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Technology life-cycles in the energy sector — Technological characteristics and the role of deployment for innovation

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ABSTRACT

Understanding the long-term patterns of innovation in energy technologies is crucial for technology forecasting and public policy planning in the context of climate change. This paper analyzes which of two common models of innovation over the technology life-cycle – the product-process innovation shift observed for mass-produced goods or the system-component shift observed for complex products and systems – best describes the pattern of innovation in energy technologies. To this end, we develop a novel, patent-based methodology to study how the focus of innovation changes over the course of the technology life-cycle. Specifically, we analyze patent-citation networks in solar PV and wind power in the period 1963–2009. The results suggest that solar PV technology followed the life-cycle pattern of mass-produced goods: early product innovations were followed by a surge of process innovations in solar cell production. Wind turbine technology, by contrast, more closely resembled the life-cycle of complex products and systems: the focus of innovative activity shifted over time through different parts of the product, rather than from product to process innovations. These findings point to very different innovation and learning processes in energy technologies and the need to tailor technology policy to technological characteristics. They also help conceptualize previously inconclusive evidence about the impact of technology policies in the past.

1. Introduction

Technological change is “at once the most important and least understood feature driving the future cost of climate change mitigation” (Pizer and Popp, 2008, p. 2768]. A better understanding of the long-term patterns of innovation in energy technologies is therefore crucial for technology forecasting and public policy planning in the context of climate change (Grubb, 2004; Pielke et al., 2008; Grubler, 2014). Responding to this need, a growing body of literature is studying innovation processes and technology policy in the energy sector (Anadon, 2012; Gallagher et al., 2012; Grubler and Wilson, 2014).

It is a particularity of the energy sector that technologies from a diverse range of sectors of the economy are employed in the extraction, conversion, and end-use of energy. Therefore, most energy innovations are not developed by energy companies but enter the sector embodied in specialized equipment or innovative fuels from other sectors, such as semiconductors (solar panels), electro-mechanical machinery (gas turbines), agriculture (biofuel feedstocks), and biochemistry (biofuel conversion technology) (Markard, 2011; Wiesenthal et al., 2011). Empirical research suggests that long-term patterns in the process and focus of innovation, often referred to as ‘technology life-cycles,’ differ across these sectors, pointing toward the need to tailor government policies to individual energy technologies (Norberg-Bohm, 2000; Trancik, 2006; Wilson, 2012; Winskel et al., 2014).

However, thus far few studies of technological change in the energy sector have systematically investigated how technology life-cycles differ between energy technologies, and few have explored the implications for energy technology policy. To address this gap, we develop a patent-based methodology to analyze the technology life-cycles of solar photovoltaics (PV) and wind power. Solar PV and wind power differ in characteristics that have been linked to life-cycle patterns – the complexity of the product architecture and the scale of the production process – enabling us to derive propositions about technology life-cycles in energy technologies more broadly.

The paper proceeds as follows. Section 2 introduces two alternative models of the technology life-cycle – the product-process innovation shift observed for mass-produced goods and the system-component shift observed for complex products and systems – and discusses the main technological determinants of life-cycle patterns discussed in the literature. Section 3 introduces the two case technologies – solar PV systems and wind turbines – and discusses key technological characteristics and indicators of technological progress over the last five decades.

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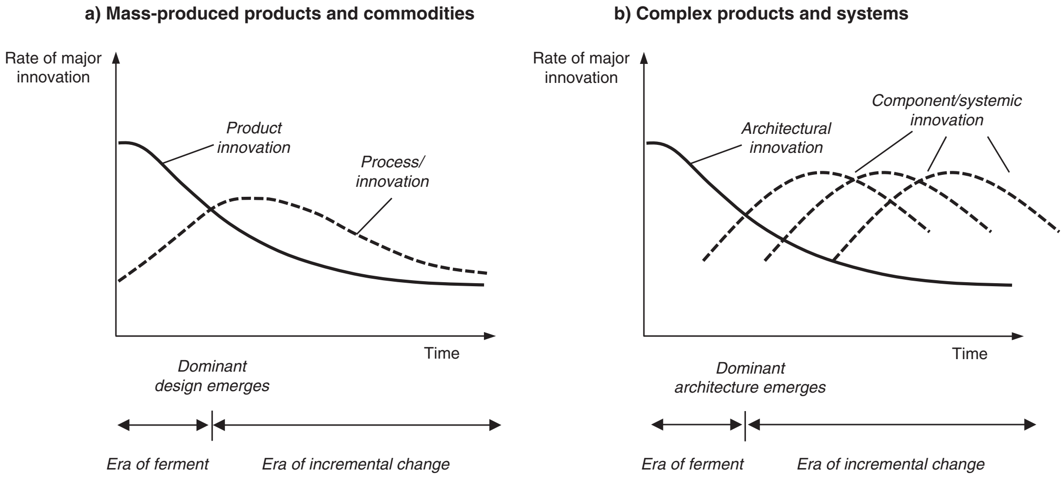

Fig. 1. Two contrasting models of innovation over the technology life-cycle: a) mass-produced goods; b) complex products and systems (Abernathy and Utterback, 1988; Davies, 1997).

In Section 4, we introduce a novel methodology to study how the focus of innovative activity evolved over time for the two case technologies. The results, which are presented in Section 5, suggest that solar PV and wind power followed very different technology life-cycle patterns. The implications for theory, public policy, and modeling practice are discussed in Section 6. Section 7 summarizes the main conclusions.

2. Theoretical perspective and literature review

The '*life-cycle*' metaphor has been used in many different contexts in research on the management and economics of innovation (Routley et al., 2013). This paper draws on the literature that uses the term life-cycle to describe the *temporal patterns* of *technological innovation* in an industry, in particular the emergence of dominant designs and the subsequent *shifts in the focus of innovation* (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978; Abernathy and Clark, 1985; Suarez and Utterback, 1993; Murmann and Tushman, 2002; Murmann and Frenken, 2006; Lee and Berente, 2013).

2.1. Two contrasting models of the technology life-cycle

Studies across a wide range of manufactured products have observed that temporal patterns of innovation often take a cyclical form – the 'technology life-cycle' – with an early stage marked by intense competition among fundamentally different design concepts followed by gradual standardization of design features (Suarez and Utterback, 1993; Murmann and Frenken, 2006; Anderson and Tushman, 1990). After a *dominant design* has emerged, technological change becomes cumulative and incremental as innovation proceeds along ordered technological trajectories (Dosi, 1982; Mina et al., 2007; Verspagen, 2007; Fontana et al., 2009; Bekkers and Martinelli, 2012).

The most influential model of the technology life-cycle, which we will refer to as the Abernathy-Utterback (A-U) model, describes technological evolution cycles of *product* and *process* innovation (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978; Suarez and Utterback, 1993; Vernon, 1966). According to the A-U model, the focus of innovation in the early years of an industry is on product innovation, as firms try to exploit the performance potential of the discontinuous innovation and compete in the market with many alternative product designs. This 'era of ferment' culminates in a dominant design as the technology's core components become standardized. What follows is an 'era of incremental change,' during which the focus of innovative activity is on process innovations and specialized materials, as firms sell into a mass market and compete primarily on the basis of costs — until a new discontinuity re-ignites design competition (see Fig. 1a). The shift from product to process innovations is enabled by the standardization of product design features, which facilitates a shift from small-batch production to mass production, and from general-purpose plants to large manufacturing facilities with highly specialized production equipment (see Table 1) (Abernathy and Utterback, 1988).

The A-U model has been extremely influential,[1] but researchers have noted that the model is valid only for a subset of technologies (Davies, 1997; Miller et al., 1995). In particular, empirical studies demonstrate that for many high-value, high-technology products there is no indication of a decline in product innovations over time (Lee and Berente, 2013; Gort and Klepper, 1982; Henderson, 1995). These *complex products and systems* never reach a phase of process innovation and large-scale production for a mass market. Rather, firms sell to a relatively small set of customers and innovative activity remains focused on product innovation throughout the life-cycle (see Table 1) (Davies, 1997; Hobday, 1998; Davies and Hobday, 2005).

Based on this evidence, Davies (Davies, 1997) introduces a model of innovation over time that replaces the product-process shift observed for mass-produced goods by a shift from innovation in the system architecture to waves of innovation in sub-systems and components (see Fig. 1b) (Davies, 1997; Davies and Hobday, 2005). As in the A-U model, the early phase is characterized by a focus on functional performance and product innovations. However, the competitive emphasis is not on specific designs but on alternative *product architectures*. After the emergence of a dominant design (constituted by a common product architecture and standardized core sub-systems), innovation along the technological trajectory is focused on individual sub-systems and components (Murmann and Frenken, 2006).[2] Over time, innovations in sub-systems and components can create performance imbalances that require changes in other parts of the system (Brusoni et al., 2001; Funk, 2009), in which case Davies refers to them as '*systemic innovations*' (see Fig. 1b).

The two models differ most significantly in their characterization of the era of incremental change, i.e., the incremental change along the technological trajectory after a dominant design has emerged (see Table 1). Three aspects are particularly important: First, with regard to the *type and breadth of innovative activity*, the A-U model predicts a surge in process innovations and a relatively narrow focus on cost reductions through improved production processes. The Davies model, in contrast, describes a steady stream of product innovations as well

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[1] The two seminal works (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978) had, as of 12/6/2014, a total of 6544 Google Scholar citations between them.

[2] For example, after the emergence of the turbojet engine as the dominant propulsion system, innovative activity in the aircraft industry focused on improving the airframe and parts of the engine, such as compressor blades, rather than shifting toward process mechanization and automation (Hatch and Mowery, 1998).

Table 1
Characteristics of the innovation and production processes in the two alternative models of the technology life-cycle (Abernathy and Utterback, 1988; Davies, 1997).

	Era of ferment	Era of incremental change	
	Mass-produced goods/complex products and systems	Mass-produced goods	Complex products and systems
Competitive emphasis on …	Functional product performance	Cost reduction	Functional product performance
Innovation stimulated by …	Revealed user needs and users' technical inputs	Pressure to reduce cost and improve quality	Evolving user needs as well as internal and external technical opportunities
Product line	Diverse, often including custom designs	Mostly undifferentiated standard products	Product variations that share common architecture but are customized to user needs
Predominant type of innovation	Frequent major product innovations	Incremental innovation in processes and materials	Sequences of systemic and incremental component changes
Important sources of knowledge	Product R&D, learning-by-doing and learning-by-using	Process R&D, learning-by-doing	Product R&D, learning-by-using
Plant	General-purpose plant located near user or source of technology	Large-scale plant tailored to particular product designs to realize economies of scale	General-purpose plant with specialized sections located near user or source of technology, little emphasis on economies of scale
Production process	Flexible and inefficient: major changes easily accommodated	Efficient, capital-intensive. And rigid: cost of change is high	Remains flexible: individual projects or small-batch production
Production equipment	General-purpose equipment, requiring highly skilled labor	Special-purpose, mostly automatic with labor tasks mainly monitoring and control	Some sub-processes automated, but mostly requiring highly skilled labor

as a broadening of the focus from core sub-systems to a broader range of sub-systems and components, with an emphasis on understanding and enhancing the complex interactions between different elements of the system. Second, the A-U model ascribes an important role to the exploitation of *economies of scale* through complex, large-scale production processes, implying a strong role for *learning-by-doing in manufacturing* (Hatch and Mowery, 1998). Davies' model, in contrast, sees the later stage of the life-cycle as still characterized by small-scale, flexible production plants that allow limited economies of scale and learning-by-doing. And third, with regard to the *role of performance uncertainty and learning-by-using*, the A-U model predicts a rapid decline in uncertainty about the functional performance of different design features and user needs. This results in very little need in the innovation process for experience from large-scale or long-term experimentation and user-producer interaction, which allows the relocation of factories to locations with cost advantages even if they are far from the actual users (Vernon, 1966). This is in stark contrast to the continued dependence on learning-by-using and the close proximity between users and producers that characterizes innovation in complex products and systems (Rosenberg, 1982).

2.2. Technological characteristics and life-cycle patterns

The ability to predict the life-cycle patterns of technologies could enable improved managerial decisions, technology forecasting, and technology policy making. But how can specific technologies be located in the continuum created by the described life-cycle models? The two models have been developed based on contrasts between vastly different technologies (e.g., infrastructure systems versus light bulbs), while most energy technologies have relatively complex designs *and* are produced in non-trivial numbers – i.e., fall somewhere in between the extremes. It is therefore not entirely clear where different types of energy technologies are located on the displayed continuum.

Davies reduces the many determinants of complexity (Hobday, 1998) to four main characteristics: (i) the *complexity of product architecture*, (ii) the *scale of the production process*, (iii) the *market structure* (bilateral oligopoly versus mass market), and (iv) the *degree of government involvement* in technological evolution (Davies, 1997).

