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Journal Article

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Publication date:
2016-03

Permanent link:
https://doi.org/10.3929/ethz-b-000109174

Originally published in:
Technological Forecasting and Social Change 104, https://doi.org/10.1016/j.techfore.2015.09.022

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Cite as: Huenteler, J., Schmidt, T. S., Ossenbrink, J., & Hoffmann, V. H. (2016). Technology life-cycles in the energy sector—Technological characteristics and the role of deployment for innovation. Technological Forecasting and Social Change, 104, 102-121.

https://doi.org/10.1016/j.techfore.2015.09.022

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 to informing 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 the two 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.

Keywords: Technology life-cycle; Energy technology; Patents; Citation-network analysis; Wind power; Solar PV

Highlights:

- We analyze the technology life-cycles of solar PV and wind power (1963-2009).
- PV followed the life-cycle of mass-produced goods and commodities.
- Wind power followed the life-cycle of complex products and systems.
- We develop a typology of energy technologies with different life-cycle patterns.
- Technology policy in the energy sector should reflect life-cycle patterns.

1. Introduction

Technological change is “at once the most important and least understood feature driving the future cost of climate change mitigation” [1, p. 2768]. A better understanding of the long-term patterns of innovation in energy technologies is therefore crucial for informing public policy planning [2–4]. Responding to this need, a growing body of literature is studying innovation processes and technology policy in the energy sector [5–7].

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) [8,9].

Empirical research suggests that long-term patterns in the process and focus of innovation differ across these sectors, pointing toward the need to tailor government policies to individual energy technologies [10–13]. However, thus far few studies of technological change in the energy sector have systematically investigated how technological characteristics influence the long-term patterns of innovation, often referred to as ‘technology life-cycles,’ 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-cycle patterns of solar photovoltaics (PV) and wind power. These two are the most rapidly growing clean energy technologies and are highly relevant for public policy: solar PV and wind power are projected to receive USD 1.7 trillion and USD 1.1 trillion in government subsidies, respectively, over the period 2013-2040 [14]. A better understanding of the processes of innovation and technological evolution in these technologies can therefore inform important technology policy decisions in the coming decades.

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. 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-cycles over the last four decades. The implications for theory and policy 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 [15]. 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* [16–22].

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 [19,21,23]. After a *dominant design* has emerged, technological change becomes cumulative and incremental as innovation proceeds along ordered technological trajectories [24–28].

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 [e.g., 16,17,19,29]. According to this model, initially the focus of innovation in 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 Figure 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) [30].

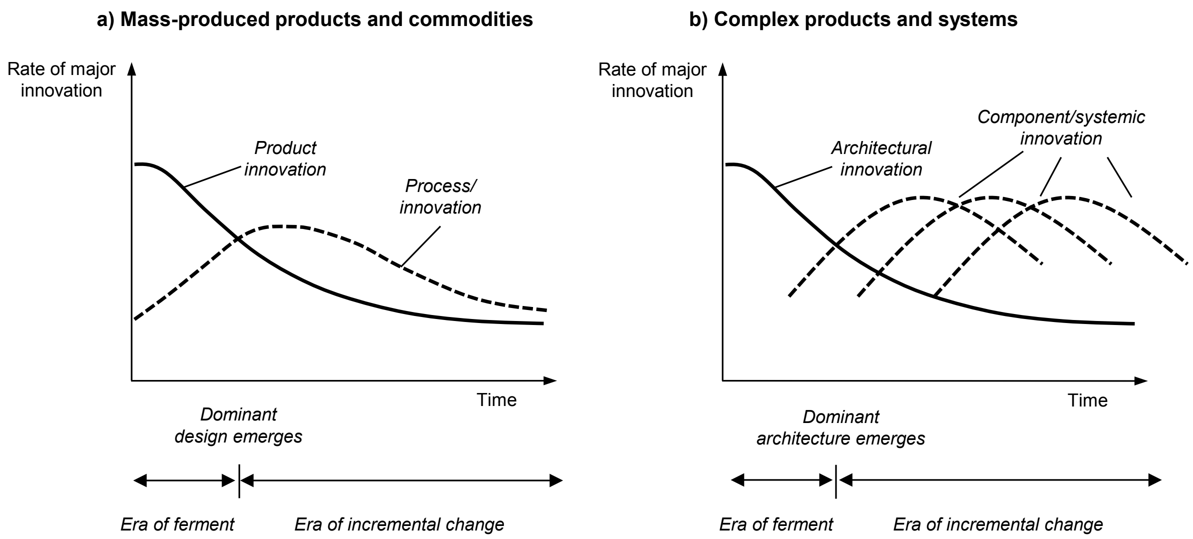

Figure 1: Two contrasting models of innovation over the technology life-cycle: a) mass-produced goods; b) complex products and systems [30,31].

