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The role of inter-sectoral learning in knowledge development and diffusion: Case studies on three clean energy technologies

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ABSTRACT

Studies in technological innovation systems (TIS) have made significant progress in explaining the dynamics of industry formation for emerging technologies, recognizing that learning is an interactive process. Recent literature suggests that knowledge development and diffusion among different sectors can play a role in the establishment of a TIS. However, we lack an understanding of how the characteristics of different sectors involved in a TIS influence inter-sectoral learning, i.e. purposive learning-by-interacting between different sectors involved in a TIS. To address this gap, we examine how patterns of inter-sectoral learning vary across three TISs – solar photovoltaic systems, wind turbines, and lithium-ion batteries. Using concepts from the literature on sectoral systems of innovation, we show that the characteristics of the different sectors involved in the TIS influence patterns of inter-sectoral learning. Thus, we provide a systematic way of explaining differences in the importance of learning-by-interacting between different technologies observed in the empirical literature, helping policymakers anticipate potential failures in inter-sectoral learning, and we suggest measures to address them. We also 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.

1. Introduction

Technological innovation has often been identified as a necessary part of any solution to address societal grand challenges such as climate change, water resource management, healthcare, and food security, while maintaining economic growth (Foray et al., 2012; Kuhlmann and Rip, 2018). Thus, several scholars have argued for a “mission-oriented” approach to supporting innovation in specific technologies in a targeted manner (Mazzucato and Perez, 2015; Wesseling and Edquist, 2018). In practice, several countries have set ambitious targets for deployment of clean energy technologies combined with industrial and innovation policies, with varying degrees of success (Anadón, 2012; Lewis and Wiser, 2007; Nemet, 2009; Peters et al., 2012; Taylor, 2008).

To explain this variation, studies in technological innovation systems (TISs) have made significant progress in explaining the dynamics of industry formation for emerging technologies. At its core, the literature on innovation systems recognizes that “learning is predominantly an interactive, and therefore, a socially embedded process” (Lundvall, 2010, p. 1), taking place in networks of actors that interact under a particular institutional infrastructure (Binz et al., 2014; Gallagher et al., 2012; Lewis, 2007; Lundvall, 1985).[1] Because of the systemic nature of innovation, the addressal of system failures[2] plays an important role in strengthening key functions of innovation systems (Bergek et al., 2008; Weber and Rohracher, 2012; Negro et al., 2012). In addition, several empirical studies have noted that ‘coordination failures’ (Aghion et al., 2009), ‘network failures’ (Keller and Negoita, 2013; Taylor, 2008) or failures in learning-by-interacting (Edquist, 2011) can hinder knowledge development and diffusion in innovation systems (Choi and Anadón, 2014; Garud and Karnøe, 2003; Kamp et al., 2004; Musiolik et al., 2012; Shum and Watanabe, 2008).

Further light has been shed on the interactive nature of technological learning by studies which have shown that learning among different sectors can play an important role in knowledge development and diffusion. On one hand, studies have shown that knowledge flows among diverse sectors can be conducive for innovation in industrial clusters (Benneworth et al., 2009; Boschma and Frenken, 2012;

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[1] Other innovation system frameworks, using a similar approach but 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).

[2] System failures can be categorized as infrastructural, capability, interaction or institutional failures (Klein Woolthuis et al., 2005).

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Fromhold-Eisebith, 2017; Uyarra, 2010) and for regional economic growth (Asheim et al., 2011; Boschma and Iammarino, 2008). On the other hand, studies have argued that learning interactions between sectors can be important even for a single technology. Bergek et al. (2015, p. 57) highlight that "many TISs are part of several sectors", and that the TIS interacts not only with the sector that it is mainly embedded in, but also with other sectors that it is related to. For example, in a study analyzing TIS formation in bio-synthetic natural gas (SNG) technologies, Wirth and Markard (2011) find that multiple sectors, including the gas sector, electricity sector, forestry, and sawmill industry, interact and play a role in the formation of the bio-SNG TIS. Similarly, in a study focusing on lithium-ion batteries in Japan, Stephan et al. (2017) show that several sectors such as the chemical sector, electronics sector and automobile sector are involved in the value chain of lithium-ion batteries, and that the sectors vary in importance for knowledge development and diffusion. Thus, they argue that the 'sectoral configuration', which refers to the number and types of sectors linked via the value chain of a TIS, influences the patterns of knowledge development and diffusion.

However, few studies have systematically investigated how the characteristics of different sectors involved in a TIS influence *inter-sectoral learning*, i.e. purposive learning-by-interacting between different sectors that contribute to knowledge development and diffusion. This gap is surprising, given that there is increasing recognition that innovation policies need to account for technology-specific learning patterns (Binz et al., 2017; Binz and Truffer, 2017; Huenteler et al., 2016b; Quitzow et al., 2017; Schmidt and Huenteler, 2016).

To address this gap, we examine how the importance of inter-sectoral learning varies across three energy-related TISs – solar photovoltaic systems, wind turbines, and lithium-ion batteries. We use a confirmatory case-based research design to test the influence of the characteristics of different sectors involved in the value chain of the TIS on patterns of learning-by-interacting. We show that the role of inter-sectoral learning between two sectors depends primarily on two sectoral characteristics – the *technological complexity*, and the *specificity of knowledge* that needs to be transferred between them. As a result, we make two primary contributions. First, we help explain the differences in empirical literature regarding importance of learning-by-interacting in clean energy TISs. We thereby provide a systematic way for policy makers to anticipate potential failures in inter-sectoral learning, and we suggest measures to address them. Second, we demonstrate that the sectoral configuration influences inter-sectoral learning for knowledge production and diffusion in a TIS. 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 the influence of sectoral characteristics on knowledge development and diffusion (Section 2.1), and the influence of sectoral configuration on inter-sectoral learning in a TIS (Section 2.2). Section 3 describes the research cases for this study – 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 of the current analysis, and avenues for further research are discussed in Section 6.

2. Sectoral configuration of technological innovation systems and inter-sectoral learning

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 common technology*.[3] In analyses using the TIS framework, the process of knowledge development and diffusion "is normally placed at the heart of a TIS" (Bergek et al., 2008, p. 414). The learning processes that underlie knowledge development and diffusion 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). In such analyses, a single technology is the focus of analysis and all actors, networks and institutions contributing to innovation processes (referred to as 'functions' in the TIS literature) pertaining to the technology constitute the TIS.

In contrast, the literature on sectoral systems of innovation (SSI) delineates an SSI along sectoral lines. It is defined as a set of activities that is unified by some linked product groups for a given or emerging demand and which shares *a common knowledge base* (Breschi and Malerba, 1997; Malerba, 2002, 2006). We follow Breschi and Malerba (1997) in distinguishing between a TIS, which encompasses networks of vertically as well as horizontally connected heterogeneous agents engaging in innovation for specific technologies, and an SSI, which focuses on relatively homogeneous agents with a common knowledge base engaging in innovation and competition in a given selection environment. Thus, we assume that both TISs and SSIs have the same type of structural elements (Bergek et al., 2015; Malerba and Adams, 2014), but they differ in terms of their system boundaries. We will see that this is a useful distinction to make, since the relative homogeneity of structural elements (particularly the knowledge base) within an SSI allows us to make hypotheses regarding the influence of their characteristics on innovation processes (or 'functions') within a TIS.

The literature on SSI emphasizes that innovation processes are strongly influenced by sectoral characteristics. Thus, for multi-component technologies with complex value chains, each value chain segment can have distinct sectoral characteristics, i.e. a single TIS can encompass actors belonging to different SSIs. However, applications of the TIS framework often neglect the sector-specific patterns of innovation (Binz and Truffer, 2017; Grubb et al., 2017) and how they interact with each other (Bergek et al., 2015). Thus, following Stephan et al. (2017) we take into account the 'sectoral configuration' of a TIS, which refers to the number and types of sectors linked via the value chain of a TIS. Doing so helps us to provide deeper insight into the differences in patterns of inter-sectoral learning in TISs with different sectors.

Fig. 1 illustrates the generic sectoral configuration of a TIS value chain. We classify the value chain segments of a generic multi-component technology into 7 categories: production equipment supply, material supply, core design and manufacturing, peripheral components supply, project development (or system integration), logistics and installation services, and end use. Each of these segments may involve one or more sectors and a single sector can be involved in more than one value chain segment.

While these 'primary segments' are essential for knowledge development and diffusion in the industry value chain, there are a number of segments which facilitate other functions such as resource mobilization and development of positive externalities, which we classify as 'supporting segments': university research and education, testing and certification services, and consulting and financial services. In the following sections, our focus will be on the role of inter-sectoral learning in knowledge development and diffusion in the primary sectors. We draw on concepts from the literature on SSI to characterize the sectors involved in different value chain segments of the TIS. We then formulate hypotheses regarding the influence of sectoral characteristics on patterns of inter-sectoral learning.

[3] We define a technology as a class of artifacts defined by a common 'operational principle' and its associated knowledge base (Murmann and Frenken, 2006).

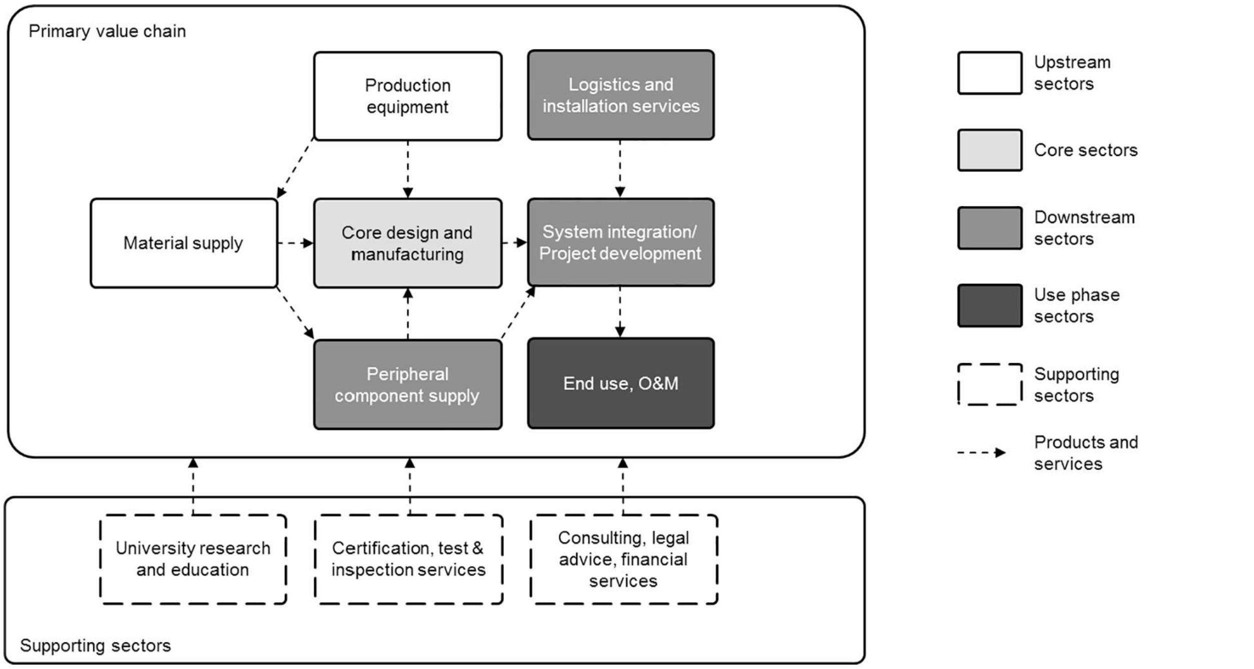

Fig. 1. Typical value chain for a TIS. Each segment in the value chain can involve one or more sectors, and a single sector can be involved in more than one value chain segment.
Adapted from Huenteler et al. (2014) and Stephan et al. (2017).