With respect to the energy sector, these determinants can be further reduced to two underlying technological characteristics. First, the degree of government involvement is similar across energy technologies, as innovation in all technologies is heavily affected by government policies, e.g., in the form of technology standards, environmental regulations, subsidy schemes, and industrial policy (Gallagher et al., 2012; Grubler and Wilson, 2014). Second, the scale of the production process in energy technologies is highly correlated with the market structure, since low-volume technologies are typically procured by large, regulated utilities (gas power plants, electricity grids), indicating a bilateral oligopoly, whereas mass-produced energy technologies are mostly used by households, either in the form of end-use technologies (e.g., heating systems or electric cars) or as decentralized, small scale energy systems (solar PV systems, solar water heaters). This leaves two main technological determinants of life-cycle patterns in the energy sector:

1. *The complexity of the product architecture*, which is understood here as driven by the number of sub-systems and components, and the complexity of their interactions in the system. On one hand, complex product architecture implies many opportunities to improve individual elements and their interaction after the emergence of a dominant design. At the same time, architectural complexity is a driver of iterations and learning-by-using in the innovation process, because it makes performance features of the final product difficult to predict (Rosenberg, 1982; Nightingale, 2000).
2. *The scale of the production process*, which is mainly driven by the modularity of the system as well as the size and homogeneity of user demand. A large process scale implies many opportunities to improve cost and functional performance through process innovations. At the same time, it often requires a prolonged process of experimentation and learning-by-doing to develop and operate the large-scale production systems with many interdependent process steps (Hatch and Mowery, 1998*)*.

The two characteristics span a technology space in the energy sector, with the two life-cycle models as two extremes (see Fig. 2). In the following sections this paper goes on to analyze two technologies with the aim of locating them in the matrix displayed in Fig. 2. We show that recognized characteristics of the A-U model and the Davies model can be observed through an analysis of the innovation patterns in energy technologies over time.

3. Research cases

This paper explores whether different technologies in the energy sector have significantly different life-cycle patterns. The cases analyzed for this purpose need to fulfill two main criteria. First, they need to differ in the two determinants of life-cycle patterns identified above: the complexity of the product architecture and the scale of the production process. Second, they need to have reached the era of incremental change, the time period when the differences we seek to identify become salient.

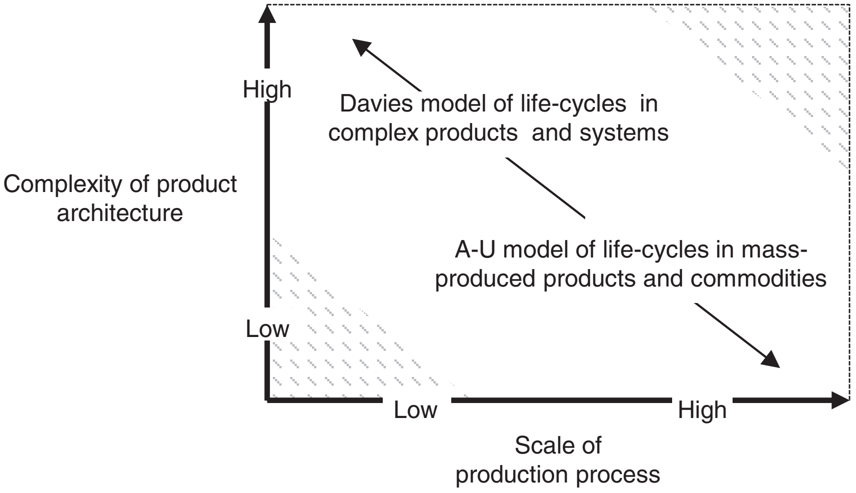

Fig. 2. Technology space in the energy sector, spanned by the scale of the production process and the complexity of the product architecture.

Solar PV and wind power were selected because they fulfill these criteria. They exhibit different degrees of complexity and different scales of production, as will be discussed in Section 3.1. In addition, both have a dominant design and are now in the era of incremental change (see Section 3.2).

3.1. Characteristics of the case technologies

To delimit the empirical scope of our analysis, we understand the term *technology* to describe a class of artifacts defined by a common 'operational principle' and its associated procedures and elements of knowledge (Murmann and Frenken, 2006). Accordingly, we consider solar PV to include all technology related to power generation using the photovoltaic effect, and wind power to include all technology using lift forces of the wind to generate electricity. Table 2, which presents the elements of solar PV and wind power systems and their functions in the system, illustrates the functional structure of both technologies. A *dominant design* is understood here as a standard in design of the technology's core components (Murmann and Frenken, 2006), which we define here as the cell concept of a PV system and the rotor in a wind turbine. Further detail on both technologies is given in Tables A.1 and A.2 in the Appendix A, which show the main engineering tasks in the two technologies as well as the main areas where a technology-specific body of knowledge has emerged.

Comparison of the two technologies shows that the *scale of the production process* is higher in the case of solar PV, while *the complexity of the product architecture* is significantly higher for wind turbines.

Solar PV systems are modular systems consisting of small generating units – the solar *cells* – interconnected to modules of around 200 W and integrated with mounting and tracking structures as well as inverters and control systems, which feed the electricity into the grid (see Table 2). They currently cost about USD 150–250 at the factory gate, depending on the exact capacity rating, efficiency, and other features such as warrantees. Solar modules' few moving parts lead to relatively low annual operation and maintenance (O&M) costs, often below 1% of the initial investment cost (annual expenses of 1% of initial investment mean that O&M cost contribute roughly 10% of the total cost of solar electricity over the lifetime of the power plant) (Moore and Post, 2008). Solar cells are produced in batches of at least several thousand on large, specialized, automated production lines which cost up to several billions of USD and can produce more than 1000 MW per year. Consequently, the market for solar modules exhibits many features of mass-manufactured commodities, even spot markets for cells and modules.

Table 2
Product architectures of solar PV and wind power systems, showing the main sub-systems and their function in the technological system.

System	System element	Function
Solar PV system	Solar cell	Absorption of solar irradiation and conversion into electric current through *photovoltaic effect*
	Solar module	Connection of 'string' of cells to achieve desired output voltage; protection of cell from moisture and structural damage; insulation of electrical current
	Mounting system	Integration of modules into larger structures (array); load carrying and transfer (mounting system); integration of module/cells into building environment (building integration); reorientation of modules/array to follow the sun (tracking system)
	Grid connection	Conversion of DC current into AC (inverter); reduction of impact of grid-side disturbances; maintenance of grid-friendly system output (electrical control system)
Wind power system	Rotor	Conversion of wind energy into rotational energy through *lift effect* (rotor blades); transfer of energy to main shaft (hub); adjustment of rotor and individual blades to wind & system conditions (rotor control system)
	Power train	Transmission of rotational energy from rotor to generator, including adjustment of rotational frequency (mechanical drive train); conversion of rotational energy into electrical energy, AC-DC conversion and frequency conversion (electrical drive train); adjustment of power-train elements to wind & system conditions (power-train control)
	Mounting & encapsulation	Load carrying and machinery enclosure (nacelle, spinner, bedplate); support turbine at designated height and load transfer to foundation (tower); load transfer into ground (foundation); regulation of operating conditions &minimization of system vibrations (climate and vibration control)
	Grid connection	Transfer of electrical energy to grid (transformer/substation, power cables); storage of electrical energy (storage system, if applicable); reduction of impact of grid-side disturbances; maintenance of grid-friendly wind farm output (grid-impact and wind-farm control)

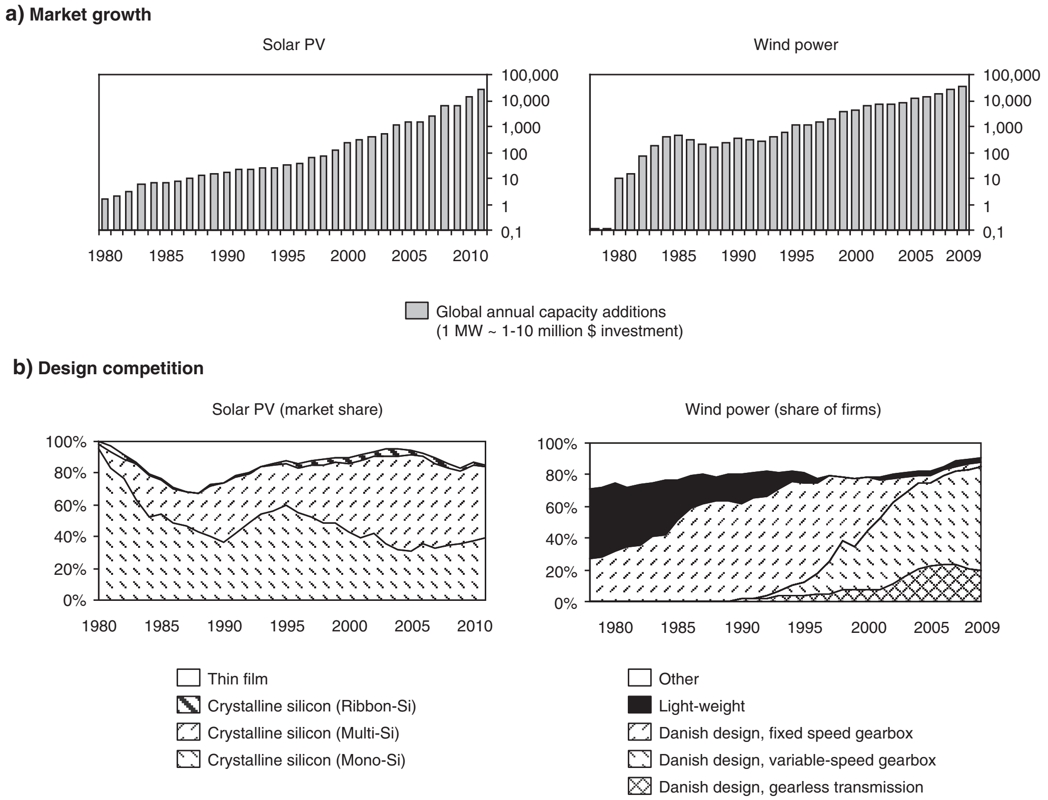

Fig. 3. a) Annual installations of solar PV (IEA, 2012) and wind power systems (Peters, 2011), p. 132] and; b) design competition in solar PV, as measured by market share of different designs (Fraunhofer, 2012), and in wind power, as measured by the share of firms with different designs active in the market (Menzel and Kammer, 2011).

Modern wind turbines, by contrast, are electro-mechanical machines that can reach up to 8 MW of electric capacity, consist of several thousand components and cost up to USD 15 million per unit (a list of key sub-systems and main functions is given in Table 2). Although typically not made-to-order, wind turbines often contain site-specific characteristics, such as sand or salt in the air, high altitude sites, or a very cold climate. The high number of moving key components is reflected in relatively high O&M costs, which often contribute 25% or more to the levelized cost of electricity over the lifetime of a wind turbine (IRENA, 2015). Wind turbine production and construction processes are dominated by what one of our interviewees called "simple industrial craftsmanship," i.e., standard industrial processes that require skilled manual labor and are performed on multi-purpose machinery, such as welding, milling, and drilling machines. Specialized equipment is used only in the blade manufacturing and installation processes, in the form of large molds and cranes. Overall, a wind turbine production facility has construction costs in the order of USD 20-200 million – i.e., an order of magnitude lower than factories for solar cells – and can produce up to several hundred MW of turbines per year.

3.2. Dominant designs and technological trajectories in solar PV and wind power

Both solar PV and wind power have passed through various stages of their lifecycles and have reached the era of incremental change. This section presents evidence for this by demonstrating (i) the presence of *dominant designs* in solar PV and wind power, as well as (ii) the maturity of the industries and the prevalence of cumulative and incremental innovation.

The markets for solar PV and wind power systems have grown exponentially over the last three decades (see Fig. 3a). In 2012, the PV industry recorded sales of around USD 80 bn and the wind industry around USD 75 bn (Pernick et al., 2013). With the growing market, dominant designs emerged in both industries in the early 1990s (solar PV) and the late 1980s (wind power), as shown in Fig. 3b. For solar PV, the chart displays market shares by shipment volume (in MW), showing that designs based on wafers of silicon have dominated the market (mono-Si, multi-Si, and ribbon-Si, collectively referred to as crystalline silicon) since the beginning of the industry. Sales of thin-film modules rose during the 1980s when the first commercial-scale installations were financed, and again slightly in the late 2000s. However, both trends were relatively quickly reversed, such that since 1993 the share of crystalline silicon cells has never fallen below 80% of the global market share.