	Era of ferment	Era of incremental change	
		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

Table 1: Characteristics of the innovation and production processes in the two alternative models of the technology life-cycle [30,31].

The A-U model has been extremely influential[1], but several studies note that the model is valid only for a subset of technologies [e.g., 31,32]. 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 [22,33,34]. These *complex products and systems* never reach a phase of process innovation and

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[1] The two seminal works [16,17] had a total of 6,544 Google Scholar citations between them on 12/6/2014.

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) [31,35,36].

Based on this evidence, Davies [31] 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 Figure 1b) [31,36]. 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 [21].[2] Over time, innovations in sub-systems and components can create performance imbalances that require changes in other parts of the system [37,38], in which case Davies refers to them as *'systemic innovations'* (see Figure 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 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* [39]. 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 [e.g., 29]. This is in stark

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[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 automatization [38].

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 [e.g., 39].

2.2. Technological Characteristics and Life-Cycle Patterns

How can specific technologies be located in the continuum created by the two described life-cycle models? Davies reduces the many determinants of complexity [e.g., 35] 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 [31].

With respect to the energy sector, these determinants can be further reduced to two underlying technological characteristics. First, innovation in all energy technologies is heavily affected by government policies, e.g., in the form of technology standards, environmental regulations, subsidy schemes and industrial policy [6,7]. Second, for energy technologies, the scale of the production process 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 [40,41].
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 [e.g., 39].

The two characteristics span a technology space in the energy sector, with the two life-cycle models as two extremes (see Figure 2). However, the 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. In the following sections this paper goes on to analyze two technologies with the aim of locating them in the matrix displayed in Figure 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.

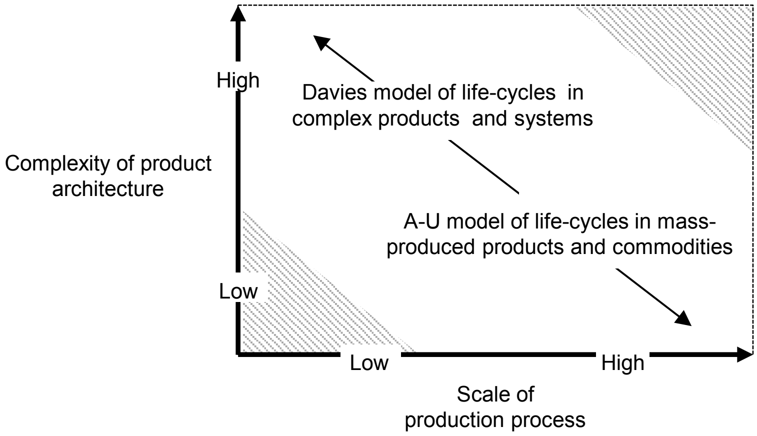


Figure 2: Technology space in the energy sector, spanned by the scale of the production process and the complexity of the product architecture.

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 fulfil 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.

Wind power and solar PV were selected because they fulfill these criteria. They exhibit different degrees of complexity and different scale 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 [21]. 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 [21], 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 Table A 1 and Table A 2 in the appendix, 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 complexity of the product architecture* is significantly higher for wind turbines, while the *scale of the production process* is higher in the case of solar PV. Solar PV systems are modular systems consisting of small generating units – the solar *cells* – interconnected to modules of around 200W and integrated with mounting and tracking structures as well as inverters and control systems, which feed the electricity into the grid (see Table 2). Solar modules have only a few components and no moving parts. 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 is reflected in a very low value of operation and maintenance (O&M) costs, which are often below 1% and rarely exceed 5% [42]. 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 on the order of 1,000 MW per year. Consequently, the market for solar modules exhibits many features of mass-manufactured commodities, even spot markets for cells and modules.