2.1. Sectoral characteristics and knowledge development and diffusion

Empirical analyses of individual SSIs have shown that there are systematic differences between sectors in terms of their patterns of innovation (e.g. technological trajectory, balance between product and process innovation) and industrial organization (e.g. position in the value chain, size of firm, degree of vertical integration, market shares, geographic concentration) (Breschi and Malerba, 1997; Castellacci, 2008; Klepper, 1996; Malerba, 2005; Pavitt, 1984). Several scholars have proposed that the patterns of innovation of a particular sector are related to sectoral characteristics that constitute the “technological regime” (Dosi, 1982; Malerba and Orsenigo, 1996, 1997; Nelson and Winter, 1982). The sectoral characteristics influence the incentives and constraints facing an innovating firm, and thus affects the basic evolutionary processes of variation and selection (Levin et al., 1985).

Most importantly for our research question, the sectoral characteristics determine the relative importance of different learning processes underlying knowledge development and diffusion (Malerba, 2002). The sectoral characteristics can be classified under four fundamental factors, namely: opportunity conditions, characteristics of the 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 sector are summarized in Table 1.

While concepts from the literature on sectoral and regional systems of innovation can be useful to provide innovation policy insights, they have certain drawbacks which must be taken into account.

First, several scholars have pointed out that there is increasing criticism of setting territorial or sectoral boundaries due to the globalized nature of industry value chains (Binz et al., 2014; Binz and Truffer, 2017; Gereffi et al., 2005; Markard and Truffer, 2008). *Second*, frameworks taking a region or sector as the unit of analysis can be inappropriate in cases where a single technology is the unit of analysis (as is often the focus of innovation and industrial policies, or environmental policies targeting clean energy technologies) (Bergek et al., 2008, 2015; Stephan et al., 2017). *Third*, in cases where different sectors are involved in different value chain segments of a multi-component technology, it is unclear how learning processes are influenced by the characteristics of each sector. Especially in cases where knowledge is co-created through learning-by-interacting between two or more sectors, it might be useful to analyze the characteristics of different sectors in relation to each other, rather than focusing on specific sectors in isolation.

Thus, we use the TIS framework while drawing on concepts from the literature on sectoral systems of innovation to answer our research question and to help further integrate the two streams of literature.

2.2. Influence of sectoral configuration on inter-sectoral learning in a TIS

Here we formulate hypotheses regarding the influence of sectoral characteristics (discussed in Section 2.1) on inter-sectoral learning required for knowledge development and diffusion. Specifically, we frame hypotheses regarding the influence of opportunity conditions and knowledge base characteristics (summarized in Table 1) on learning-by-interacting between a focal sector and a second sector.

First, the *level of opportunity* determines the potential for knowledge development and diffusion and hence learning processes within the focal sector. A sector's level of opportunity is determined by its closeness to science, external sources of technical knowledge and maturity of the sector (Levin et al., 1985). Thus, it conditions the role of learning processes in general, including through R&D, knowledge spillovers,

Table 1
Sectors can be characterized in terms of four factors and their underlying 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	Specificity	The degree to which knowledge is specialized in 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.

learning-by-producing, learning-by-using, and learning-by-interacting (Kamp et al., 2004; Malerba, 1992).

Second, the *sources of opportunity* specify the reliance on certain sources for learning and knowledge development. Technological knowledge external to the focal sector can be acquired in form of knowledge spillovers from advances in science and technology, inter-sectoral spillovers, and learning-by-interacting (Cohen and Levinthal, 1989; Malerba, 1992). The reliance on sources of knowledge external to the focal sector thus represents a second prerequisite for learning-by-interacting.

To summarize, the role of inter-sectoral learning in knowledge development and diffusion in a focal sector is conditioned by level of opportunity and the existence of sector-external sources of opportunity. Thus, we propose that given a certain level of opportunity and a sector-external source of opportunity, the characteristics of the sector-external source of knowledge determine the role of inter-sectoral learning in knowledge development and diffusion.

First, the *specificity of the sector-external source of knowledge* determines the degree of dependence on specific actors and application domains as knowledge sources for the focal sector (Malerba and Orsenigo, 1997). High specificity may arise from specialization of knowledge domains of upstream sectors or from specialization of application domains in downstream sectors (Adams et al., 2015; de Figueiredo and Silverman, 2012). In either case, the more highly specialized the sector-external knowledge, the less likely it is that inter-industry spillovers in the form of standardized knowledge would be readily applicable in the focal sector. Instead, knowledge acquisition in such cases is likely to involve purposive learning-by-interacting to overcome cognitive distance and to codify knowledge (Nooteboom, 2000, 2009). For instance, sectors catering to highly specialized user demand often rely on user-producer interaction to develop specialized knowledge related to the application domain (Stewart and Williams, 2005), institutional contexts (Jeannerat and Kebir, 2016) and desirable attributes in new products or services (Thomke and Von Hippel, 2002; von Hippel, 1994). Thus, we hypothesize that for a sector with a given level of opportunity and a sector-external source of opportunity, the greater the specificity of the sector-external knowledge, the greater the need for inter-sectoral learning for knowledge development and diffusion.

Second, the *complexity of the sector-external source of knowledge* determines the need for trial-and-error experimentation or learning-by-doing. We follow Simon (1962) and Murmann and Frenken (2006) in defining the complexity of a system in terms of two elements: the number of elements comprising the system, and the extent to which the elements are interdependent. Several studies have demonstrated that it can be difficult to anticipate technological performance of innovations in complex technologies, 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). Thus, in case a sector relies on sector-external knowledge that is complex and has uncertain outcomes in terms of technological performance, learning-by-interacting would be required to acquire it. Thus, we hypothesize that for a sector with a given level of opportunity and a sector-external source of opportunity, the greater the complexity of the sector-external source of knowledge, the greater the need for inter-sectoral learning for knowledge development and diffusion.

Finally, the appropriability conditions determine the ease with which the stock of knowledge can be protected from externalities and spillovers. They depend on factors such as institutional environment for intellectual property rights, trade secrecy, and control of complementary assets (Levin et al., 1985; Malerba and Adams, 2014). While high appropriability is unfavorable for knowledge spillovers, it does not directly influence learning processes, including learning-by-interacting for knowledge development and diffusion. Similarly, cumulativeness of knowledge determines the extent to which new knowledge builds on older knowledge. It arises primarily from increasing returns due to learning economies (Arthur, 1989; Unruh, 2000). Both appropriability and cumulativeness determine the geographic and market concentration of innovators. While they may be correlated with each other (high cumulativeness at the firm level implies high appropriability) and the sectoral characteristics discussed above (e.g. cumulativeness is correlated with complexity) (Frenken, 2006; Levin et al., 1987), one cannot make direct inferences about the underlying learning mechanisms solely based on them.

3. Case selection and unit of analysis

In this study, we focus on the TISs of three technologies – wind turbine systems, solar photovoltaic systems, and lithium-ion batteries – for several reasons. *First*, we use the diverse case selection strategy (Seawright and Gerring, 2008) for a confirmatory case study design.

Table 2
Description of the value chains and sectoral configurations for the TISs for wind turbines, solar photovoltaics, and lithium-ion batteries. 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 Resins, and Nonvulcanizable Elastomers (2821)	Semiconductors and related devices (3674)	Industrial Inorganic Chemicals, Not Elsewhere Classified (2819)
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)

Thus, we choose technologies whose value chain segments exhibit diverse sectoral characteristics. To do so, we choose technologies whose TISs include several value chain segments belonging to different sectors (see Section 3.1), which enables us to observe differences in sectoral characteristics and inter-sectoral learning within a TIS. *Second*, the sectors involved in the value chains of the technologies have varying sectoral characteristics, since their knowledge bases have varying levels of complexity (see Section 3.2). *Third*, all three technologies are likely to play a significant role in the future energy system, and thus understanding the patterns of innovation in these technologies is especially important from a public policy perspective.

3.1. Sectoral configurations of the case technologies

We describe each of the value chain segments and the associated sectors for the three technologies in Table 2. These descriptions are 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).

To summarize, due to the multi-component nature of the three case technologies, their TISs involve a number of different sectors linked through the technologies' value chains.

3.2. Characteristics of the core sectors of the case technologies

To ensure diversity in our case selection, we characterize the three case technologies in terms of the complexity of the knowledge base for two value chain segments that are important determinants of patterns of innovation: core design and manufacturing, and production equipment supply (Huenteler et al., 2016b).

Wind turbines are electro-mechanical machines that convert kinetic energy of wind into electric power. Since the early 1980s, the market for wind turbines has come to be dominated by the 'Danish design' (Garud and Karnøe, 2003), which features a three-blade upwind rotor (Menzel and Kammer, 2012). The overall system can be divided into four major sub-systems: the rotor, the powertrain, the mounting and encapsulation subsystem, and the system integration subsystem (Hau, 2010; Huenteler et al., 2016a). The rotor and powertrain have a particularly 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 (Hoppmann et al., 2013), out of which c-Si is 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. The rocking chair cell commercialized in 1991 has emerged as the dominant design (Nitta et al., 2015; Yoshio et al., 2009). LIBs consist of individual cells (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 parameters in cell and battery pack design, which are highly mutually interdependent (Santee et al., 2014). Manufacturing steps for LIBs can be summarized as: mixing of the active material of each electrode with carbon black and polymer binders to form a slurry; slurry coating, calendaring, slitting and drying to form the electrodes; winding the electrode, filling it with 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 sensitive and dependent on each other, and also on the product design parameters, making the manufacturing process very complex.

To summarize, out of the six value chains segments discussed above, four have highly complex knowledge bases: core design and manufacturing for wind turbines, production equipment supply for solar PV, and both core design and manufacturing and production equipment supply for LIBs.