For wind power, Fig. 3b shows trends in the number of companies actively pursuing different design concepts. The graph illustrates that the 'Danish Design' has come to dominate the industry since the late 1980s, when the phase-out of generous tax incentives in California resulted in a shake-out of firms producing light-weight turbines (Garud and Karnøe, 2003). The Danish design is characterized by a rotor that (a) faces toward the incoming wind, (b) features three rotor blades and (c) operates with relatively low rotational speeds. The dominance of the Danish design has only increased since then, albeit with different designs of the transmission system (notably variable-speed gearboxes and gearless transmissions).

Technological change within the dominant designs has been cumulative and incremental over the last three decades, indicating an era of incremental change.[3] Two prominent indicators of technological change in electricity technologies are investment cost[4] for new installations (which reflects equipment prices) and efficiency. Both trends are

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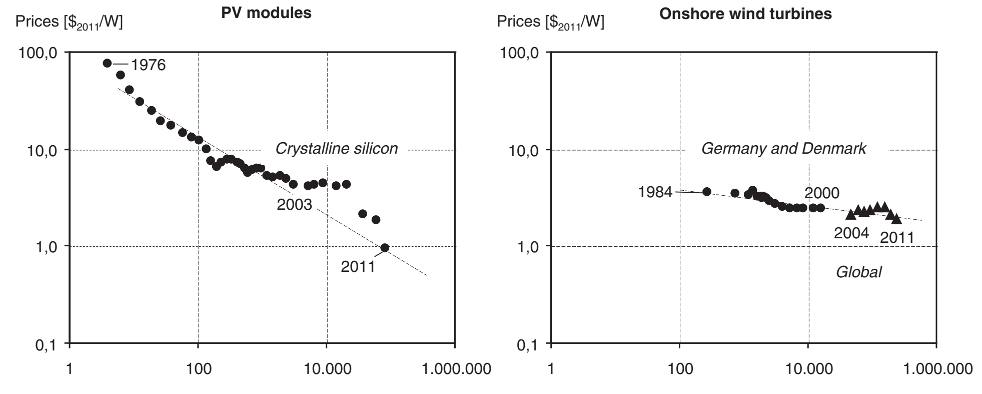
[3] The maturity of the industries is further demonstrated by the high relative share of corporate R&D expenditures in total R&D in the two industries, which stands at 58% in solar PV and 76% in wind power (Wiesenthal et al., 2011).

[4] Since fuel costs do not apply and operation and maintenance are comparatively low, investment costs dominate the economics of renewable electricity.

a) Investment costs



b) Conversion efficiency

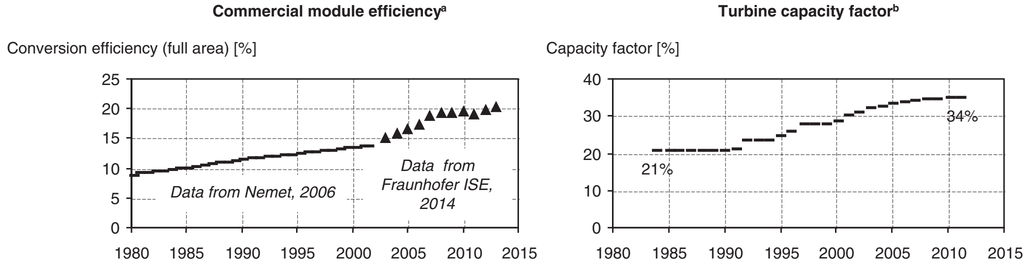


Fig. 4. Technological change within the dominant designs in solar PV and wind power: a) Trends in investment cost displayed as 'experience curves,' i.e., logarithmic unit prices over the logarithmic cumulative production (BNEF, 2012a; BNEF, 2012b); the recent plateaus in PV and wind turbine prices do not reflect technological discontinuities; they were mainly driven by imbalances between supply and demand (Candelise et al., 2013; Bolinger and Wiser, 2011); b) quality indicators commonly used by industry: crystalline silicon PV module conversion efficiency (Nemet, 2006; Fraunhofer, 2014), and wind turbine capacity factors (the ratio of actual power generation to continuous power generation of a wind turbine generator) (BNEF, 2012a). The PV module efficiency data shows industry-average module efficiency up to 2001 and best-in-class c-Si module efficiency from 2003.

shown in Fig. 4 a and b for *crystalline silicon PV modules* and *Danish-design wind turbines*, respectively. The data illustrate that initial prices came down incrementally over the last decades. At the same time, suppliers were able to gradually increase the *technology quality* of the power generation equipment.[5]

4. Data and methodology

4.1. Empirical strategy

Section 3 provided evidence for the finding that both solar PV and wind power went through different stages of the technology life-cycle. However, the presented indicators offer few cues about the focus of innovative activity and whether the patterns conform to one or another model of the technology life-cycle.

This section introduces our patent-based methodology for studying the technology life-cycles in solar PV and wind power. Patents have been used extensively to study trends in innovation in technological systems, in part because they are readily available as large empirical datasets (Fleming and Sorenson, 2001; Rosenkopf and Nerkar, 2001). However, large patent datasets make in-depth analyses difficult – such as the identification of product and process patents – while containing only a small number of patents with significant technological or commercial value (Griliches, 1990). Therefore, researchers have long been searching for ways to identify valuable patents, which can then be analyzed in more detail (Harhoff et al., 2003; van Zeebroeck, 2011).

Several studies in recent years have applied connectivity algorithms to the network formed by patents (as vertices) and patent citations (as arcs) in order to identify technologically significant patents (Verspagen, 2007; Fontana et al., 2009; Bekkers and Martinelli, 2012; Choi and Park, 2009; Epicoco et al., 2014; Ho et al., 2014). The idea is that patent citations contain valuable information about knolwedge 'inheritance' between patents and can thus be used to identify key linkages in technological evolution (Martinelli and Nomaler, 2014). External validations show that this approach can reduce a large patent dataset to a small selection of patents that were highly relevant for technological progress at the time of filing (Fontana et al., 2009; Barberá-Tomás et al., 2011). The sequence of these relevant patents is a representation of the core of the technological trajectory and provides insights into how the focus of innovative activity changed as the technology evolved over time (Verspagen, 2007; Martinelli, 2012; Epicoco, 2013). Recent research further demonstrates that the topical focus of *patenting* along the technological trajectory also corresponds well to trends in *innovative* activity in the industry and that patent-citation networks can therefore be used to identify the emergence of dominant designs and technology life-cycle patterns (Huenteler et al., 2014). However, until now, few studies have combined this approach with a systematic representation of the technological system and classified the identified patents accordingly, as has been done in detailed analyses of technological evolution in specific fields (Rosenkopf and Nerkar, 1999; Prencipe, 2000).

This paper integrates a citation-network analysis with a manual classification of the identified patents. *First*, we develop a patent and patent-citation dataset for solar PV and wind power for the period 1963–2009 (Section 4.2). *Second*, we apply two connectivity algorithms to this dataset to identify the core trajectory for both technologies

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[5] Patent applications grew exponentially in both technologies since the early 1990s and now stand at several thousand per year (see Fig. 5 below). This surge in patenting is consistent with typical patterns in the era of incremental change (Anderson and Tushman, 1990; Henderson, 1995).

(Section 4.3). *Third*, we manually classify the top 1500 patents according to their technological focus – e.g., product design versus production process – to identify whether the technological trajectories match either of the two representations of the technology life-cycle (Section 4.4).

4.2. Patent data

We compiled the database of patent and patent citation data with the objective of obtaining a comprehensive dataset of global patenting in the two technologies over the time period 1963 to 2009.[6] The patent data were extracted from the proprietary Derwent World Patent Index (DWPI) database, which collects data from 48 patent offices. We chose DWPI because it facilitated the assessment of patent content by providing expert-generated abstracts of all patents (see Section 4.4), including translated abstracts for non-English entries in the database.

The search string was developed through a two-step procedure (Huenteler et al., 2014). First, we compiled a list of relevant keywords extracted from the innovation literature.[7] Then we iteratively applied the keywords to the initial set of International Patent Classification (IPC) classes listed in the 'Green Inventory' of the World Intellectual Property Organization (such as the class 'wind motors' F03D) and curtailed the keyword list by manually checking random samples for irrelevant patents.[8] Second, additional IPC classes were added to the search string based on information on co-filings of relevant patents. Final tests indicated about 6% and 13% false positives as well as about 9% and 14% false negatives for solar PV and wind power, respectively.[9] Because connectivity algorithms are robust to false positives, we focused on reducing the error of exclusion when constructing the search filter — partly at the expense of the error of inclusion (Huenteler et al., 2014). Therefore, after retrieving the citation data of all patents (see below), we extended the database in a second iteration to include those 1000 outside patents that received the most citations from the patents in the database.[10]

The citation data were extracted from the DWPI and Thomson Innovation databases, which together cover most of the patent offices' data. We cleaned the citation data from duplicate citations between different patents in the patent families and excluded circular references.[11] One problem that arises when using citation data is that early patents have a disproportionately high likelihood of being cited because the population of potential citing patents is higher than for new patents (Huenteler et al., 2014). Therefore, in order to avoid a bias toward older patents, we discarded all citations with a lag between filings of cited and citing patents of more than five years (Nemet, 2009; Nemet and Johnson, 2012). In a last step, we removed all unconnected patents, i.e., all patents without citation links to any other patent in the database. The final database contains 26,775 solar patent families[12] (55,687 linkages with a lag ≤5 years) and 8907 wind patent families (18,718).

Given the time period represented in the database, our analysis is able to reliably identify technologically significant patents until at least 2005. Fig. 5 shows how patents and citations are distributed over time.[13]

4.3. Connectivity analysis

In order to identify differences in the development of solar PV and wind power, we applied connectivity algorithms to the patent data. We designed the analysis to address two aspects of the broader research question: *In step 1*, we identified the current[14] trajectory of innovative activity and traced back the technological foundations of this current trajectory. The results of this step are used to characterize the current stage of the technological lifecycle in the two technologies (i.e., at the end of the observed period in 2009) and can yield insights into where the technology is heading at the moment. *In step 2*, we analyzed how and when the current trajectory emerged as the industry's dominant trajectory and which alternative paths of development existed in the past (and were abandoned). The results of this step are used to characterize the technology life-cycle as a whole, including significant shifts in the focus of innovative activity in the past. For both analyses, we used connectivity algorithms to extract sub-networks small enough to be categorized manually (see Section 4.4).

Both analyses employ the *search path link count* (SPLC) algorithm and the *critical path method* (CPM). The SPLC algorithm aims to identify the most important arcs (i.e., citations) in the network (Verspagen, 2007; Huenteler et al., 2014; Hummon and Doreian, 1989). A 'search path' is every possible way from a sink in the network (i.e., a patent that only *cites* and does not get cited) to a source (patents that only *get* cited). The 'link count' enumerates all possible search paths in the network and counts how often an arc lies on such a search path. The count is then assigned as a weight to each adjacent patent, thus identifying patents along the most important technological linkages in the network. Because the weight of patents in the network is highly skewed, with a few patents holding most of the aggregate weight, this algorithm can be used to reduce the complexity of the network significantly — e.g., in the case of wind power, 158 of the 8907 connected patents hold 80% of the total weight between them (494 patents hold 95%). Building on the results of the SPLC, the CPM determines the search path with the largest total sum of arc weights (Fontana et al., 2009; Epicoco et al., 2014). We implemented the algorithms using Pajek (de Nooy et al., 2011).

To characterize the current stage of the technological life-cycle (step 1), we applied the SPLC and the CPM to the full network 1963–2009 for each technology (networks B in Table 3 below) to identify the core trajectory or 'backbone' of the trajectory (sub-networks C in Table 3) (Epicoco, 2013; Huenteler et al., 2014; Prabhakaran et al., 2015). As a robustness test, we also extracted and analyzed the top 80% and top 95%-weight networks (a so-called vertex-cut algorithm; D and E in Table 3) (Batagelj and Mrvar, 2004). As such, step 1 reveals the most important patents and citation linkages in the full network — i.e., the current dominant trajectory and its technological roots. However, it does not reveal when the current trajectory was selected or what the alternatives were. Because the algorithm uses all information contained in the network to evaluate each patent, the evaluation of patents filed in year t changes over time as new patents are filed in t + 1, t + 2, etc. This means that previously important trajectories that turned out to be dead ends are no longer visible when analyzing today's patent-citation network. Therefore, step 2 is necessary to analyze the technology life-cycle in 'real time'.

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[6] The search was conducted in 2013 but the database was truncated after 2009 to account for the time lag between patent filing and publication.

[7] A total of six experts from the two industries provided feedback on the identified keywords.

[8] We applied the keywords to the titles, abstracts and claims of patents.

