms from the electronics sector, battery-manufacturing sector, power sector, and chemicals sector. In contrast, Shum and Watanabe (2008) find that interactive learning between downstream sectors, i.e. system integrators, utilities and end-users enabled innovation in the BOS subsystem of solar PV in the US.

We explain these differences as an outcome of different sectoral configurations, and we add further nuance by explicitly examining interactive learning in the entire TIS value chains of three technologies. Thus, policies aiming to establish and promote innovation in certain parts of the TIS value chain should be adapted to their sectoral configuration and characteristics to avoid 'network failures' (Keller and Negoita, 2013) and enable 'interface improvement' (Taylor, 2008). Particularly, innovation in technologically complex sub-assemblies with inputs from sectors with distinct, specialized knowledge bases (e.g. production equipment for solar PV and lithium-ion batteries, cells for lithium-ion batteries, and core sub-assemblies for wind turbines) can be promoted through policies to facilitate network formation and inter-sectoral knowledge exchange. Examples of such measures include publically funded collaborative R&D projects and test facilities (Keller and Negoita, 2013), and support for platforms such as industry associations, public research institutes and test facilities with the specific mandate to act as facilitators of inter-sectoral knowledge exchange (Garud and Karnøe, 2003). Furthermore, to localize, achieve and maintain competitiveness through technology transfer in value chain activities that require sustained learning-by-interacting, even nations with pre-existing sectoral knowledge bases need to create conditions to facilitate prolonged and sustained relationships with foreign firms. Examples include policies to enable foreign direct investments and international R&D collaboration (Quitzow et al., 2017). On the other hand, innovation in sectoral outputs catering to specialized or context-specific demand (e.g. installation and system integration of rooftop solar PV, logistics and installation of offshore wind turbines) can be supported through facilitation of formal and informal exchange of knowledge through industry conferences (Taylor, 2008), regularly updated industry-wide standards for performance, component interfaces and professional training (Shum and Watanabe, 2008), and tying targeted public support for specific application to requirements for data sharing within and across applications.

We believe that these insights are particularly relevant for policies aiming to develop an industry base around lithium-ion batteries. Unlike solar PV or wind in which the knowledge base is primarily related to manufacturing processes and product design respectively (Huenteler et al., 2016b), LIBs require expertise in both domains, with significant cross-sectoral interactive learning. Thus, policies need to perform two functions. First, they need to enable experimentation and scaling up of production processes, a function that has so far been performed by the consumer electronics industry. This can be achieved by creating certainty in market growth and by providing funding for collaborative R&D and pilot and demonstration manufacturing facilities to research consortia with actors from sectors involved in the LIB value chain, especially to promote innovation in relatively mature applications. Second, they need to support application-oriented product innovation through targeted support of less mature niches, and through the above-mentioned measures to incentivize data sharing and user-producer interaction. Examples of such emerging and relatively less mature applications include electric vehicles, frequency regulation, and grid investment deferral.

Finally, our results also indicate the varying role of home markets: depending on the importance of interactive learning in different parts of the value chain, early home markets might be advantageous for different sectors. For wind turbines, interactive learning with the end-use sector has been necessary for innovation, which explains the importance of home markets for the final product (Lewis and Wiser, 2007). On the other hand, for solar PV and lithium-ion batteries, interactive learning between upstream and core sectors has been necessary for innovation, making home markets for manufacturing equipment more relevant. Thus, while simply creating demand for early-stage technologies through deployment policies might be insufficient to support core sectors in the long term, it can help create a sustained competitive advantage for upstream sectors with complex technologies and hence cumulative and appropriable knowledge bases such as in the case of solar PV (Dewald and Fromhold-Eisebith, 2015; Quitzow, 2015) and lithium-ion batteries.

6.3. Conclusions, limitations and future research

Our analysis indicates that the sectoral configuration of a TIS can determine the patterns of learning-by-interacting in its value chain. Particularly, differences in sectoral characteristics such as the levels and sources of opportunity, as well as the complexity and specificity of knowledge base can lead to differences in importance of learning-by-interacting for the knowledge development and diffusion function. Thus, future TIS analyses can provide additional insight by explicitly taking into account the sectoral configuration. Further, we explain the differences in importance of learning-by-interacting in the existing literature based on our analysis, and provide recommendations as to how policies aiming to enable TIS formation around technologies or specific value chain activities can be adapted to account for these differences.

Given the scope and methodology employed in our empirical analysis of three TISs based on a mixed-method research design, there are some inherent limitations, which we highlight here. We further suggest avenues for future research. First, we analyze the patterns of learning-by-interacting in the value chain of a TIS while staying agnostic to the surrounding institutional arrangement. In reality, depending on the context, policies or institutional arrangements could be conducive or unfavorable for learning-by-interacting. Future analyses could validate and build on our approach by explaining the success or failure of TIS formation in specific contexts by linking the sectoral configuration and associated patterns of learning-by-interacting to the policies and institutional setup (e.g. in terms of varieties of capitalism) in those contexts. Second, we use patent data as one of the indicators of the levels and sources of opportunity in the TIS value chain, which biases our results due to under-reporting of innovative activity in certain value chain activities such as project development, financing and after-sales services. While we address this limitation to some extent by further relying on interview data to identify not only the levels and sources of opportunities, but also the underlying learning processes, future analyses could explicitly analyze learning and innovation in downstream sectors, especially as they become increasingly important in terms of total cost of clean energy technologies. Finally, while we qualitatively analyze the where in the TIS value chain learning-by-interacting is required and explain our observations based on the characteristics of the sectoral configuration, we do not quantify the magnitude of effect of sectoral characteristics on the extent of learning-by-interacting. Future analyses could use other data sources such as industry surveys to quantify the effect of sectoral characteristics on learning-by-interacting.

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