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). We carried out semi-structured interviews with actors involved in different value chain segments of the case technologies to understand their levels and sources of opportunity, complexity and specificity of the knowledge base, and the need for inter-sectoral learning. We supplemented and triangulated the results of the qualitative analysis using patent data, which we describe in Section 4.2.

4.1. Qualitative analysis of interview data

We used qualitative methods since they allow for studying of the underlying mechanisms of a phenomenon in greater depth as compared to quantitative methods (Eisenhardt and Graebner, 2007). To choose our interview partners, we use stratified purposeful sampling, stratifying across value chain segments for each technology (Palinkas et al., 2015; Patton, 1990). Within each value chain segment, we aimed to develop a representation of a 'typical case'.

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.[4] Each interview lasted between 45 and 60 min (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 levels and sources of opportunity, complexity and specificity of knowledge base, and associated learning interactions, if any. We used the software MAXQDA for coding and analyzing the interview data.

[4] 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 3
List of interviewees.

Interview number	Technology	Actor	Value chain position	Designation
1	Wind turbines	OEM	Core	Chief Technology Officer
2		OEM		Head of wind turbine engineering
3		OEM		Sales director
4		OEM		Project manager, project development
5		OEM		Regional Product Strategy Manager
6		Blade manufacturer		Plant Director
7		Gearbox manufacturer		Head of Electrical Systems
8		Electrical drivetrain manufacturer		Manager for Medium-Voltage Converters
9		Utility	Downstream	Project manager, offshore wind
10		Installation and construction		Director of Field Services
11		University R&D	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		Production equipment		President and CEO
17		Cell manufacturer	Core	Group leader
18		Module manufacturer		Project manager
19		Project developer	Downstream	Director Strategy & Business Development
20		Research and consulting		Senior project manager, energy industry
21		Project developer		Business Development Manager
22		Inverter manufacturer		Vice President of Products
23		Inverter manufacturer		Managing Director
24		Research and consulting	Support	Director
25		R&D institution		Professor
26		Consulting firm		Project manager, renewables business
27	Lithium-ion batteries	Material manufacturer	Upstream	President, Process & Chemical Engineering
28		Material manufacturer		Director, Research & Development
29		Production equipment		Chief executive officer
30		Production equipment		Head of Market Segment Battery Solutions
31		Cell manufacturer	Core	Senior Manager
32		Cell manufacturer		Executive Director, Product Planning Strategy & Innovation
33		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		R&D institute		Head of Electrochemical Materials Research
38		Grid R&D organization	Downstream	Head of business development

4.2. Patent content analysis

To supplement our qualitative findings, we used patent data as quantitative proxies for sectoral characteristics of value chain segments of the case technologies (Archibugi and Planta, 1996; Basberg, 1987; Jaffe and de Rassenfosse, 2016). First, we used patent data to measure the *level of opportunity*. 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. Thus, we used the number of highly cited patents in a sector as a proxy for its level of opportunity.

Second, we used patent data to identify the *sources of opportunity*. 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 used the relative share of product versus process innovation in a sector as an indicator for sources of opportunity.

As a first step for the patent analysis, we compiled a database of patent applications pertaining to the three technologies filed globally from 1960 to 2015,[5] 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[6] and keywords.[7] 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

[5] 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.

[6] 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.

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

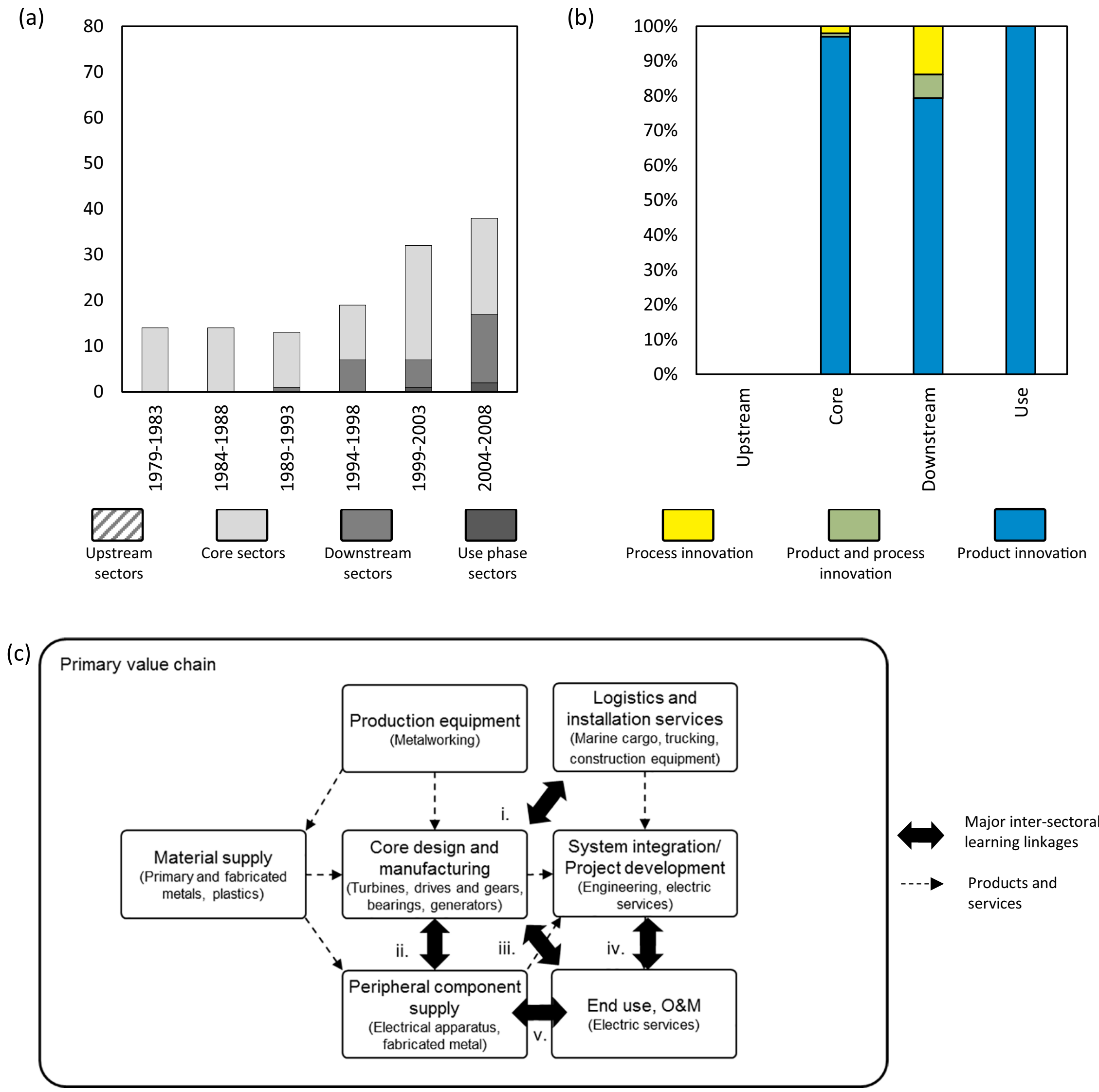

Fig. 2. (a) Number of patents pertaining to sectors involved in wind turbine TIS, indicating levels of opportunity (b) Relative shares of process and product innovation in different sectors, indicating sources of opportunity (c) Patterns of inter-sectoral learning in wind turbine TIS.

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.[8]

Finally, the subset of patent data thus obtained was manually coded to locate the knowledge embodied in the patent to its corresponding value chain segment, 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 coded each patent based on its title, abstract and claims. In case of disagreement, consensus was reached following a discussion between the coders.

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

5. Results

We present the observed patterns of inter-sectoral learning for the three case technologies in Sections 5.1, 5.2 and 5.3. For each technology, we organize the results by dividing the industry value chain into three major parts: upstream, core, and downstream sectors (c.f. Fig. 1). For each part of the value chain, we describe the level and sources of opportunity, the complexity and specificity of knowledge base, and the inter-sectoral learning processes involved in knowledge development and diffusion. We support these results using a three-panel figure for each technology.

5.1. *Inter-sectoral learning in wind turbine TIS*

5.1.1. *Upstream sectors*

We find that upstream sectors exhibit relatively low levels of opportunity and inter-sectoral learning (WIN2, 4, 11). The patent data indicates that material supply has been the least important value chain segment in terms of innovation, with no patents related to materials in the analyzed sample (Fig. 2a).[9] 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 inter-sectoral learning in material supply is also very small (WIN2, 4, 11).

We also find that opportunity levels in production equipment and manufacturing processes for wind turbines are lower as compared to 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 has a specialized knowledge base. "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.

5.1.2. Core sectors

We find that opportunity levels in the wind industry are highest in the core segment of rotor and powertrain subsystem design. This is reflected in the patent data (Fig. 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 (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 key components in-house (interaction ii in Fig. 2c) and they source other components from suppliers. "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). Gearboxes and generators use specialized knowledge bases from other sectors (Table 4), 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. 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 (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 (iii, v; 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 sector has reduced in recent years (WIN12). This is because OEMs understand better which data to collect, how to collect it remotely, and because "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).

5.1.3. Downstream sectors

We find that opportunity levels in downstream sectors are lower as compared to core sectors, but the importance of downstream sectors has steadily increased in recent years (see Fig. 2a). Downstream sectors represent 25% of all highly cited patents. 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, the locus of innovative activity shifts to the peripheral components (Murmann and Frenken, 2006). The design of power converters, towers and foundations is dependent on specific turbine design parameters (see Table 4), and so new designs are introduced by OEMs themselves, or through close interaction and testing in collaboration with component suppliers (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 Fig. 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 (i, WIN4, 6, 11). Third, the need for interaction in downstream sectors was further increased due to deployment of turbines in different use environments (iii). 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).[10]

To summarize, we find that core sectors engaging in rotor and powertrain design have high levels of opportunity (see Fig. 2a and b), with increasing focus on downstream product and process innovation in recent years (see Fig. 2a). Learning in the wind industry is driven by a high degree of interaction among core sectors (ii), and interaction with downstream sectors, particularly by original equipment manufacturers obtaining feedback from the use phase of the technology (iii, iv, v in Fig. 2c).

[9] For a more disaggregated view of the distribution of patents across different value chain segments, please refer to Appendix E.

[10] 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).

Table 4
Interview quotes illustrating sectoral characteristics and occurrence of inter-sectoral learning in the wind turbine TIS.