[9] To test for false positives, we randomly tested a total of about 1000 patents for each technology (50 patents for each of the 18 and 20 four-digit IPC classes in the search strings for solar PV and wind, respectively). For false negatives, we checked how many of the patents filed by the top 12 pure-player PV manufacturers (by 2012 cell market share) and 8 pure-player wind turbine manufacturers (in 2010 by market share) were included in our database.

[10] Almost all of these are relevant solar and wind patents that did not explicitly mention the keywords included in our list. Most deal with specific electrical components or subsystems, such as inverters, generators, transformers, etc.

[11] Whenever we found circular references, i.e., mutual citations between patents, we deleted the citation coming from the patent with the earlier priority date. Such citations can occur when examiners add citations to new patents filed during the examination process, or when patents are filed in multiple countries.

[12] We used patent families instead of individual patents to avoid double-counting of multiple filings in different offices.

[13] Received citations drop rapidly after 2005 because patents after this date did not have a full five-year window of possible citing patents in the database.

[14] We approximate the 'current' trajectory by analyzing the network at the end of the observed period, i.e., 2009.

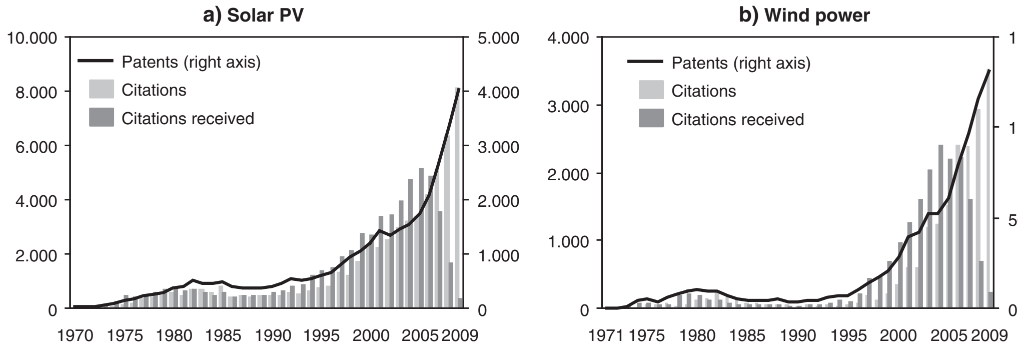

Fig. 5. Descriptive statistics of the patent network over time. Only citations with a lag of ≤5 years are included. The trends in patenting are in line with other studies that find a surge in patenting activity in the era of incremental change (Lee and Berente, 2013; Gort and Klepper, 1982).

Table 3
Descriptive statistics of patent data (all networks except network A only include linkages with lag <=5 years).

Technology	A	B	C	D	E	F
	Full network (including linkages with lag > 5 years)	Full network	Critical path	80%-weight network	95%-weight network	Sequential critical paths
Time period	1963–2009	1963–2009	1963–2009	1963–2009	1963–2009	1963–1975 1963–2009
Solar PV	32,919 (129,993)	26,775 (55,687)	35 (53)	322 (1063)	915 (2069)	3 (2) ... 35 (53)
Wind power	11,330 (41,268)	8907 (18,718)	36 (60)	158 (499)	494 (1827)	4 (3) ... 36 (60)

To *characterize the technology life-cycle as a whole* (step 2), we applied the CPM to a series of 35 gradually growing networks N_t, starting with a network N_{1975} covering the years 1963–1975[15] and ending with the full network N_{2009} covering 1963–2009 (eight of them are displayed in Fig. 10 in 5-year steps). We then merged the critical paths into one network and color-coded each node by the last network N_t in which it is part of the critical path (sub-networks F in Table 3). This analysis reveals dead ends and abandoned trajectories hidden in the data. Descriptive statistics of the full networks and all sub-networks are provided in Table 3 below.

4.4. Patent-content analysis

In the final stage of our analysis, we manually coded the abstracts and claims of the patents in the sub-networks C to F in order to identify the focus of innovation over the technology life-cycle (Huenteler et al., 2014).

The classification of the patent abstracts was done according to the coding schemes shown in Table 4 (solar PV) and Table 5 (wind power). For each of the two technologies, we differentiated 5 functional elements of the system: The system level (i.e., inventions that claimed entire PV systems or wind turbine designs) and four different sub-systems each (see Table 4). In addition, within each sub-system category (e.g., cells, rotors), we classified whether the patent refers to product innovations or process innovations. Tables 4 and 5 provide examples for each of the resulting 9 classes of patents per technology. One mechanical engineer and one electrical engineer independently classified each of the patents according to the abstract's focus in the technological system. Overall the agreement between the two coders was 87%. In cases of disagreement, the coders reached a consensus after discussing the patent content in detail.[16]

5. Results

This section's structure follows the sequence of analyses presented in the methodology section. We start by characterizing the current stage of the technology life-cycle of the two technologies (section 5.1). Then we characterize the technology life-cycle as a whole, including significant shifts in the focus of innovative activity in the past (Section 5.2).

5.1. Characterizing the current life-cycle stage

The core trajectories in the full networks of solar PV and wind power (see Fig. 6a and b, and in Tables A.3 and A.4 in the Appendix) allow us to characterize the current stage of the life-cycle, including the focus and the technological foundations of current innovative activity (analysis step 1 of the connectivity analysis). Two main differences between the technologies stand out. *First*, the breadth of innovative activity is remarkably different: the critical path of the PV patent network primarily contains patents related to the cell, with only two module patents as exceptions. The critical path of the wind power patent network, in contrast, contains patents that are spread across the four sub-systems: 8, 10, 15, and 3 patents in the rotor, power train, grid connection, and mounting & encapsulation, respectively. Additionally, the path in the wind network shows a sequential pattern, focusing first on the rotor (which can be seen as a core sub-system), until 1987, before shifting to the power train (mid-1980s to mid-2000s), grid-connection issues (from late 1990s) and mounting & encapsulation structures (since the early 2000s). *Second*, the two technologies differ in the *type of innovation* along the current trajectory, in particular the relative emphasis on product and process innovations. As can be seen from the color-coding in Fig. 6a, the patents along the critical path in solar PV are almost exclusively focused on the cell production process. Indeed, 25 of the last 26 nodes on the critical path, covering the period 1987–2009, are cell-related process innovations. Only the first 9 patents and one later patent (in 2004) on the critical path are product innovations. The wind network in Fig. 6b, by contrast, shows virtually the opposite: There is not a single process-related patent on the critical path; in fact, only 3 of the top 494 patents representing the top 95% of the vertex

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[15] The year 1975 was chosen as a starting point because at that time the cumulative number of patents exceeded 100 for both technologies (257 for PV, 111 for wind).

[16] As a final robustness test we discussed our results for the focus of innovative activity over time with academic experts on the solar PV and wind power industries (five and four experts, respectively). All nine confirmed the trends displayed in the data.

Table 4
Coding scheme for patents in solar PV.

Content code		Content	Example
PV system		Novel PV system design in which novelty has to do with the design of at least two of the four sub-systems (cell, module, mounting system and grid connection)	Tubular photovoltaic solar cells situated at the focus of a line-generated parabolic reflector (US 3,990,914)
Cell	Product	Novel design of cell or cell materials	Layered photovoltaic cell with more than one active junction for higher efficiency (US 4,017,332)
	Process	Novel production process for cell or cell materials	Production process for crystalline thin-film cell (US 5,130,103)
Module	Product	Novel design of module, including cell separation, cell interconnection, or cell encapsulation, including specific materials and components	Amorphous silicon solar cell element encapsulated by a filler with low moisture permeability (US 5,344,498)
	Process	Novel production process for module, module materials, or module components	Solar cell module manufacturing method with improved sealing characteristics (US 20,040,191,422)
Mounting system	Product	Novel design of array, mounting system, or tracking system (including control system)	Modular PV mounting system with batten-and-seam type interconnection that can be attached to roof (US 5,232,518)
	Process	Novel production or installation process for array, mounting system, or tracking system	Method to install rooftop solar system (US 20,010,034,982)
Grid connection	Product	Novel design of inverter, cabling, storage, or control system (incl. Grid integration control system)	Circuitry design for PV system with earth leakage circuit breaker (US 6,107,560)
	Process	Novel manufacturing or installation method for inverter, cabling, storage, or control system	Inverter manufacturing method (JP 4,915,907)

Table 5
Coding scheme for patents in wind power.

Content code		Content	Example
Wind turbine system		Novel wind-turbine design in which novelty has to do with the design of at least two sub-systems (rotor, power train, mounting & encapsulation, and/or grid connection)	Vertical axis turbine with novel rotor and novel drive-train arrangement (US 3,902,072) or horizontal-axis rotor with rotor-integrated generator (US 4,289,970)
Rotor	Product	Novel design of rotor or rotor components (incl. rotor control system)	Rotor arrangement with teetering hub and rotor control mechanism (US 4,201,514)
	Process	Novel manufacturing or installation method for rotor or rotor components	Rotor blade manufacturing method (JP 4,641,366)
Power train	Product	Novel design of power train or power train components (incl. power train control system)	Compact, gearless power train (US 6,921,243)
	Process	Novel manufacturing or installation method for power train or power train components	Manufacturing method for magnets of multi-polar generator (EP 2,389,512)
Mounting & encapsulation	Product	Novel design of nacelle, tower or foundation (including climate and vibration control system)	Tower-nacelle arrangement in which transformer is mounted inside the top of the tower (US 7,119,453)
	Process	Novel manufacturing or installation method for nacelle, tower, or foundation	Installation method for offshore wind turbine tower (GB 2,460,172)
Grid connection	Product	Novel design of transformer, substation, cabling, or wind farm integration (incl. grid integration control system)	Electrical connection of wind turbines in a wind farm, including substation and individual transformers and cabling (US 7,071,579)
	Process	Novel manufacturing or installation method for transformer, substation, or cabling	Method of mounting power cables (ES 2,283,192)

weight (network E) relate to the production or installation process.[17] Both differences between solar and wind can be observed not only in the critical paths but also in the larger networks D and E (see Table 3) containing 80% and 95% of the cumulative vertex weight, respectively (networks D for solar and wind are shown in Fig. A.1 in the Appendix A).

The patterns observed in Fig. 6 allow us to draw conclusions about the innovation process in the (current) era of incremental change in the two technologies: in solar PV, the current trajectory of innovative activity is dominated by cell process innovations, which draw relatively little on knowledge developed for other parts of the system (such as module interconnection and encapsulation, mounting structures, or grid integration routines). In contrast, the current trajectory of innovative activity in wind power is centered on product innovations. These product innovations draw not only on knowledge from the sub-system in question but are also based on innovations in other parts of the system, as can be seen from the citations that cross sub-system boundaries. This result points toward the complexity of the product architecture and the 'systemic' nature of innovation in wind power.

The two observations from the critical paths remain valid in looking at quantitative indicators describing the broader trajectory. Fig. 7a and b shows comparable data for the *breadth* of innovative activity, represented by the share of innovative activity in different parts of the system for solar PV and wind power. The graphs illustrate that the focus on the cell sub-systems remains more or less unchanged (cell innovations represent between 60% and 90% of the weighted activity for most of the observed period). By contrast, the focus in wind turbine technology is *sequential* and shifts through different parts of the system in such a way that each sub-component has a share of at least 40% of the weighted activity in different time periods. The *type of innovation* can be compared in Fig. 8a and b. In solar PV the focus shifts over time from product innovations, which represent an average of 64% of the weight between 1972 and 1985, to process innovations with an average 73% of the weight in 1990–2009. The focus of innovative activity in wind power did not shift to process innovations (which are completely absent from the 80%-weight network), but to *systemic patents*, as shown in Fig. 8b. Systemic patents are defined

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[17] More detail on the patents on the critical paths is presented in Tables A.3 and A.4 in the Appendix A.

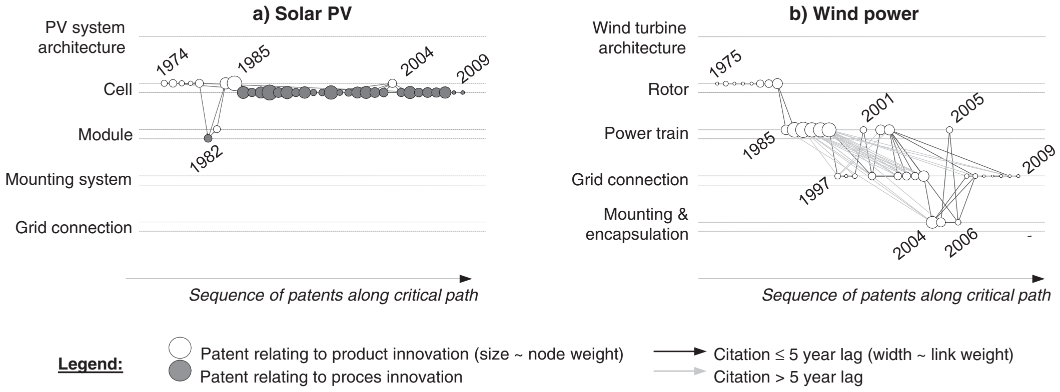

Fig. 6. Critical paths in full networks (network C in Table 3) showing the currently dominant trajectory of innovative activity. Citations with a lag of more than 5 years were not included in the connectivity analysis but are nonetheless shown in Fig. 6 to illustrate the multitude of linkages between patents in wind power.