Focal sector	Sectoral characteristic	Exemplary quote	Source
Core (Gearbox design and manufacturing)	Complexity of knowledge base	"When wind turbines are scaled up, the companies shift many parameters at the same time: they change the gearbox, the generator, the blades, etc. That is always very new technical territory – the companies can't estimate before testing how these components will **interact**." "You just mend one of those components directly, the generator, the coupling supplier, oil flue systems, controller systems, sensors, yes. It's not a one-way direction. It's an **interaction** between all these suppliers. Of course it is coordinated by the OEM."	WIN7
Downstream (Power converter)	Specificity of knowledge base	"Typically, it starts with a pre-concept, and then our OEM customers provide us with a specification, and that is the basis of our development, but of course we keep **continuous contact** with them, giving them feedback, and they come back to us with **special requirement**s they have. These special requirements could be special turbine behavior they want to see, that they want to add a special control algorithm in the turbine. How to handle it, how to deal with it." "I think the industry has not been able to standardize the electrical drive to such an extent that exactly it's known what we expect. I think **each turbine is a bit unique**, and has to be discussed in detail."	WIN8

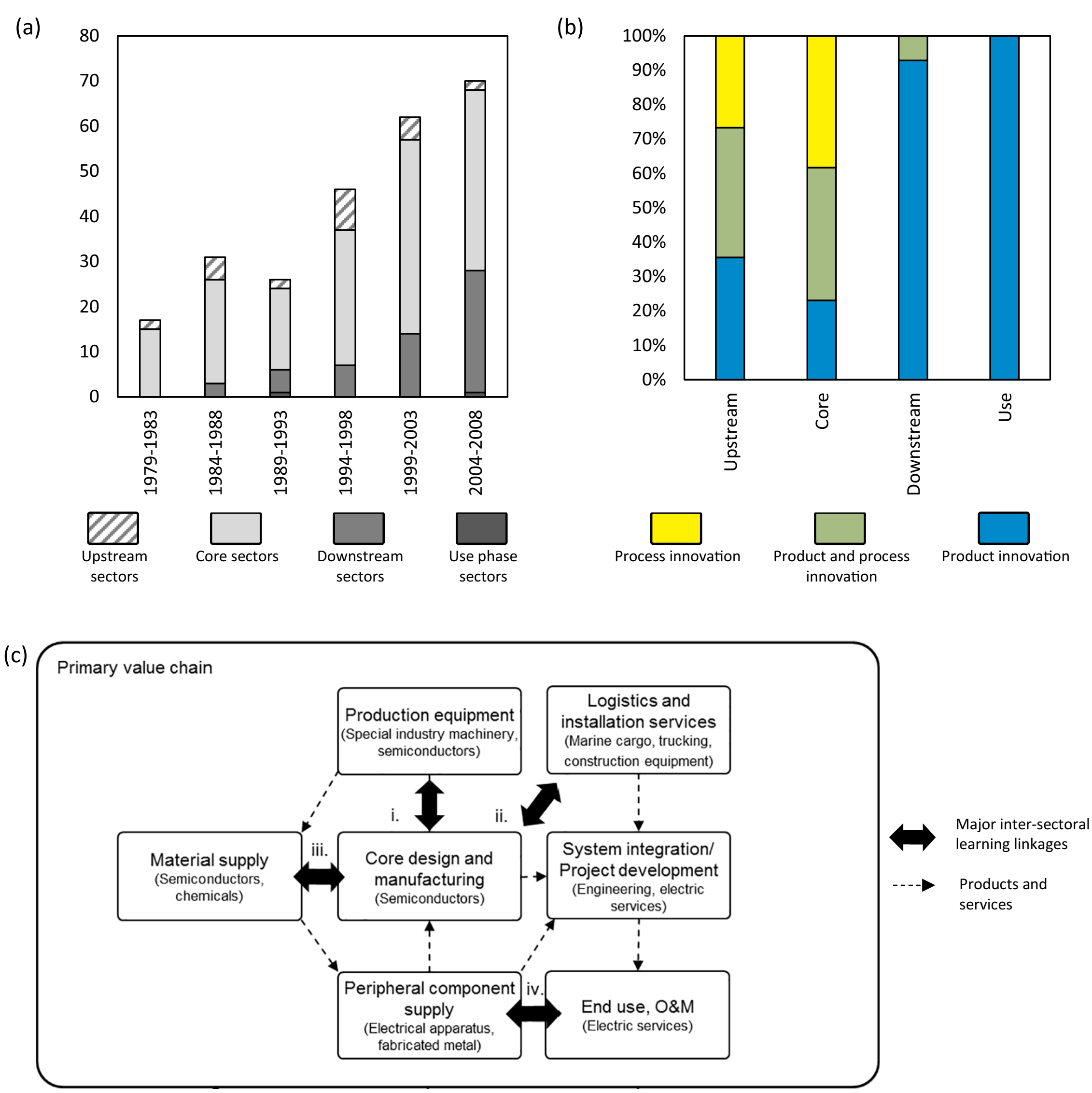

Fig. 3. (a) Number of patents pertaining to sectors involved in solar PV TIS, indicating levels of opportunity (b) Relative shares of process and product innovation in different sectors, indicating sources of opportunity (c) Patterns of inter-sectoral learning in solar PV TIS.

5.2. Inter-sectoral learning in solar PV TIS

5.2.1. Upstream sectors

We find that for solar PV, opportunity levels are highest in the upstream segments of production equipment supply and processes for cell manufacturing. About 12% of all highly cited patents for solar PV are related to innovations in materials or related production processes (Fig. 3a), and 49% of all patents disclose process innovations for cell and module manufacturing (Fig. 3b).[11] In addition, 88% of process innovation patents are related to innovations in materials and cell manufacturing processes. Another prominent 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, inter-sectoral learning plays an important role for knowledge development and diffusion in upstream sectors (i, iii in Fig. 3c). "Until the completed cell, the feedback and the interaction are very concentrated, since the actors work relatively close together" (SPV24). 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 (SPV16, 19). 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" (SPV19). The interviewees also noted that although the successful introduction of significant material innovations is unlikely, it would require significant interactive learning (SPV19).[12] According to one production equipment manufacturer (PEM) "…when it comes to new concepts like epitaxial growth then you need input [from material suppliers]" (SPV16). 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 sector-internal science-based knowledge involved in these innovations (SPV15, 17, 18). 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 Fig. 3c). First, due to the complex nature of the production line from polysilicon wafers to cells, innovation is often based on data from full-scale production lines (see Table 5). Upgrades often 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" (SPV15). Thus, the cell manufacturers play an important role in suggesting improvements based on their experience with operating the production equipment (SPV15, 19, 26). 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 (SPV17, 18, 19). 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, Switzerland and the US (Zhang and Gallagher, 2016) – countries that 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.

5.2.2. Core sectors

We find that knowledge development and diffusion in core value chain segments of solar PV took place in two ways. 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 (SPV18, 24). About 63% of all highly-cited solar PV patents are related to innovation in cell and module design and manufacturing. There is a continued focus on product and process innovation throughout the observed time period, with a relatively higher focus on process innovation (Fig. 3b).

Product innovations in cells were enabled by close collaboration with R&D institutions (SPV1, 2, 4) in countries such as Australia, Germany, Japan, Switzerland, and the US (Gallagher, 2014). However, with standardization of cell design, the relative importance of learning-by-searching 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" (SPV19). As discussed above, innovations in production processes were enabled by interactive learning between cell manufacturers and PEMs (see section on "Upstream sectors").[13]

According to the interviewees, interaction with downstream sectors is not very significant for innovations in cells and modules (SPV15, 17, 26). Sources of opportunity for product innovation are sector-internal and 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 (SPV18, 19, 24). Further, one requires "no complicated engineering know-how to understand what the problem is" (SPV19) since the defective modules can be transported to the lab, tested, and diagnosed using sector-internal science-based knowledge.

5.2.3. Downstream sectors

With falling module costs, BOS components for mounting and system integration comprise an increasingly larger share of the total system cost (IRENA, 2016), resulting in relatively higher level of

[11] For a more disaggregated view of the distribution of patents across different value chain segments, please refer to Appendix E.

[12] 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.

[13] 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.")

opportunity in downstream sectors (Fig. 3a).[14] Additionally, even though BOS components are mature and have relatively low complexity, innovation is also driven by deployment across different use environments. For example, the installation system needs to be designed for specific applications such as off-grid, grid-connected open field, rooftop, or building-integrated systems. Installation system designs have gradually been refined in terms of suitability for these applications, as well as ease of installation through learning-by-interacting with installers (see Table 5; Shum and Watanabe, 2008). Similarly, 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 the core value chain segments of cell design and manufacturing and the upstream segment of material supply exhibit high levels of opportunity (see Fig. 3a), with gradually increasing focus on downstream product innovation in recent years (see Fig. 3b). Knowledge development and diffusion in the solar PV industry is driven by a high degree of inter-sectoral learning among upstream sectors, particularly between the cell manufacturers and production equipment suppliers (see i in Fig. 3c).

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 (LIB27, 30, 33), since up to “200 properties of a cell can be varied such as densities, porosities, areas of active material” (LIB29). From a material supplier's perspective, “understanding of the interactions within the cell can be understood through interactions with the cell manufacturer” (LIB27, see Table 6). As a result, long-term collaborations between firms from the chemical sector and cell manufacturers are quite common in the LIB industry, with some large cell manufacturers (such as Hitachi, BYD and LG Chem) even benefiting from in-house chemical production divisions. Similarly, European chemical sector 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.

Knowledge development and diffusion in production equipment and manufacturing processes also involves close interaction with cell manufacturers (i in Fig. 4c). This is because production equipment for processes such as electrode slurry mixing, electrode coating, calendaring, and slitting is highly specialized, meaning that installation, maintenance and upgrades are done exclusively by PEMs (LIB30, 36).

Table 5
Interview quotes illustrating sectoral characteristics and occurrence of inter-sectoral learning.

Focal sector	Sectoral characteristic	Exemplary quote	Source
Upstream (production equipment supply)	Complexity of knowledge base	“Pilot production is still useful for learning, but there are still a lot of **questions and unknowns** for which you can only get feedback from large scale.” “As processes become more and more mature and scale is increasing, it is becoming more essential to have **close cooperation** between machine and cell or module manufacturers.”	SPV15
Downstream (Inverter and mounting system)	Specificity of knowledge base	“So we spend a lot of time talking to standards body, installers, regulators, yeah… You bet there's a lot of **interaction** that goes on.” “And with the installers, we are trying to **understand what their limitations are**, what they … what would make their lives easier. So we can design that into our product.”	SPV22

5.3. Inter-sectoral learning in lithium-ion battery TIS

5.3.1. Upstream sectors

We find that opportunity levels in LIB value chains are high in the upstream sectors involved in material supply, and core component design and manufacturing. These segments taken together account for 86% of the patents for LIBs (Fig. 4a).[15] Further, we observe high levels of opportunity 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 Fig. 4c). Sector-internal R&D enables material suppliers from the chemical sector to develop expertise in individual material chemistries (LIB27, 36) and underlying processes such as “the root causes of degradation and how to customize the material through additives, dopants and morphology” (LIB27). However, this is not sufficient due to

In addition, cell manufacturing process parameters, material composition, and cell performance are all interdependent, leading to high complexity (LIB27, 30, 33, 36, 37). 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,[16] and from close interaction with major cell manufacturers such as Panasonic, LG Chem, Samsung SDI, Sanyo and Sony (see Table 6). Thus, the sectors involved in material supply, production equipment supply and cell manufacturing are closely interlinked, requiring a high degree of information exchange which is mediated by the cell manufacturer.

5.3.2. Core sectors

We find that knowledge development and diffusion in the LIB industry takes place in two ways. First, it involves product innovation to improve performance parameters such as energy density, safety and lifetime. Second, it involves 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,

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

[15] For a more disaggregated view of the distribution of patents across different value chain segments, please refer to Appendix E.

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

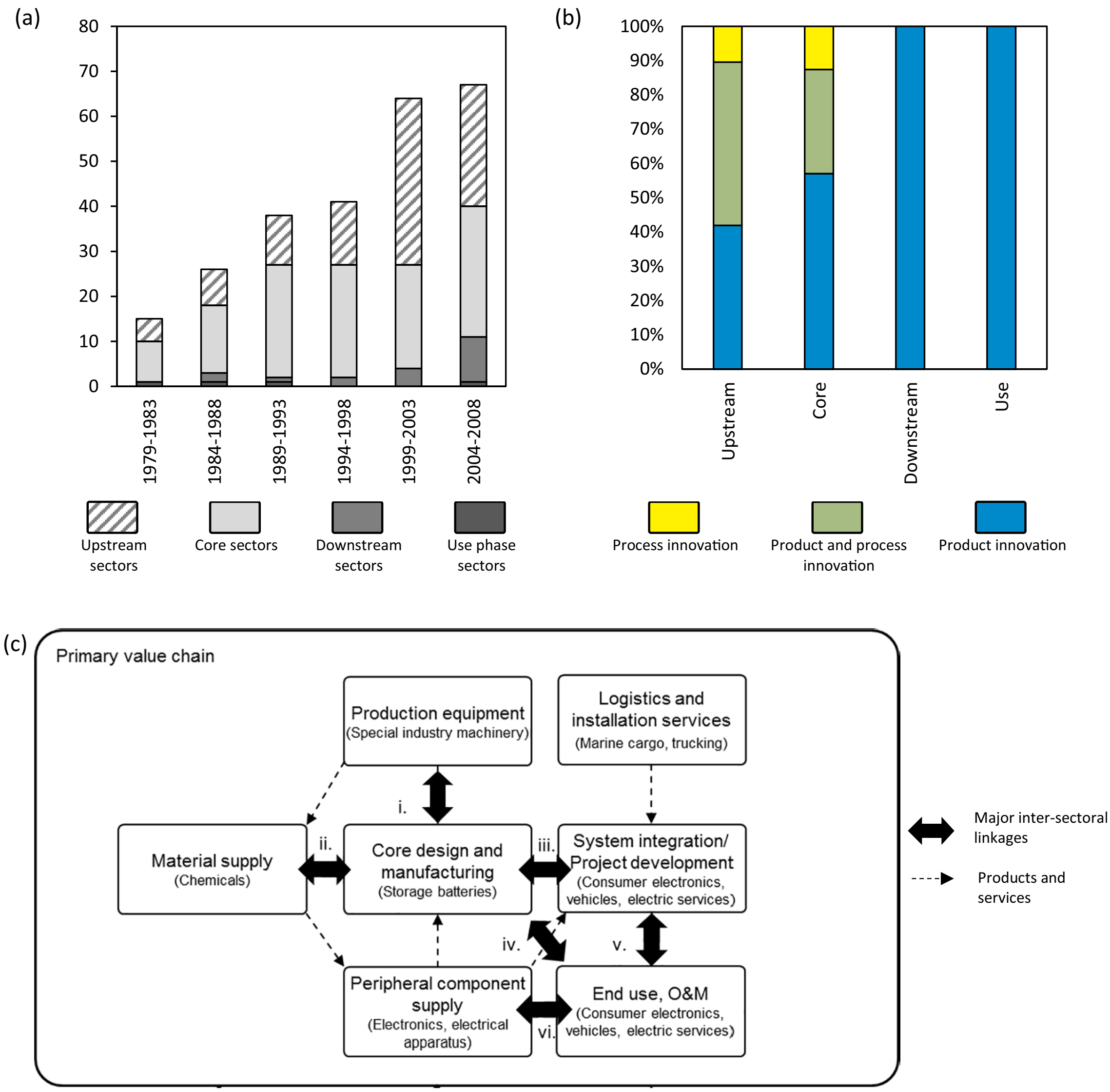

Fig. 4. (a) Number of patents pertaining to sectors involved in lithium-ion battery TIS, indicating levels of opportunity (b) Relative shares of process and product innovation in different sectors, indicating sources of opportunity (c) Patterns of inter-sectoral learning in lithium-ion battery TIS.

Fig. 4b) lie in between those observed for the core value chain segments for wind turbine systems (93% and 5%, Fig. 2b) and solar PV systems (42% and 27%, Fig. 3b). 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 the chemical sector (ii). 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 (LIB27, 36); or introducing and increasing the amount of silicon in graphite on the anode side (LIB27, 28, 36). 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").

At the same time, cell manufacturers obtain feedback on cell lifetime and performance in different end use sectors (iii, iv). Historically, cell chemistries have been dictated by specific requirements of the consumer electronics industry, and have benefitted from > 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. Due to dynamic and varying conditions in the use environment, electric vehicles have been described as "the most challenging application to develop cells" (LIB37). However, the industry in recent years has been described as an "open loop" (LIB31). Cell manufacturers still rely on extensive in-house testing to ensure reliability since the "nascent state of the industry makes feedback more difficult" (LIB31). 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" (LIB34), 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 (LIB35). 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 (LIB33, 37).

5.3.3. Downstream sectors

We find that the level of opportunity in downstream sectors is highly dependent on the application (LIB33, 34, 35). We observe a much smaller number of patents in downstream value chain segments

(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 (Fig. 4a). 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 (LIB31). However, for more demanding applications in the automobile and power sector with higher opportunity levels in BOS and specialized requirements, learning is enabled by extensive feedback from different use environments (LIB35). System integrators work with end users to optimize system design to their specific requirements (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" (LIB33). Collection of data related to usage profiles, environmental conditions, and battery performance is often facilitated by the use of sensors. However, learning-by-interacting with end use sectors is still necessary in the 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" (LIB35).

To summarize, we find that sectors involved in core value chain segments of cell design and manufacturing, and the upstream segment of material supply exhibit high levels of opportunity (see Fig. 4a), with increasing emphasis on material innovations in the second half of the observed time period. Learning in the LIB industry is driven by inter-sectoral learning among the upstream segments of cell design and manufacturing, production equipment supply, and material supply on the production side, as well as among the downstream segments of battery design and manufacture, system integration, and end use (see Fig. 4c).

Table 6
Interview quotes illustrating sectoral characteristics and occurrence of inter-sectoral learning.

Focal sector	Sectoral characteristic	Exemplary quote	Source
Upstream (Production equipment supply)	Complexity of knowledge base	"The understanding of **interactions between all the process steps** involved is one of the biggest challenges because you have so many different steps in battery manufacturing. From the raw material production, then the whole cell manufacturing is quite a long process chain. Still today I believe that most interactions of all these process steps in terms of product quality, in terms of process efficiency are not fully understood yet." "For the large plants, now we have at least one service engineer, which is staying there. Basically, if they start with the commissioning, the startup of the plant, and get familiar with everything, more or less one person at the plant will stay."	LIB30
Upstream (Material supply)	Specificity of knowledge base	"Ideally we would like to have measurements in lab adapted to the technical set up used by the customers. We would like to know, for example, **how customers do the cathode coating process** and replicate it on a pilot scale in our own lab to present the data to our customers when we develop new solutions."	LIB27

5.4. Summary of results

To summarize, we find that (i) the wind turbine TIS is characterized by a high degree of learning-by-interacting among core and downstream sectors, (ii) the solar PV TIS is characterized by a high degree of learning-by-interacting between production equipment suppliers and core subsystem manufacturers, and (iii) the LIB TIS is characterized by learning-by-interacting both between upstream and core sectors, and between core and downstream sectors.

The sectoral characteristics influencing learning-by-interacting (discussed in Section 2.2) of one upstream, core, and downstream sector for each of the case technologies are described in Table 7. The summary is based on the coded interview data and patent data presented in Sections 5.1, 5.2 and 5.3.

6. Discussion and conclusion

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

This study builds on the work by Stephan et al. (2017) to further integrate the sectoral configuration into TIS analysis. Previous studies such as Binz and Truffer (2017) have highlighted that sectoral differences can lead to different modes of innovation, distinguishing between Science, Technology and Innovation (STI) and Doing, Using and Interacting (DUI). Our study extends this argument by taking a value chain perspective, thus demonstrating that different sectoral configurations (i.e. differences in characteristics of sectors linked by the value chain of a TIS) can result in different patterns of inter-sectoral learning and hence knowledge development and diffusion. Further, by examining the micro-level learning processes in multi-sector industry value chains, we help explain the differences in empirical literature regarding importance of learning-by-interacting between sectors in clean energy TISs (Keller and Negoita, 2013; Shum and Watanabe, 2008). We find that the role of inter-sectoral learning for knowledge development and diffusion depends on sectoral characteristics, 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 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 differ in terms of inter-sectoral learning, we disaggregate the segments in the TIS value chain and characterize their respective sectors.

First, we find that in cases where the different subsystems of a *complex technology* are reliant on distinct, highly *specific knowledge bases* from different sectors, inter-sectoral learning is necessary for knowledge (co-)development. In such cases, the firm manufacturing the core subsystem or assembling the different subsystems acts as the mediator

Table 7
Summary of sectoral characteristics for specific sectors involved in the wind turbine, solar PV and lithium-ion battery TISs. The row labeled "Importance of inter-sectoral learning" indicates the importance of inter-sectoral learning between the sectors characterized in the rows above and below it.