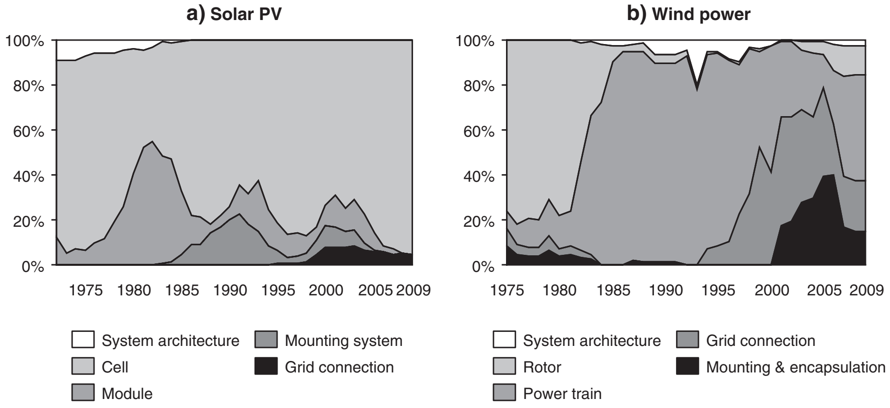

Fig. 7. Share of innovative activity in different parts of the technological system (based on patent-content categorization of 95%-weight networks D, which are shown as graphs in Fig. A.1 in the Appendix A).

here as patents that received more than half of their citations from patents in other sub-systems.[18] Their share increased from 49% in 1980–89 to 67% in 1990–99 and 58% in 2000–09. This, again, illustrates the systemic nature of innovation in wind power, as do the patterns of citations seen in Fig. 6b.

5.2. Characterizing previous stages of the technology life-cycle

As discussed in Section 4.3, the results presented thus far allow us to characterize the current stage of the technology life-cycle, but they offer only limited information on shifts in the patterns of innovation in the two technologies in the past. This section reports results that aim to identify and characterize these past life-cycle stages (step 2 of the connectivity analysis). The algorithms are the same as above but were applied not to the full network but to a series of gradually growing networks N_t where t is the year up to which patents are included in the network.

The results for the series of networks yield a detailed picture of how the current trajectories in the two technologies *emerged over time* and which alternative trajectories were abandoned. The first main set of observations is contained in Fig. 9, which shows that the critical paths in the two networks gradually stabilized. Specifically, the figure presents a 'hazard rate,' which is a measure of variation of the core trajectory, for patents on the critical paths of the gradually growing networks (Huenteler et al., 2014). This hazard rate is to be interpreted as follows: for each year t (on the x-axis), the graph shows how many patents on the critical path of N_t are *no longer* on the critical path when five years of additional patent data are added to the network — i.e., on the critical path of N_{t+5}. The decline of the hazard rate in both technologies means that the critical path gradually stabilized over time, albeit with a major discontinuity in solar PV around 1995 (see below). One can derive from these graphs an approximation of the time when the period of major competition between alternative trajectories ended. This provides insights into the technology life-cycle as a whole, specifically the emergence of a dominant design: If one defines a trajectory as stable once it conserves at least 50% of the patents on the critical path over a period of five years (i.e., the hazard rate remains below 50%), a stable technological trajectory emerged in PV in 1996 and in wind power in 1984 (or 1989, when the value is exactly 50%). These dates roughly match the data on design competition in the market presented in Fig. 3 as well as qualitative accounts of the emergence of dominant designs in the two technologies (Nemet, 2009; Menanteau, 2000; Bergek and Jacobsson, 2003).

The second set of more detailed observations is contained in Fig. 10, which integrates the critical paths of 8 different networks (N_{1975}, N_{1980}, N_{1985}, … N_{2009}) in one graph.[19] Each patent in the graph is colored with

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[18] The seven system-level patents were excluded from this analysis.

[19] To test the robustness of this approach, we compared the network combining the 8 critical paths (network 'I') to one that combines all patents that are on at least three critical paths ('II'). In solar PV, all 65 patents of II are also part of I, which contains 92 patents. In wind power, II contains 50 patents, 38 of which are part of I, which has 47 patents; those that are not on I are patents from the late 1970s and early 1980s on the system level and in the sub-system rotor, thus adding little information to Fig. 10.

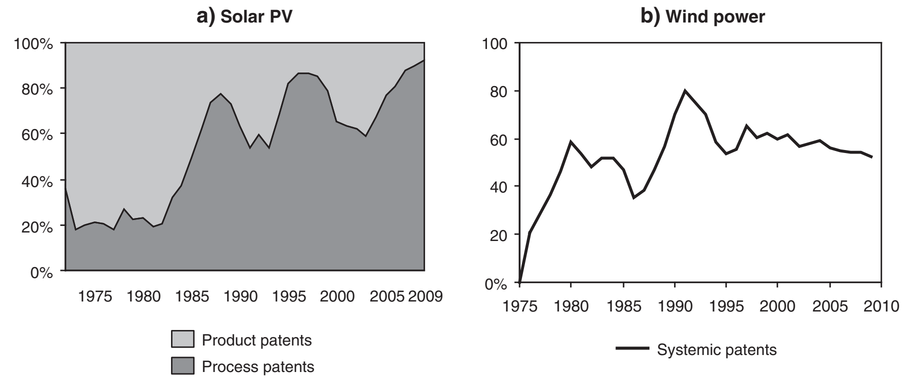

Fig. 8. a) Shift from product to process innovation along life-cycle in solar PV, b) Share of 'systemic patents' in wind power over time, defined as patents that received more (>50%) citations from patents in other sub-systems than from their 'own' sub-system. Both graphs show 5-year moving averages and are based on patent-content categorization of 95%-weight networks D, which are shown as full graphs in Fig. A.1 in the Appendix A.

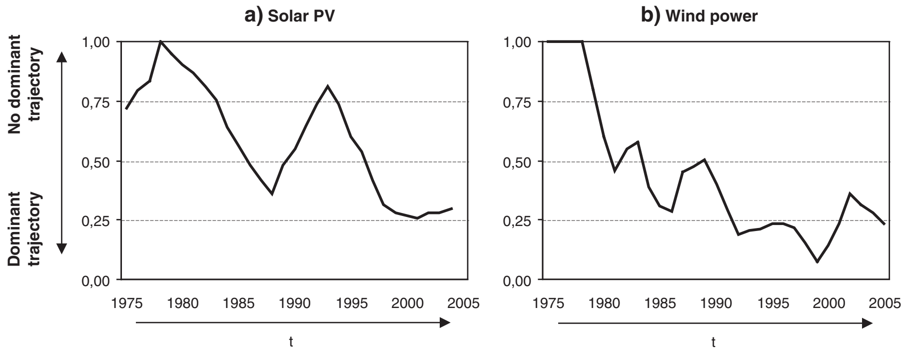

Fig. 9. Hazard rates of patents on the critical path, indicating share of patent that is still on critical path after five years of new patent filings have been added to the network.

a different shade of gray, indicating the last critical path the patent is part of.[20] The graph allows us to analyze two aspects of the earlier stages of the technology life-cycle. *First*, Fig. 10 allows one to analyze how the overall focus of innovative activity in the two technologies evolved in 'real time.' Unlike in Fig. 6, the evaluation of earlier patents is not influenced by the (ex-post) information on which trajectory eventually 'succeeded.' In the case of solar PV, for example, Fig. 10a shows that there was a period (until 1995, and then again briefly in 2002–03) when *module innovations* were very important. This information cannot be observed from an examination of the currently dominant trajectory in Fig. 6a. However, the graph also illustrates that the industry already focused strongly on process innovations in the early years of the industry. This reinforces the contrast to wind power shown in Fig. 6. In wind power, Fig. 10b demonstrates that the currently dominant trajectory had already emerged by the late 1970s. Only a handful of non-white patents are located on alternative trajectories that branch off here and there in the late 1970s and mid-1980s, and the additional critical paths add little information to the analysis of the focus of innovative activity.

Second, Fig. 10 allows us to analyze innovation along individual trajectories that had been important but are now out of focus. The graph shows three such trajectories for each of the two technologies. Detailed information on these trajectories is given in Table 6. In solar PV, it is notable that trajectory (b) in Fig. 10a, which contains a large number of patents from 1980 to 1995, shows a remarkable back-and-forth between product and process innovations. This reflects that most of these patents relate to thin-film PV technology, which is characterized by a strong interdependence of product and process innovations.[21] In wind power, too, the trajectories represent alternative technological paths pursued in the early days of the wind industry. The first one (a), vertical axis turbine designs, represents an alternative product architecture, since rotor and power train are integrated vertically, rather than horizontally. Trajectories (b) and (c) represent different mechanical mechanisms to mitigate turbine vibrations and mechanical mechanisms to control rotor speed. The linkages across different sub-systems in trajectories (a) and (b) point toward the systemic pattern of innovation, as do the observations in Figs. 6-8 above. It is further noteworthy that not a single patent on any of the eight critical paths in wind power has been on the process level, which supports the observation made from Fig. 6b.

6. Discussion

Our results suggest that solar PV and wind power followed very different technology life-cycles over the last four decades but that both patterns can be explained with existing theoretical models. Linking the temporal patterns in solar PV and wind power to the theoretical

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[20] For example, the color code for 1985 indicates that the patent is part of the critical path of N_{1985} but not thereafter.

[21] In thin-film solar PV, the process of module and cell manufacturing is much more integrated than in crystalline silicon PV, which is reflected in the stronger focus on module patents on this trajectory. This is due to a combination of two factors: First, there are many more design variations possible due to a larger choice of possible materials. Second, the economic and technological feasibility of alternative thin-film cell designs and materials hinges almost entirely on the production process, because the production process (i) is even more automated than that of crystalline-silicon cells and (ii) does not allow the use of production equipment from the chip industry. See, e.g., (Jager-Waldau, 2004). Indeed, manufacturers of thin-film modules have had much more problem translating the high-efficiencies and high-yields of smaller, laboratory-constructed cells to production volumes [e.g., 79].

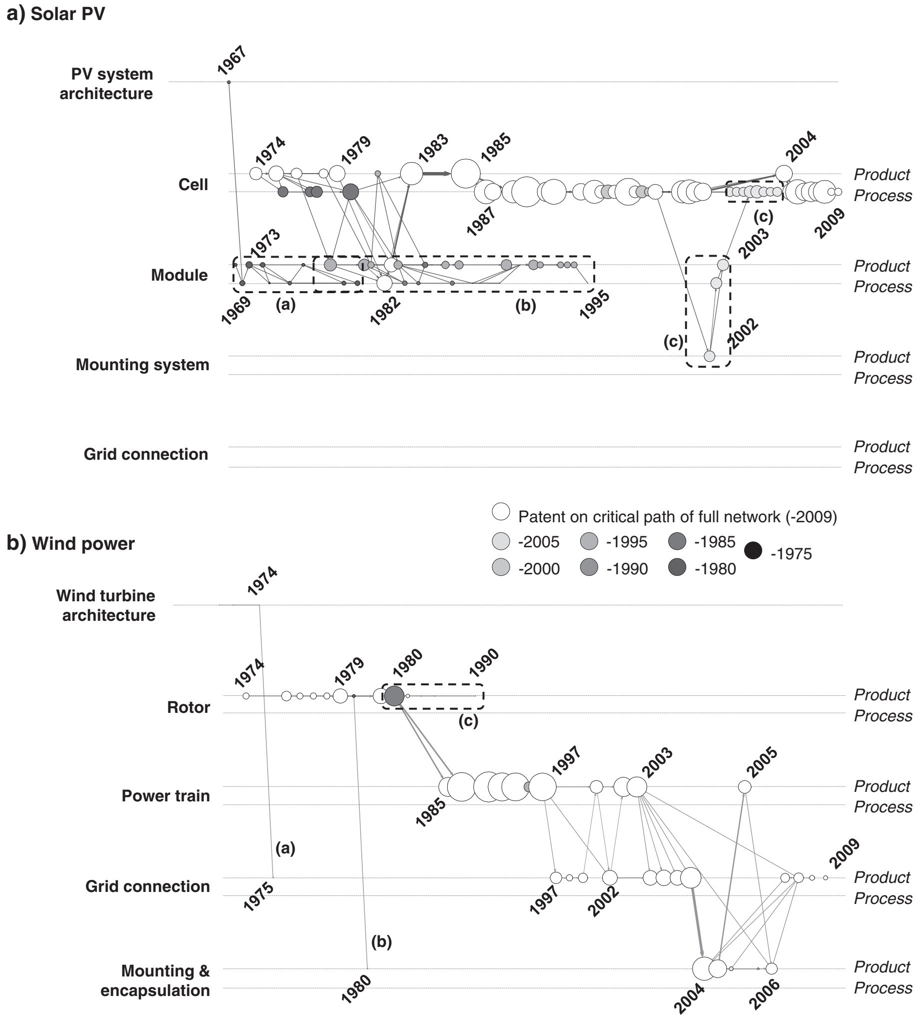

Fig. 10. Networks for solar PV and wind power which combine patents from the 8 critical paths of networks N_{1975}, N_{1980}, N_{1985} … N_{2009} to illustrate competing trajectories and emergence of currently dominant trajectory. The color of each patent (node) indicates the year of the last critical path that the patent is part of. The letters (a)–(c) indicate the 'abandoned' trajectories.

models allows us to draw conclusions from the literature about the two technologies. In particular, the models point toward very different innovation and learning processes in the two technologies, differences that are likely to be even larger when the entire technology space in the energy sector is examined.