		Wind turbines	Solar PV	Lithium-ion batteries
Upstream (production equipment supply)	Level of opportunity	Low	High	High
	Sources of opportunity	Internal	Users (i.e. cell and module manufacturers), R&D	Users (i.e. cell manufacturers), R&D
	Complexity of knowledge base	Low	High	High
	Specificity of knowledge base	Low	High (technology-specific)	High (technology-specific)
Importance of inter-sectoral learning		Low	High	High
Core design and manufacturing	Level of opportunity	High	High	High
	Sources of opportunity	Sub-system suppliers, users	Production equipment suppliers, R&D	Production equipment suppliers, R&D, material suppliers, users (e.g. electric vehicle manufacturers)
	Complexity of knowledge base	High	Low	High
	Specificity of knowledge base	Medium (technology-specific)	High (technology-specific)	High (technology- and application-specific)
Importance of inter-sectoral learning		High	Low	Low
Downstream (Mounting system)	Level of opportunity	Medium	Medium	Low
	Sources of opportunity	Core sectors, installers	Installers	Internal
	Complexity of knowledge base	Medium	Low	Low
	Specificity of knowledge base	High (technology- and site-specific)	Medium (site- and application-specific)	Medium (application-specific)

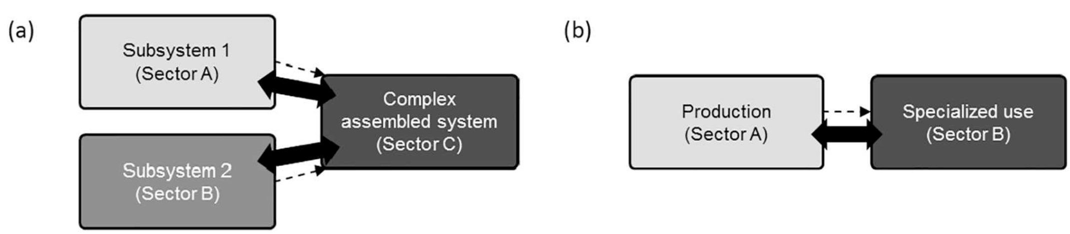

Fig. 5. (a) Learning-by-interacting among sectors with distinct, specific knowledge bases supplying subsystems for complex technology. The firm manufacturing the core subsystem or assembling the subsystems mediates learning interactions with the suppliers. (b) Learning-by-interacting among sectors, where the using sector has specialized user requirements.

of learning-by-interacting with the suppliers (Fig. 5a). For example, cells for lithium-ion batteries require specialized knowledge inputs from the chemicals sector, 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 likelihood of failures in learning-by-interacting. For example, the rotor, drivetrain, and related control systems for wind turbines are complex but all require wind turbine-specific knowledge in mechanical engineering, and are generally designed in-house by OEMs.

Second, *specialized demand* for a sector's outputs can also lead to the need for learning-by-interacting among using and producing sectors (Fig. 5b). Thus, even for innovations in non-complex technologies with specialized user requirements, an initial phase of user-producer interaction is required. This is because understanding and codifying user specifications, or standardization of interfaces between sub-systems or components requires the acquisition of specialized knowledge through close interaction with the user. Further, new forms of specialized demand for a sector's outputs can arise because of the use of the technology in a new sector or use environment.

In addition, by analyzing the patterns of inter-sectoral learning in the lithium-ion battery TIS, we find that the patterns of innovation do not conform to either of the two typical technology life-cycle models discussed by Huenteler et al. (2016a), i.e. mass-produced goods and complex products. Instead, 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. Thus, they can be considered a case of dually complex, mass-produced technologies. Innovation in this case is a multi-optimization problem drawing on specialized knowledge bases of multiple sectors (chemical sector, electronics sector, machinery and end use sector) simultaneously. Thus, it requires learning-by-interacting among material suppliers, production equipment manufacturers, cell manufacturers, system integrators and end users, with cell manufacturers acting as a central node for coordination of inter-sectoral learning.

6.2. Implications for policy: addressal of failures in inter-sectoral learning

Several studies have suggested that policies aiming to establish and promote innovation should be designed to avoid 'network failures' (Edquist, 2011; Keller and Negoita, 2013) and enable 'interface improvement' (Taylor, 2008). We contribute to this stream of literature by providing a systematic way of identifying the need for inter-sectoral learning linkages in emerging and mature TISs, allowing policies aiming to address network failures to be employed in a more targeted manner.

First, policies to facilitate inter-sectoral learning should be targeted towards promoting 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). Examples of such measures include publically funded collaborative R&D projects (Keller and Negoita, 2013), and support for platforms such as industry associations (Taylor, 2008), public research institutes and test facilities with the specific mandate to act as facilitators of inter-sectoral knowledge exchange (Garud and Karnøe, 2003). Furthermore, for successful technology transfer in value chain segments that require sustained inter-sectoral learning, even nations with pre-existing sectoral knowledge bases need to create conditions to facilitate long-term relationships with foreign firms. Examples include policies to enable foreign direct investments and international R&D collaboration (Quitzow et al., 2017).

Second, policies to promote inter-sectoral learning should be targeted towards 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), especially in emerging TISs and new application domains. This can be done through regularly updated industry-wide standards for performance, component interfaces and professional training (Shum and Watanabe, 2008), and tying application-specific deployment policies to requirements for data sharing within and across applications.

Third, as discussed in Section 6.1, we find that lithium-ion batteries have a dually complex nature. Thus, the literature on technology life-cycles would suggest that innovation policies need to perform two functions (Huenteler et al., 2016a). First, policies need to enable learning-by-producing and scaling up of production processes by creating growing markets. Second, they need to support application-oriented product innovation through targeted support of less mature niches such as grid-connected applications. Based on our findings, we propose that due to the importance of inter-sectoral learning, policy makers should also be aware of a potential third function for innovation policy: prevention of failures in learning-by-interacting among different sectors. Possible measures include supporting collaborative R&D, pilot and demonstration manufacturing facilities for research consortia, and strategic partnerships among sectors involved in the LIB value chain. Support for emerging and relatively less mature applications with specialized needs can be combined with measures to incentivize data sharing.

Finally, our results also indicate the varying role of home markets: depending on the importance of inter-sectoral learning in different parts of the value chain, early home markets might be advantageous for different sectors. For wind turbines, learning-by-interacting with the end-use sector has been necessary for knowledge development and diffusion, which explains the importance of home markets (Lewis and Wiser, 2007). On the other hand, for solar PV and lithium-ion batteries, learning-by-interacting between upstream and core sectors has been necessary for innovation, making home markets for manufacturing equipment more relevant. Thus, in such cases, simply creating home markets for early-stage technologies through deployment policies might be insufficient to ensure competitiveness in core sectors in the long term. However, it can help create a sustained competitive advantage for upstream sectors with complex knowledge bases such as in the case of production equipment for 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 inter-sectoral 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 can lead to differences in importance of inter-sectoral learning for knowledge development and diffusion. 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 segments 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.

First, we analyze the patterns of inter-sectoral learning in a TIS while staying agnostic to the surrounding institutional arrangement. In reality, depending on the context, policies or institutional arrangements determine other TIS functions, and 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 inter-sectoral learning to the policies and institutional setup (e.g. in terms of varieties of capitalism) in those contexts.

Second, we use patent data as an indicator of the level and sources of opportunity in the TIS value chain, which biases our patent-based results due to under-reporting of innovation in certain value chain segments. Our interviews indicate that process innovations are more likely to be protected as trade secrets as compared to product innovations, and that innovations in services such as project development, financing and after-sales services are typically not patented. By relying on interview data as our primary data source to identify the levels and sources of opportunity, we believe that this concern is of minor relevance. Thus, while the *absolute* level of process innovations might be underrepresented in the patent data, we still observe a relatively high share of process innovation in solar PV and lithium-ion batteries. This is in agreement with the high level of opportunity in upstream sectors of these technologies, as per the interview data. Further, the *relative* emphasis on product versus process innovation across value chain segments is in agreement with the sources of opportunity suggested by the interviews. Nevertheless, 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 inter-sectoral learning 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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Appendix A

Table A1 shows a typical interview guide used for conducting semi-structured interviews for the case studies. Generic words (indicated here in angular brackets) were replaced by appropriate specific instances of case technologies and sectors during the interviews.

Table A1
Typical interview guide used in the case studies.

Category	Exemplary questions
Opportunity level	Generally in your eyes what are the key challenges when it comes to innovation in ⟨technology⟩? What have been the critical points of focus for innovation so far?
	What are the critical points of focus for innovation now and in the near future?
Complexity of knowledge base	Do you have different concepts for ⟨sectoral output⟩? If yes, what are the relative advantages or disadvantages?
	How difficult is it to predict and simulate ⟨sectoral output⟩?
	Do modifications in ⟨sectoral output⟩ require adaptations elsewhere? What about processes? How well understood are these interfaces?
Inter-sectoral learning among primary sectors	What are the different stages in the process of introducing innovations in ⟨sector⟩? (e.g. R&D, prototype, testing etc.)
	What kind of interaction and knowledge exchange do you have with other actors in the industry?
	Has the nature of interaction with the other actors changed over time?
	Do you obtain feedback about technology performance from the use phase? Do other actors contact you to obtain this data?
Inter-sectoral learning with supporting sectors	What is the role of ⟨supporting sector⟩ in innovation and problem solving?
	What kind of interaction and knowledge exchange do you have with them?
	Has their role changed over time?
Industry structure	What determines whether ⟨value chain segment⟩ is done in-house by the OEM, or by a different actor?
	Is there any benefit of you being located close to any other actor in the value chain?
	Is there any benefit of you being located close to the site of end-use?

Appendix B

Tables B1 to B3 list the patent classification codes which were used to extract patent data from the EPO PATSTAT database, and provide a brief description of each code.

Table B1
Codes used to extract wind turbine system patents.

Code	Scheme	Description
B23*	IPC	Machine tools; metal-working not otherwise provided for
B29*	IPC	Working of plastics; working of substances in a plastic state in general
B60P*	IPC	Vehicles adapted for load transportation or to transport, to carry, or to comprise special loads or objects
B63B 35/00	IPC	Vessels or like floating structures adapted for special purposes
F01D 5*	IPC	Blades; blade-carrying members; heating, heat-insulating, cooling or anti-vibration means on the blades or the members
F03D*	IPC	Wind motors
F16C*	IPC	Shafts; flexible shafts; elements or crankshaft mechanisms; rotary bodies other than gearing elements; bearings
F16D*	IPC	Couplings for transmitting rotation; clutches; brakes
F16H*	IPC	Gearing
E02D*	IPC	Foundations; excavations, embankments; underground or underwater structure
E04H 12*	IPC	Towers; masts or poles; chimney stacks; water-towers; methods of erecting such structures
H02K*	IPC	Dynamo-electric machines
H02G*	IPC	Installation of electric cables or lines, or of combined optical and electric cables or lines
H01F*	IPC	Magnets; inductances; transformers; selection of materials for their magnetic properties
H01B*	IPC	Cables; conductors; insulators; selection of materials for their conductive, insulating or dielectric properties
H02M*	IPC	Apparatus for conversion between ac and ac, between ac and dc, or between dc and dc, and for use with mains or similar power supply systems; conversion of dc or ac input power into surge output power; control or regulation thereof
H02P*	IPC	Control or regulation of electric motors, electric generators or dynamo-electric converters; controlling transformers, reactors or choke coils
H02J*	IPC	Circuit arrangements or systems for supplying or distributing electric power; systems for storing electric energy
G01M*	IPC	Testing static or dynamic balance of machines or structures; testing structures or apparatus not otherwise provided for
G01N*	IPC	Investigating or analyzing materials by determining their chemical or physical properties
Y02E 10/7*	ECLA	Wind energy

Table B2
Codes used to extract solar photovoltaic system patents.

Code	Scheme	Description
B23K*	IPC	Soldering or unsoldering; welding; cladding or plating by soldering or welding; cutting by applying heat locally, e.g. Flame cutting; working by laser beam
B28D*	IPC	Working stone or stone-like materials
C01B-033*	IPC	Silicon; compounds thereof
C23C*	IPC	Coating metallic material; coating material with metallic material; surface treatment of metallic material by diffusion into the surface, by chemical conversion or substitution; coating by vacuum evaporation, by sputtering, by ion implantation or by chemical vapour deposition, in general
C30B*	IPC	

(continued on next page)

Table B2 (*continued*)

Code	Scheme	Description
		Single-crystal-growth; unidirectional solidification of eutectic material or unidirectional demixing of eutectoid material; refining by zone-melting of material; production of a homogeneous polycrystalline material with defined structure; single crystals or homogeneous polycrystalline material with defined structure; after-treatment of single crystals or a homogeneous polycrystalline material with defined structure; apparatus therefor
E04D-013-*	IPC	Special arrangements or devices in connection with roof coverings; protection against birds; roof drainage; sky-lights
H01L-031-*	IPC	Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of such radiation into electrical energy or for the control of electrical energy by such radiation; processes or apparatus peculiar to the manufacture or treatment thereof or of parts thereof; details thereof
H01L-021-*	IPC	Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof
H01L-025-*	IPC	Assemblies consisting of a plurality of individual semiconductor or other solid state devices
H01L-051-*	IPC	Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part; processes or apparatus specially adapted for the manufacture or treatment of such devices, or of parts thereof
H02M*	IPC	Apparatus for conversion between AC and AC, between AC and DC, or between dc and dc, and for use with mains or similar power supply systems; conversion of dc or ac input power into surge output power; control or regulation thereof
H02J*	IPC	Circuit arrangements or systems for supplying or distributing electric power; systems for storing electric energy
H02S*	IPC	Generation of electric power by conversion of infra-red radiation, visible light or ultraviolet light, e.g. using photovoltaic (PV) modules
H02N-00-6*	IPC	Electric machines not otherwise provided for - generators in which light radiation is directly converted into electrical energy
H01R*	IPC	Line connectors; current collectors
G01B*	IPC	Measuring length, thickness or similar linear dimensions; measuring angles; measuring areas; measuring irregularities of surfaces or contours
G01R*	IPC	Measuring electric variables; measuring magnetic variables
G05F-001*	IPC	Systems for regulating electric or magnetic variables - automatic systems in which deviations of an electric quantity from one or more predetermined values are detected at the output of the system and fed back to a device within the system to restore the detected quantity to its predetermined value or values, i.e. Retroactive systems
Y02E 10/5*	ECLA	Photovoltaic (PV) energy
Y02B 10/1*	ECLA	Integration of renewable energy (PV) sources in buildings

Table B3
Codes used to extract lithium-ion battery system patents.

Code	Scheme	Description
C01D 15*	IPC	Lithium compounds
H01M 4/13*	IPC	Electrodes for accumulators with non-aqueous electrolyte, e.g. for lithium-accumulators; Processes of manufacture thereof
H01M 4/405	IPC	Electrodes composed of or comprising lithium alloy active material
H01M 4/382	IPC	Electrodes composed of or comprising lithium active material
H01M 4/36	IPC	Selection of substances as active materials, active masses, active liquids
H01M 4/62	IPC	Selection of inactive substances as ingredients for active masses, e.g. binders, fillers
H01M 4/04	IPC	Processes of manufacture in general for electrodes
H01M 4/64	IPC	Carriers or collectors
H01M 4/90	IPC	Selection of catalytic material
H01M 4/96	IPC	Carbon-based electrodes
H01M 2300	IPC	Electrolytes
H01M 2*	IPC	Constructional details or processes of manufacture of the non-active parts
H01M 10/05-8*	IPC	Construction or manufacture of accumulators
H01M 10/04	IPC	Construction or manufacture in general of secondary cells
H01M 10/42	IPC	Methods or arrangements for servicing or maintenance of secondary cells or secondary half-cells
H01M 10/052	IPC	Li-accumulators
H01M 2200*	IPC	Safety devices for primary or secondary batteries
H01M 10/60	IPC	Heating or cooling; Temperature control
H02H 7/18	IPC	Emergency protective circuit arrangements specially adapted for specific types of electric machines or apparatus or for sectionalised protection of cable or line systems, and effecting automatic switching in the event of an undesired change from normal working conditions for batteries and accumulators
H02J 7/00	IPC	Circuit arrangements for charging or depolarising batteries or for supplying loads from batteries
H01M 10/46	IPC	Accumulators structurally combined with charging apparatus
H01M 10/48	IPC	Accumulators combined with arrangements for measuring, testing or indicating condition, e.g. level or density of the electrolyte
G01R 31/36	IPC	Apparatus for testing electrical condition of accumulators or electric batteries, e.g. capacity or charge condition
G01R 19/16-542	IPC	Arrangements for measuring currents or voltages or for indicating presence or sign thereof for batteries
Y02E 60/122	ECLA	Lithium-ion batteries
Y02T 10/701-1	ECLA	Lithium ion battery

Appendix C

A subset of the patent database consisting of top cited patents was selected for the quantitative analysis. As mentioned in Section 4.2, the number of forward citations of a patent is a good indicator of its economic value. However, certain studies have raised concerns about the comparability of forward citations at different points in time. Since the number of citations made per patent and number of patents issued is increasing over time, there are concerns around 'citation inflation', i.e. the depreciation in value of patent citations over time. While it is unclear how to adjust for this effect, we used two alternative 'extreme' sampling strategies to ensure the robustness of the observations made in Section 5.

First, we assumed that all citations have equal value, and selected the top 5% patents in terms of forward citation count (Fig. C1). Second, we assumed that citations received by a patent published in one year are completely incomparable to a patent published in another year, and selected the top 5% patents in terms of forward citation count for each year (Fig. C2). In Section 5, we followed an 'intermediate' sampling strategy of normalizing the forward citation for each patent by the average forward citations for all patents in that year, and selected the top 5% patents in terms of normalized forward citation count. We observe in Figs. C1 and C2 that the trends observed in Section 5 are robust to the choice of sampling strategy.

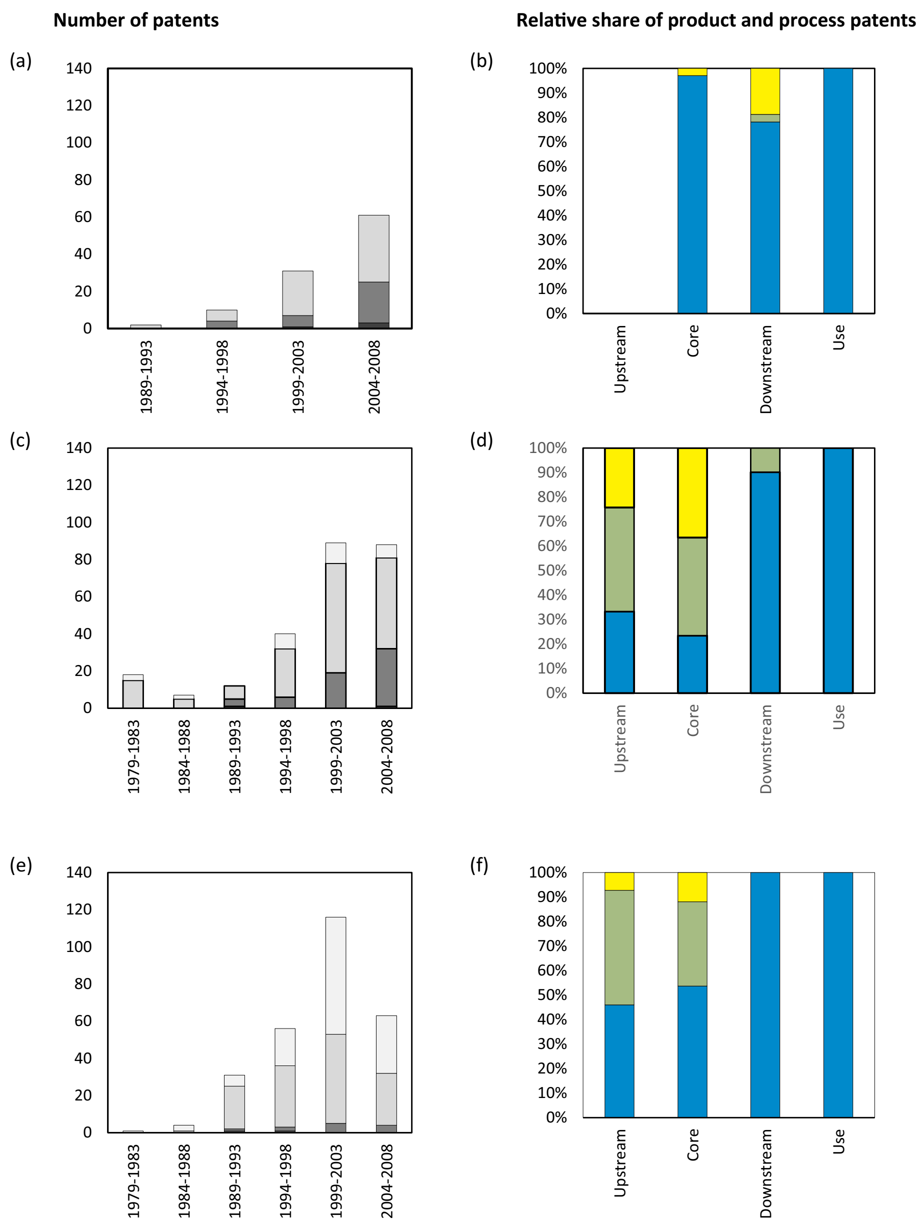

Fig. C1. Levels and sources of opportunity for (a) wind turbines, (b) solar PV and (c) lithium-ion batteries as represented by top 5% most cited patents.