6.1. Technology life-cycles in energy technologies

Our results demonstrate that the technology life-cycle of solar PV conforms well to the predictions of the A-U model of mass-produced goods: early product innovations were followed relatively quickly by a surge of process innovations in solar cell production. Wind power, on the other hand, went through a life-cycle that closely resembles the predictions from the Davies model for the life-cycle of complex-products and systems: after an initial period with competing product architectures, the focus of innovative activity shifted over time through different parts of the product, rather than from product to process innovations.

As discussed in Section 3.1, the two technologies differ in the two main determinants of these patterns, the complexity of the product architecture and the scale of the production process. However, they are by far not the most extreme cases within the energy sector. Looking beyond the technologies analyzed in this paper, it quickly becomes clear that the dichotomy of 'complex products and systems' and 'mass produced technologies' alone does not suffice to describe the full variety of energy technologies. Fig. 11 locates a broader set of energy technologies in the technology space generated by the two characteristics. Complex products and systems can be further divided into *infrastructure systems*, which are highly complex and provided through a project-based production process, and thus hardly involve any process innovation; and *design-intensive products*, which are produced in small but significant quantities and thus involve some form of process innovation. On the other end of the spectrum, mass-produced goods are divided into *continuous-flow processes*, for which the process is the primary focus of innovation from the beginning, and *process-intensive products*, which involve some experimentation with different product designs in the beginning. Comparing the two analyzed technologies with those listed in these four categories, it becomes clear that solar PV and wind power are in fact relatively similar. Wind turbines can be characterized as design-intensive products, which implies that the systemic nature of innovation will be even more pronounced in other, more complex technologies. Solar PV systems can be characterized as process-intensive products, some of which will thus exhibit an even earlier and more pronounced focus on process innovations.

The graphic also shows two groups of technologies that do not fit on the diagonal continuum: (i) *low-tech products*, which are relatively simple, are produced in very small batches and have the potential for neither significant product nor process innovation, and (ii) *mass-produced complex products*, which involve continued product and process innovations over the entire life-cycle. Deducing from the patterns observed for the technologies *on* the diagonal, low-tech

Table 6
Technological details on the abandoned trajectories in solar PV and wind power visible in Fig. 10.

Trajectory	Solar PV	Wind power
(a)	PV trajectory (a) focuses on ways to encapsulate solar cells in laminates that are radiation-transparent and protect the cells from water and other environmental influences (e.g., US 4,067,764, US 4,009,054, and US 4,224,081). These innovations are technologically independent of the current trajectory but are nonetheless important parts of current PV technology.	Wind trajectory (a) is representative of a few early critical paths that focus on alternative, vertical-axis rotor designs (e.g., US 3,883,750, US 4,012,163, and US 4,115,027), a technological path that was pursued in the 1970s and 80s but then quickly abandoned outside of small niche applications. Connected to this is the option to store electricity in a flywheel, which can be linked to vertical axis turbines more easily than to current turbines (US 4,171,491, US 3,944,840, US 4,035,658).
(b)	PV trajectory (b), which spans a period from the late 1970s to the mid-1990s, relates to the electrical integration of *thin-film modules* (e.g., US 4,315,096, US 4,624,045, and US 4,650,524), a technology that was long regarded as the most promising technology but which is now increasingly marginalized (see Fig. 3 above).	Wind trajectory (b) relates to early attempts to utilize mechanical mechanisms to control turbine vibrations which can cause mechanical turbine failures. It branches off to an early patent claiming a mechanism to control vibrations induced by the reorientation of a horizontal rotor to changing wind directions (US 4,692,094; also US 4,557,666).
(c)	PV trajectory (c) contains patents relating to encapsulation and mounting elements (e.g., US 7,238,879, US 7,303,788) as well as patents relating to the production of specific materials for thin-film cells (e.g., US 8,038,909, US 8,309,163). The latter suggest that renewed focus on thin-film cells in the mid- to late 2000s in some parts of the industry (cf., Fig. 3) is also reflected in the patent network.	Wind trajectory (c) is representative of several critical path patents in the late 1980s that describe alternative, mechanical mechanisms to control the rotational speed of a rotor of a horizontal axis turbine (e.g., US 5,096,378, US 4,692,095), The trajectory branches off to a mechanical rotor control system (using a spring and a rotating mass which adjusts the orientation of each blade to the wind to avoid over-speeding). These mechanical mechanisms represent alternatives to electronic control systems, which are now standard throughout the industry.

products can be expected to have relatively little absolute potential for learning and cost reductions; mass-produced complex products, on the other hand, can be expected to exhibit large potentials in both areas of learning and economies of scale.

6.2. The role of deployment for innovation in different energy technologies

Our analysis points toward very different sources of relevant experience and potentials for innovation in the two analyzed technologies and the energy technology space in general. In particular, the two contrasting models of the technology life-cycle discussed in Section 2.1 suggest that technological trajectories in the energy sector differ in the role of deployment in the innovation process in later stages of the technology life-cycle. (The identified characteristics of the innovation process primarily relate to innovation related to hardware – a limitation further elaborated on in Section 6.6.)

First, economies of scale in manufacturing, and thus *the absolute size of the supported market*, are much more important for mass-produced goods than for complex products and systems. Mass-produced goods need the prospect of a large market to realize economies of scale in manufacturing and to justify investments into R&D for specialized production equipment and materials. In complex products and systems, where most production facilities remain general-purpose, other variables besides market size are more important for the empirical relationship between deployment policies and innovations or cost reductions. *Second*, by facilitating feedback cycles between R&D and technology users, deployment can play a significant role in reducing technological uncertainty in complex products and systems, where uncertainty about product performance and user needs remains high throughout the technology life-cycle. While existent, the benefits from additional long-term and large-scale testing for the R&D process can be expected to be much smaller in mass-product products. *Third*, because user-producer interaction is so important, geographical and organizational proximity of markets and users can be very important for the R&D and innovation process in complex products and systems. In contrast, proximity appears much less relevant for mass-produced goods.

6.3. Reconciling empirical evidence

Our analysis links quantitative evidence on systematic differences between solar PV and wind power to characteristics of the two technologies. These findings help in reconciling two areas of conflicting evidence about the impact of deployment policies on innovation.

First, there is an ongoing academic debate over whether subsidies for technology deployment can stimulate innovation and technological learning, or just enable firms to exploit existing designs and economies of scale (Nemet, 2006; Nemet, 2009; Hoppmann et al., 2013). The life-cycle models that match our findings for the two technologies suggest that the effect depends on characteristics of the supported technology. Indeed, deployment subsidies in solar PV primarily enabled innovations in manufacturing (Norberg-Bohm, 2000; Hoppmann et al., 2013) and cost reductions through economies of scale (Nemet, 2006). In wind

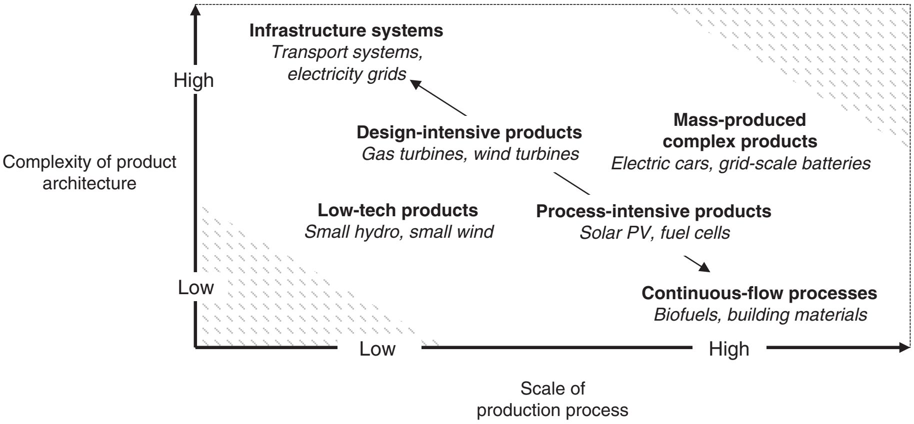

Fig. 11. Stylized classification of different energy technologies according to scale of production process and complexity of product architecture.

power, by contrast, experience generated in government-supported markets was a key driver of product innovation (Andersen, 2004). However, a very large market alone was not sufficient to stimulate innovation in wind turbines, as experience with the early US wind policies suggests (Nemet, 2009). Rather, deployment subsidies in wind power worked best when they were combined with measures to facilitate learning by interacting in the form of knowledge transfer between turbine producers, turbine owners, and researchers (Kamp, 2004; Tang and Popp, 2014).

Second, our analysis also provides a starting point for explaining the importance of 'home markets' for technological innovation, which has been observed for some energy technologies but not for others. The literature on technology life-cycles suggests that geographical proximity to users remains important for innovators in complex technologies such as wind power, while it is no longer required in a technology like today's solar PV, at least not for innovation in hardware. These predictions match very well with empirical evidence that is available individually for the two technologies: While home markets appear to be 'a prerequisite' for innovation and competitive success for firms in the wind turbine industry until today (Dechezleprêtre and Glachant, 2014; Lewis and Wiser, 2007), research on solar PV has found such a relationship between domestic markets and innovation and firm competitiveness only in the early years of the industry (Hoffmann et al., 2004; Peters et al., 2012). Comparing the evidence between the two cases, Barua et al. (2012) conclude from a multi-country case study that "domestic deployment is key to building... domestic industries" in wind power, whereas in PV "a large domestic manufacturing industry and significant domestic deployment do not necessarily go hand-in-hand" (p. 2–3).[22]

6.4. Implications for technology policy

In recent years, rather than focusing solely on public investment in R&D, many countries are providing subsidies for the large-scale deployment of relatively mature clean energy technologies in order to induce innovations and 'buy-down' cost (PCAST, 1999; Gallagher, 2014). Solar PV and wind power alone are projected to receive USD 1.7 trillion and USD 1.1 trillion in deployment subsidies, respectively, over the period 2013–2040 (IEA, 2014). Much of the policy debate on the function of these so-called 'deployment policies' in the innovation process is centered on *learning-by-doing* in manufacturing and *economies of scale*, reflecting the A-U technology life-cycle model.[23] However, our analysis shows that the energy sector comprises technologies that do not conform to this model of the technology life-cycle.

Our findings regarding the characteristics of innovation in mass-produced goods and complex products and systems can serve as guideposts for technology policies that aim to make use of deployment to stimulate innovation in energy technologies (see Fig. 12 and Table 7). We believe that these policy implications are particularly relevant for those technologies that have just reached, or are about to reach, the era of incremental change.

For mass-produced goods, large markets, ideally coordinated internationally, are needed to enable the necessary economies of scale and the learning-by-doing in production. If the prospect of such a market is too uncertain, a 'chicken-and-egg' situation can arise in which the market does not grow because costs are too high and costs cannot come down because the market is too small (Tang and Popp, 2014). At the same time, policy support needs to make sure that cost competition remains high, e.g., by auctioning off subsidized tariffs or by dynamically adjusting incentives. For larger and more complex technologies such as wind turbines, geothermal systems, nuclear power plants, and tidal energy systems, deployment policies have to go beyond simply subsidizing scale in order to fully realize their potential innovation impact. For these technologies, deployment policies need to be understood as R&D policies rather than merely as subsidies. Rather than enabling economies of scale, deployment policies should be targeted at creating 'performance-driven' niche markets (Grubler and Wilson, 2014): they should not aim for very large roll-out of existing technologies but be explicitly targeted at reducing technological uncertainty, for example by providing grants for innovative product features, tying subsidies to requirements to publish cost and performance data, or by financing experimentation in different geographical and climatic environments. Furthermore, deployment policies could be accompanied by measures to enhance user-producer interaction (e.g., technology platforms or grants for consortia), improve market transparency (again, by collecting and publishing performance data) and gradually adjust performance standards (e.g., as it has been done with grid-integration requirements for wind turbines).

6.5. Implications for modeling and forecasting of technological change

Energy sector roadmaps and public policy planning in the context of climate change often rely on models of technological learning to forecast future technology costs. Much like the policy debate, these models typically reflect the A-U technology life-cycle model, in that they assume that learning-by-doing is the predominant impact of deployment on innovation. The impact of deployment is most commonly modeled as one- or two-factor learning curves, also referred to as experience curves, which link cumulative installations – i.e., manufacturing output – to cost reductions (Kahouli-Brahmi, 2008). However, the relationship between cumulative production and costs has often not been a very accurate predictor of technological change in the past (Taylor and Fujita, 2013). Our analysis points toward three promising avenues for models to differentiate between types of energy technologies (see Fig. 11) to improve forecasts of energy technology costs, as detailed below. Future research should validate if these model specifications indeed lead to better model predictions.

First, learning curves should reflect that the dominant learning mechanisms differ between energy technologies, for example by using cumulative manufacturing output as predictor of technological progress for mass-manufactured goods, and cumulative use experience (e.g., measured in GW-years) for complex products and systems (Andersen, 2004). *Second*, learning curves should reflect the different role of domestic and global deployment for innovation by relating global output to global cost variables in the case of mass-manufactured goods and – at least for the larger markets such as China, the US, and large European countries – country-specific output to country-specific cost variables in the case of complex products and systems. *Third*, models should reflect that cost reductions are not the only innovation impact of deployment in the case of complex products and systems. In these technologies, deployment often enables progress in features other than cost, including safety in the case of nuclear power or technology quality. In the case of wind power, for example, the experience gained in the market enabled the development of turbines tailored to specific resource conditions, including low-speed, low-temperature, and desert winds, gradually enlarging the wind resource suitable for commercial development. While these variables are often not linked to cumulative deployment in economic models, our analysis suggests that they should be.

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[22] The differing role of geographical proximity is reflected in processes of catching up of emerging economies in the two industries. In wind power, catching up almost always involves significant support for a domestic market, and often required some form of protectionist intervention by governments (Lewis and Wiser, 2007). The cases of China, Taiwan, and Malaysia, in contrast, which emerged as hubs of PV cell and module production without supporting a significant domestic market, show that countries can reach competitiveness in PV manufacturing without supporting local demand (Barua et al., 2012).

[23] For example, the German feed-in tariff for solar power (a form of subsidized electricity tariff), which with about USD 10bn10 bn per year is currently the largest deployment policy in the world, was designed as "market entry assistance to allow for cost reductions, which will then facilitate the diffusion of photovoltaic through the market" (Huenteler et al., 2015). (German Federal Diet, 1999). The US tax credit under the U.S. 'Recovery Act' in 2009 had the objective "to help renewable energy technologies achieve economies of scale and bring down costs" (Jager-Waldau, 2004). (The White House, 2009).

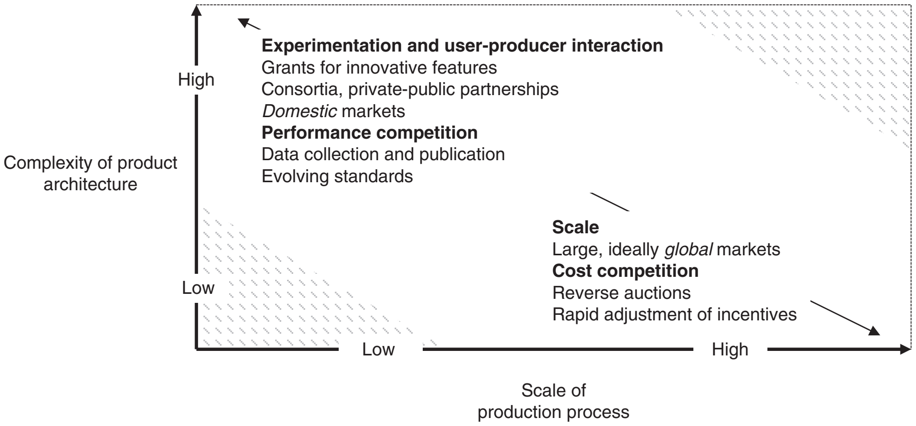

Fig. 12. Characteristics of deployment policies if tailored to the characteristics of the two life-cycle models.

6.6. Limitations and further research

An empirical study such as the one presented in this paper has several inherent limitations. Since the validity of the inferences formulated above for the design of technology policy hinges on the validity of the applied methodology, three aspects have to be highlighted, which lend themselves as avenues for future research.

First, in using patents as indicators for innovation we implicitly assume that patented knowledge is an unbiased indicator of technological progress. This introduces a bias against the 'soft cost' of energy technology, including financing, permitting, planning, logistics, and customer acquisition. However, especially for smaller projects, soft cost becomes increasingly important as hardware cost fall in later stages of the life-cycle. These soft costs are most likely driven by domestic policies, even for globally traded mass-produced goods, which means that technology policies solely focused on hardware may miss out on opportunities to drive down soft costs through domestic deployment (Huenteler et al., in press). Further research should explore the relative importance of different learning mechanisms for soft costs as well as the impact of domestic and foreign deployment policies.

Using patents as indicators also introduces a bias against knowledge that is openly shared, tacit, or protected through means other than patenting. This is important for our analysis because it may introduce a bias against process innovations. The fact that we found very few process patents in wind power along the trajectory may be due to a bias against process knowledge in general. Some process-related knowledge is inherently tacit, including the experience gained by workers operating complex manufacturing equipment. Furthermore, since much of the relevant information can be revealed through reverse engineering anyway, a product innovation is more likely to be patented than a process innovation, which inventors may appropriate by other means, most notably secrecy. However, because this bias against process innovations should be similar for both technologies, it should not affect the conclusion that there are significant differences between the two technologies. Future research could focus on a combination of indicators to assess life-cycle patterns to address this bias.

Second, for lack of available citation data, we could not include Chinese patents in our analysis. From a latecomer position China has caught up quickly in clean technologies since the early to mid-2000s. Especially in solar PV, Chinese firms have come to dominate the global market. Our patent data show a surge of Chinese patent filings in both technologies since about 2010. Understanding the Chinese firms' influence on the technological trajectory and the observed life-cycle patterns is highly relevant for the academic literature and the policy community. Once Chinese citation data are systematically available in commercial patent databases, future research should include it. *Third*, our broader conclusions need to be validated by characterizing the life-cycles of additional technologies in the energy sector. The fact that the two selected technologies already show significantly different life-cycle patterns suggests that there is much to learn when comparing the more extreme areas of the space mapped in Fig. 11. Especially in the lower left and upper right corners of the framework, intuition suggests that empirical analyses could reveal patterns that have thus far not been described by the two traditional life-cycle models. Beyond the energy sector, we believe that the methodology and indicators developed in this paper open up promising research opportunities toward a systematic characterization of life-cycle patterns across a wide range of technologies.

7. Conclusion

Technological change in energy technology can play a major role in mitigating climate change and reducing the environmental footprint of energy production and consumption. To stimulate the necessary

Table 7
Characteristics of deployment policies if tailored to the characteristics of the two life-cycle models.

	Mass-produced energy technologies	Complex energy technologies
Primary objective	Enable economies of scale & learning by doing in commercial-scale production processes, enable manufacturer-supplier interaction	Enable full-scale experimentation in use-environment, reduce uncertainty about product innovations, enable user-producer interaction
Geographical scope	Large-scale (ideally global)	Close to producers
Primary actors in innovation process	Manufacturers & their suppliers (materials, production equipment)	Users, manufacturers, and component suppliers
Creating pressure to innovate	Cost competition drives innovation - > governments need to continuously adapt remuneration, minimize entry barriers and standardize regulation across jurisdictions	Evolving requirements and technological opportunities drive innovation - > incentivize continuous experimentation; create transparency about performance characteristics; monitor and continuously adapt performance requirements
Complementary policies	Rapid adjustment of incentives, reverse auctions	Grants for innovative features; consortia; private-public partnerships

innovation, governments will likely spend trillions of USD of public resources on technology policies for clean energy technologies over the coming decades. This paper mapped the patterns of innovation over the technology life-cycle in solar PV and wind power in order to gain insights about how these resources can be spent effectively.

In particular, the paper analyzed which of two common models of innovation over the *technology life-cycle* best describes the pattern of innovation in the two technologies. The results suggest that solar PV technology followed the life-cycle pattern of *mass-produced goods*, a model that typically applies to technologies with relatively simple product architecture and a large-scale production process: early product innovations were followed by a surge of process innovations, especially in solar cell production. Wind power systems, in contrast, more closely resembled the life-cycle of *complex products and systems*, a model that has been developed for technologies with a complex product architecture and low-volume production: the focus of innovative activity shifted over time from the system architecture and core components to different sub-systems and components of the product, rather than from product to process innovations.

The findings allow us to draw conclusions about the patterns of technological learning in energy technologies from the general literature on technology life-cycles, and to make sense of seemingly conflicting evidence about innovation and policy impacts in the two technologies. In solar PV, most innovations after the first large-scale deployment of the technology in the 1980s were focused on the production process, which points toward a predominant role of *learning-by-doing*, *economies of scale in manufacturing* and *innovations in production equipment*. In wind power, most innovations introduced novel subsystem and component designs, which points toward the importance of *learning-by-using*, *product up-scaling* and *innovations in operation* & *maintenance*. These differing patterns correspond well to existing studies of technological learning in the two technologies and help put these studies in comparative context.

Besides the conclusions about the innovation process, the contrasting characterizations of the learning processes in the two technologies have important policy implications, in particular with regard to public policies that subsidize and facilitate large-scale deployment and use of these technologies. The different life-cycle patterns suggest that deployment policies play very different roles in innovation in the two technologies: in a learning process that is centered on the production process, deployment policy support can be crucial to enable learning-by-doing, large-scale production, and markets for production equipment. By contrast, in a learning process that is centered on the product design, deployment policy support can be crucial to enabling learning-by-using, gradual up-scaling, and markets for specialized operation & maintenance service providers.

Our findings suggest that models of future technological change in the energy sector should account for the technology-specific role of large-scale deployment in the innovation process. Technology-specific learning-curve specifications, including (i) differentiation of learning-by-doing and learning-by-using, (ii) global and country-specific learning effects, and (iii) linkages between cumulative deployment and measures of technological change other than cost (e.g., measures of technology quality) are promising avenues for research to improve forecasts of technological progress in the energy sector.

Differences in the role of deployment for innovation also point toward the need for technology-specific policy instrument designs, especially in view of the current practice of one-size-fits-all instruments that some governments employ to stimulate energy innovation, e.g., through tax credits or feed-in tariffs for *all* types of renewable electricity, or mandates for *all* kinds of alternative fuels and vehicle drivetrains. Few people would support a 'one-size-fits-all' innovation policy approach for the semiconductor, machinery, biotechnology, oil and gas, and chemical industries. The findings of this paper indicate that it may be equally misleading to lump together solar PV systems, wind turbines, biomass gasification, carbon capture and storage, and fuel cells when designing policy instruments to stimulate innovation in clean energy technologies.

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Appendix A

Table A.1
Main engineering tasks in solar PV product and process development (areas of PV-specific knowledge are shaded in gray).

System element	Product design	Production process
Solar cell	• Design of cell materials and arrangement • Design of electrical contact patterns	• Process, equipment and plant design for production of cell materials • Process, equipment and plant design for production of solar cell; surface treatment; contact printing • Design of optical and electrical testing equipment
Module	• Design of module circuitry • Design of encapsulation materials, back cover and frame	• Process, equipment and plant design for cell interconnection, encapsulation, aluminum frame and glass processing • Design of optical and electrical testing equipment
Mounting system	• Design of load carrying structures and control system • Transport-, installation-, and O&M-friendly design	• Metalworking and assembly • Electronics manufacturing and assembly
Grid connection	• Design and dimensioning of control and power electronics	• Electronics manufacturing and assembly

Table A.2
Main engineering tasks in product and process development wind power (areas of wind-specific knowledge are shaded in gray).