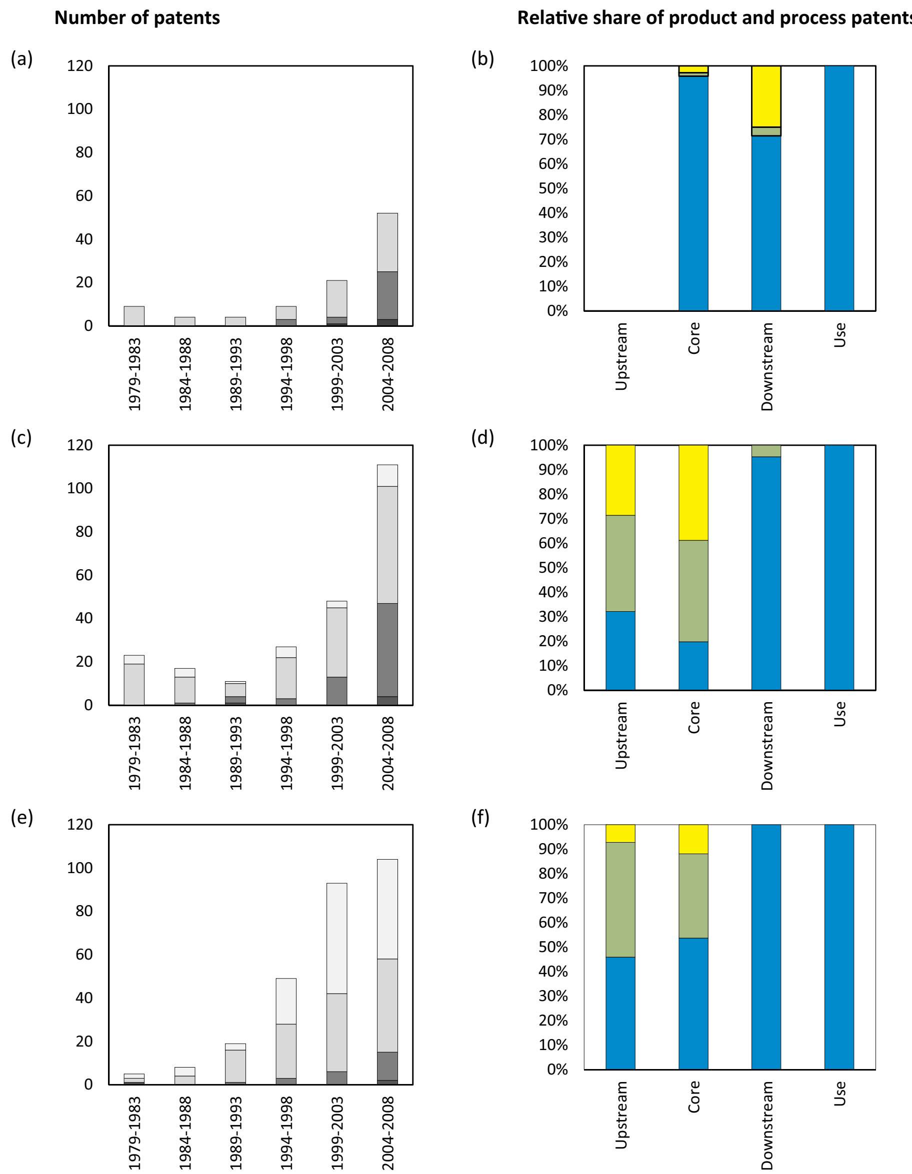

Fig. C2. Levels and sources of opportunity for (a) wind turbines, (b) solar PV and (c) lithium-ion batteries as represented by the annually top 5% most cited patents.

Appendix D

Tables D1 to D3 show the coding scheme used to analyze the patent data.03

Table D1
Coding scheme for solar PV patents.

Sector	Value chain segment		Description
Upstream	Material	Product	Novel material for solar PV system.
		Process	Novel production process for material for solar PV system.
Core	Cell	Product	Novel design of cell.
		Process	Novel manufacturing process for cell.
	Module	Product	Novel design or arrangement of cell encapsulation, interconnection, and cells within the module.
		Process	Novel process for manufacture or assembly of cell encapsulation, interconnection, and cells within the module.
Downstream	Grid integration	Product	Novel design of inverter, connection, or power control system for solar PV system integration.
		Process	Novel process for manufacture or installation of inverter, connection, or power control system for solar PV system integration.
	Mounting system	Product	Novel design of mounting system or tracking system.
		Process	Novel process for manufacture or installation of mounting system or tracking system.
Use	System monitoring	Product	Novel design of monitoring systems for solar PV system.
		Process	Novel process for manufacture or installation of monitoring systems for solar PV system.

Table D2
Coding scheme for wind turbine patents.

Sector	Value chain segment		Description
Upstream	Material	Product	Novel material for wind turbine system.
		Process	Novel production process for material for wind turbine system.
Core	Rotor	Product	Novel design of rotor, or any of its components (blades, hub, rotor control).
		Process	Novel process for manufacture or assembly of rotor, or any of its components (blades, hub, rotor control).
	Powertrain	Product	Novel design of powertrain, or any of its components (transmission, generator, electronics and control).
		Process	Novel process for manufacture or assembly of powertrain, or any of its components (transmission, generator, electronics and control).
Downstream	Grid integration	Product	Novel design of transformer, substation, cabling, or power converter for wind turbine system integration.
		Process	Novel process for manufacture or installation of transformer, substation, cabling, or power converter for wind turbine system integration.
	Mounting system	Product	Novel design of nacelle, tower, or foundation.
		Process	Novel process for manufacture or assembly of nacelle, tower, or foundation.
Use	System monitoring	Product	Novel design of monitoring systems for wind turbines.
		Process	Novel process for manufacture or installation of monitoring systems for wind turbines.

Table D3
Coding scheme for lithium-ion battery patents.

Sector	Value chain segment		Description
Upstream	Material	Product	Novel material or combination of materials for lithium-ion batteries.
		Process	Novel production process for materials for lithium-ion batteries.
Core	Cell	Product	Novel design of the cell, or any of its components (anode, cathode, seperator, electrolyte).
		Process	Novel manufacturing process for the cell, or for its components (anode, cathode, seperator, electrolyte).
	Battery pack	Product	Novel design or arrangement of battery management system, thermal management system, or cells within the battery pack.
		Process	Novel process for manufacture or assembly of battery management system, thermal management system, or cells within the battery pack.
Downstream	Grid integration	Product	Novel design of inverter, connection, or power control system for battery system integration.
		Process	Novel process for manufacture or installation of inverter, connection, or power control system for battery system integration.
	Mounting system	Product	Novel design of battery casing or mounting system.
		Process	Novel process for manufacture or installation of battery casing or mounting system.
Use	System monitoring	Product	Novel design of monitoring systems for lithium-ion batteries.
		Process	Novel process for manufacture or installation of monitoring systems for lithium-ion batteries.

Appendix E

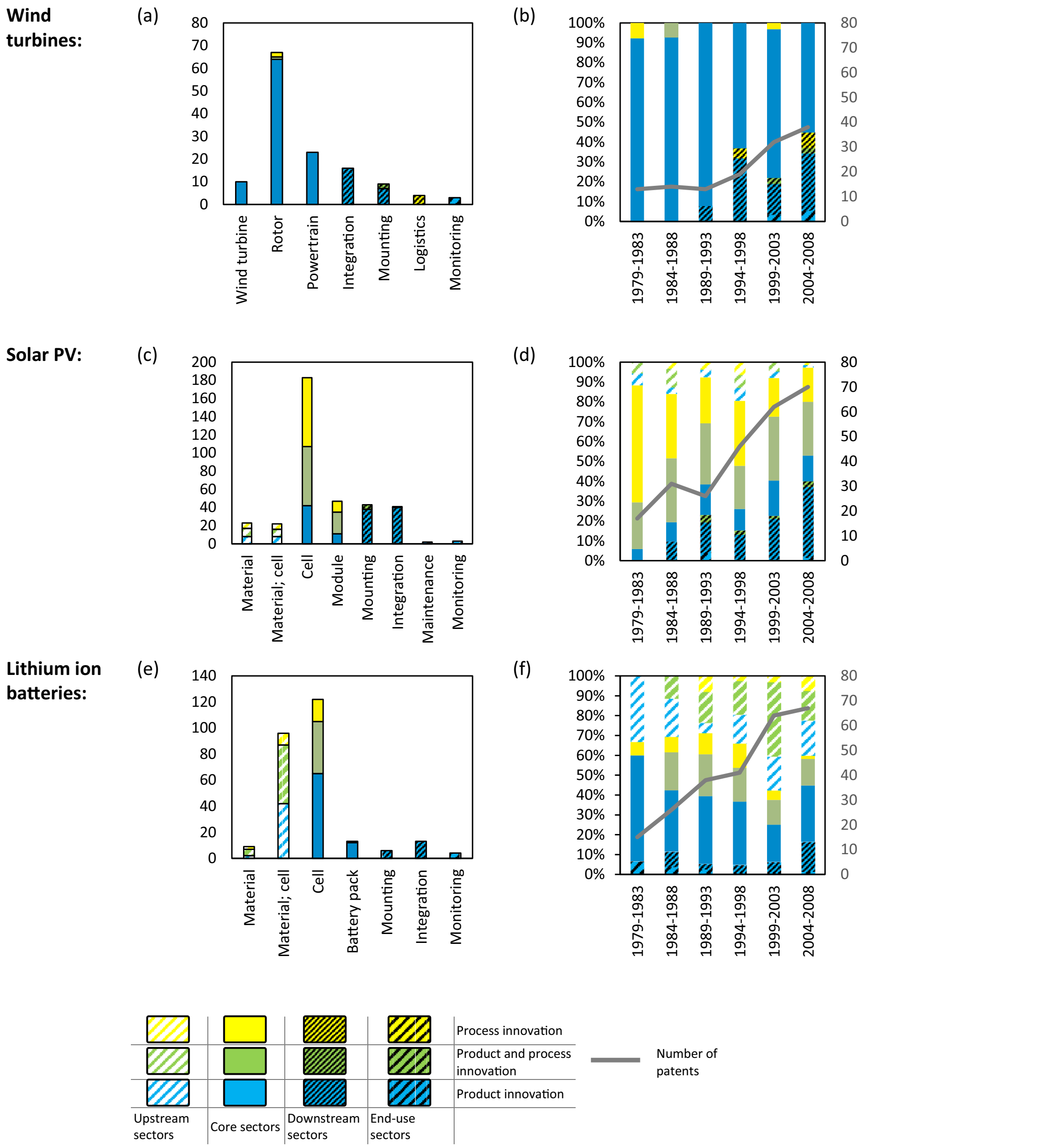

Fig. E1. (a, c, e) Number of patents pertaining to each industry value chain segment (b, d, f) Relative shares of patents pertaining to value chain segments, indicating type of innovation over time.

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