System element	Product design	Production process
Rotor	• Development of structural materials and coating • Aerodynamic and structural design • Choice of rotor control • Design and integration of electric motors, gears, hydraulics, control systems and power sources	• Processing of composites and core materials • Design of specialized molds • Design of non-destructive testing equipment and procedures • Metalworking, electrical manufacturing and assembly
Power train	• Design of mechanical drive-train architecture • Dimensioning and material selection for hub, bearings, shafts, brakes, gearbox, lubrication, joints and couplings • Choice of generator topology • Design and dimensioning of generator, power electronics, cooling and control systems	• Metalworking and assembly • Electrical equipment manufacturing and assembly • Electronics manufacturing and assembly
Mounting & encapsulation	• Design of load transfer, noise insulation and thermal management • Aesthetic and aerodynamic design • Transport-, installation-, and O&M-friendly design • Dimensioning of tower and foundation for static and dynamic load transfer	• Composite processing (thermal and chemical process engineering) • Metalworking • Steel processing • Concrete production
Grid connection	• Design of wind-farm circuitry, voltage transfer, electrical insulation • Choice and design of storage technology • Design of control strategy and software • Design and integration of control system elements	• Electrical equipment manufacturing and assembly • Electronics manufacturing and assembly

Table A.3
Patents along critical path of solar PV citation network 1963–2009.

Priority patent	Application	Focus of invention	Focus of invention	Assignee	Assignee type
US 3,978,333	15-Apr-74	Cell concept (polycrystalline silicon)	Cell (product)	E. Crisman	Individual
US 4,064,521	28-Jul-75	Cell concept (amorphous silicon)	Cell (product)	RCA	Cell manufacturer
US 4,126,150	28-Mar-77	Non-reflecting surface layers for solar cell	Cell (product)	RCA	Cell manufacturer
US 4,162,505	24-Apr-78	Cell concept (amorphous silicon)	Cell (product)	RCA	Cell manufacturer
US 4,272,641	19-Apr-79	Cell concept (tandem junction amorphous silicon)	Cell (product)	RCA	Cell manufacturer
US 4,419,530	11-Feb-82	Procedure to connect cells in module	Module (process)	Energy Conversion Devices Inc.	Cell manufacturer
US 4,443,652	9-Nov-82	Cell interconnection in module	Module (product)	Energy Conversion Devices Inc.	Cell manufacturer
US 4,514,583	7-Nov-83	Substrate sheet for thin-film module	Cell (product)	Energy Conversion Devices Inc.	Cell manufacturer
US 4,677,250	30-Oct-85	Substrate sheet for thin-film module	Cell (product)	Astrosystems Inc.	Cell manufacturer
US 5,087,296	26-Jan-87	Production process for polycrystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,130,103	24-Aug-87	Production process for crystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,094,697	16-Jun-89	Production process for crystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,403,771	26-Dec-90	Production process for polycrystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,856,229	10-Mar-94	Production process for crystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,854,123	10-Mar-94	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,326,280	2-Feb-95	Production process for crystalline thin-film cell	Cell (process)	Sony	Cell manufacturer
US 6,294,478	28-Feb-96	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,054,363	15-Nov-96	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,221,738	26-Mar-97	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,582,999	12-May-97	Production process for silicon-on-insulator cell	Cell (process)	Silicon Genesis Corp.	Production equipment provider
US 6,613,678	15-May-98	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,664,169	8-Jun-99	Production process for microcrystalline cell	Cell (process)	Canon	Cell manufacturer
US 6,573,126	16-Aug-00	Production process for silicon-germanium-on-insulator based cell	Cell (process)	Massachusetts Institute of Technology	Public sector
US 6,794,276	27-Nov-00	Production process for a substrate for thin-film solar cell	Cell (process)	Soitec Technologies	Cell manufacturer
US 7,019,339	17-Apr-01	Production process for germanium heterostructure cell	Cell (process)	California Institute of Technology	Public sector
US 7,341,927	17-Apr-01	Production process for silicon heterostructure cell	Cell (process)	California Institute of Technology	Public sector
US 7,846,759	21-Oct-04	Multi-junction cell concept	Cell (product)	Aonex Technologies	Materials supplier
US 7,911,016	27-Jul-05	Production process for thin-film cell	Cell (process)	Silicon Genesis Corp.	Production equipment provider
US 7,759,220	5-Apr-06	Production process for thin-film cell	Cell (process)	Silicon Genesis Corp.	Production equipment provider
US 7,655,542	23-Jun-06	Production process for microcrystalline silicon cell	Cell (process)	Applied Materials	Production equipment provider
US 8,203,071	18-Jan-07	Production process for thin-film multi-junction cell	Cell (process)	Applied Materials	Production equipment provider
US 7,875,486	10-Jul-07	Production process for thin-film cell	Cell (process)	Applied Materials	Production equipment provider
US 7,908,743	31-Aug-07	Method of forming contacts on thin-film cell	Cell (process)	Applied Materials	Production equipment provider
US 8,062,922	5-Mar-08	Production process for thin-film cell	Cell (process)	Global Solar Energy	Cell manufacturer
US 8,318,530	24-Jul-09	Production process for thin-film cell	Cell (process)	Solopower	Cell manufacturer

Table A.4
Patents along critical path of wind-patent citation network 1963–2009.

Priority patent	Application	Focus of invention	Focus of invention	Assignee	Assignee type
SE 005,407	12-May-75	Blade with integrated over-speeding control mechanism	Rotor (product)	Svenning Konsult AB	Engineering consultancy
DE 2,655,026	4-Dec-76	Rotor-hub arrangement with teetering hub and two blades	Rotor (product)	U. Huetter (Indiv.)	Individual
US 4,297,076	8-Jun-78	Control system for two-bladed rotor with adjustable tips	Rotor (product)	MAN	Turbine manufacturer
US 4,274,807	31-Jul-78	Three-bladed turbine with hydraulic pitch mechanism	Rotor (product)	C E Kenney (Indiv.)	Individual
US 4,366,387	10-May-79	Two-bladed downwind turbine with teetering hub and aerodynamic pitch mechanism	Rotor (product)	Carter Wind Power	Turbine manufacturer
US 4,435,646	24-Feb-82	Rotor with teetered hub and mechanical pitch control system	Rotor (product)	North Wind Power	Turbine manufacturer
US 4,565,929	29-Sep-83	Two-blade turbine with novel drag brake and control system	Rotor (product)	Boeing	Turbine manufacturer
US 4,703,189	18-Nov-85	Torque control system for variable-speed power train	Power train (product)	United Technologies	Turbine manufacturer
US 4,700,081	28-Apr-86	Operation strategy for variable-speed power train	Power train (product)	United Technologies	Turbine manufacturer
US 5,083,039	1-Feb-91	Variable-speed power train architecture and power control	Power train (product)	US WindPower	Turbine manufacturer
US 5,155,375	19-Sep-91	Speed control system for variable-speed power train	Power train (product)	US WindPower	Turbine manufacturer
US 5,652,485	6-Feb-95	Power train control for variable wind conditions	Power train (product)	U.S. EPA	Public sector
US 6,137,187	8-Aug-97	Variable-speed power train architecture and power control	Power train (product)	Zond Energy Systems	Turbine manufacturer
US 6,566,764	23-May-00	Variable-speed power train adapted to smoothen power output	Power train (product)	Vestas Wind Systems	Turbine manufacturer
US 6,670,721	10-Jul-01	Inverter control system for grid-friendly power output	Grid connection (product)	ABB	Generator supplier
DE 1,048,225	28-Sep-01	Collective control method for turbines in a wind farm	Grid connection (product)	Enercon	Turbine manufacturer
US 7,190,085	8-Apr-03	Variable-speed power train architecture	Power train (product)	Alstom	Generator supplier
US 7,042,110	7-May-03	Variable-speed power train architecture	Power train (product)	Clipper Windpower	Turbine manufacturer
US 7,205,676	8-Jan-04	Generator control optimizing response to grid failure	Grid connection (product)	Hitachi	Turbine manufacturer
JP 055,515	27-Feb-04	System to control nacelle vibrations	Mounting & encapsulation (product)	Mitsubishi HeavyInd.	Turbine manufacturer
US 7,309,930	30-Sep-04	System to control turbine vibrations	Mounting & encapsulation (product)	General Electric	Turbine manufacturer
US 7,342,323	30-Sep-05	Power train control routine based on upstream wind measurements	Power train (product)	General Electric	Turbine manufacturer
US 7,400,055	1-Feb-06	Control routine to suppress tower vibrations	Mounting & encapsulation (product)	Fuji Heavy Industries	Turbine manufacturer
US 7,851,934	14-Sep-06	Control routine to respond to grid faults	Grid connection (product)	Vestas	Turbine manufacturer
US 7,911,072	14-Sep-06	Control routine to respond to grid faults	Grid connection (product)	Vestas	Turbine manufacturer
US 7,714,458	22-Feb-08	Control routine to respond to grid-side load shedding	Grid connection (product)	Nordex	Turbine manufacturer
US 7,949,434	16-Jun-08	Control system for wind farm with redundant control unit	Grid connection (product)	Nordex	Turbine manufacturer

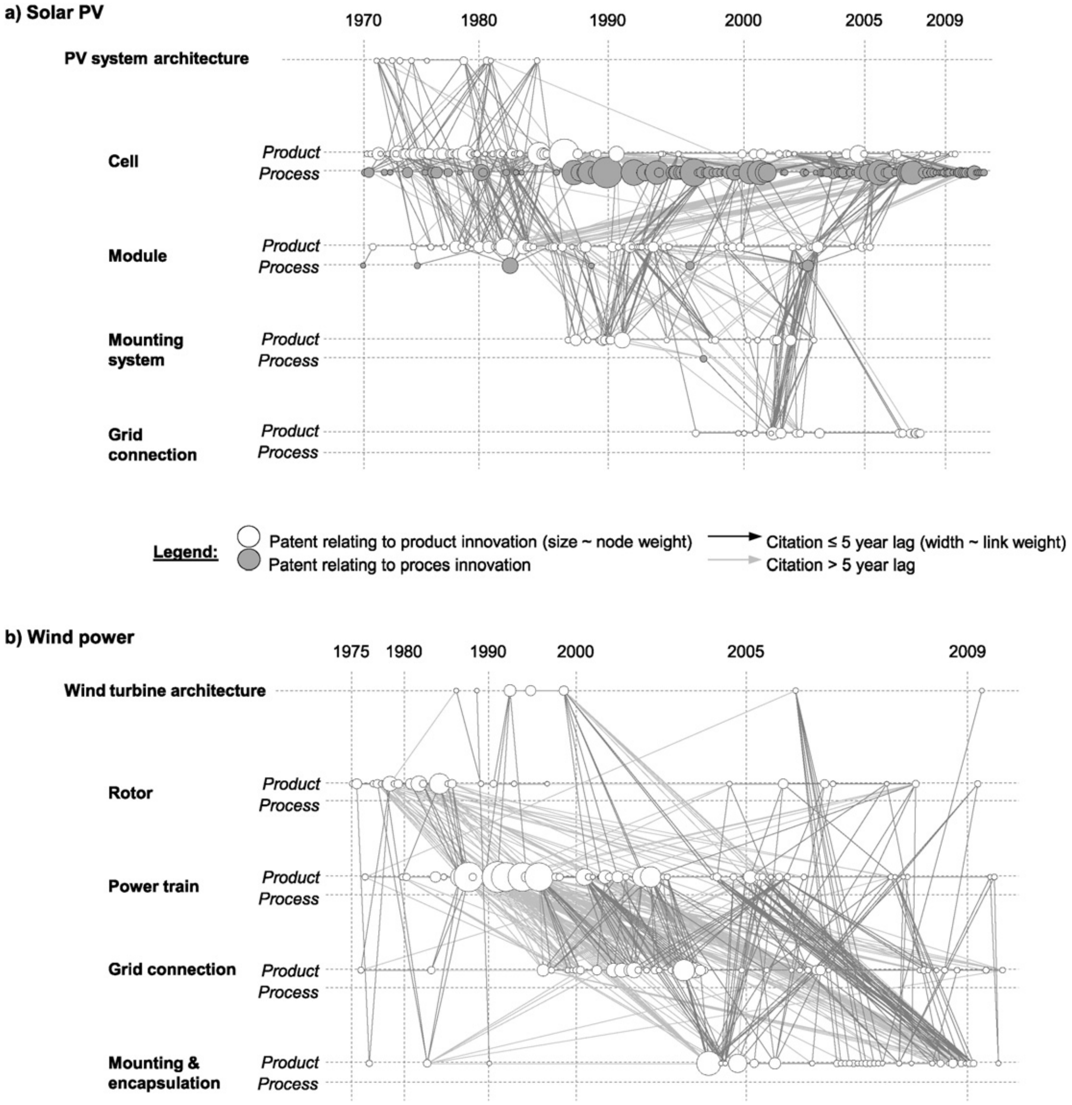

Fig. A.1. Patents in 80%-weight network (full networks D in Table 4) ordered by time of patent filing and their focus in the technological system; linkages indicate citations.

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