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 and dust in the air, high altitude sites or a very cold climate. The high number of moving key components is reflected in high O&M costs, which make up 20-25 % of the cost of electricity over the lifetime of a wind turbine [43]. 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 moulds and cranes. Overall, a wind turbine production facility has construction costs on the order of USD 20-200 million, depending on annual production capacity, and can produce up to several hundred MW of turbines per year.

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)

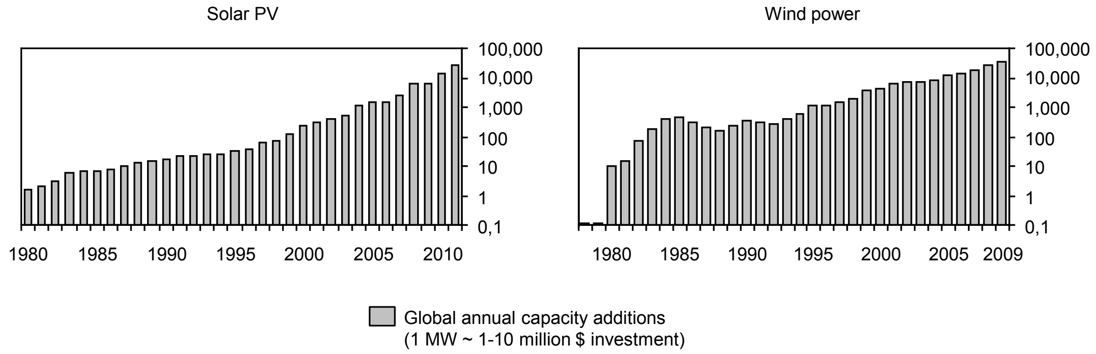
3.2. Dominant Designs and Technological Trajectories in Solar PV and Wind Power

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 and (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 Figure 3a). In 2012, the PV industry recorded sales of around USD 80bn and the wind industry around USD 75bn [44]. 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 Figure 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, Figure 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 [45]. 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).

a) Market growth



b) Design competition

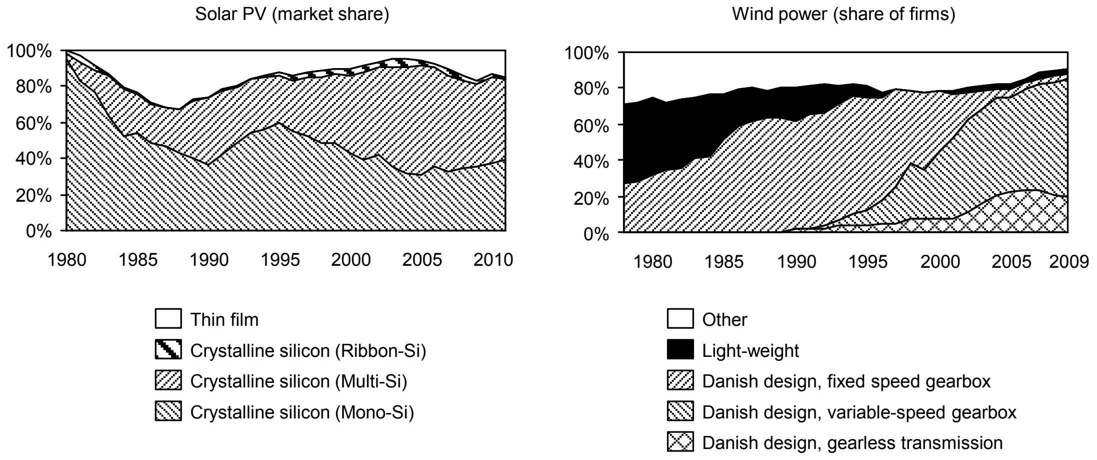


Figure 3: a) Annual installations of wind power systems [46, p. 132] and solar PV systems [47]; b) Design competition in solar PV, as measured by market share of different designs [48], and in wind power, as measured by the share of firms with different designs active in the market [49].[3]

Technological change within the dominant designs has been cumulative and incremental over the last three decades, indicating an era of incremental change.[4] Two prominent indicators of

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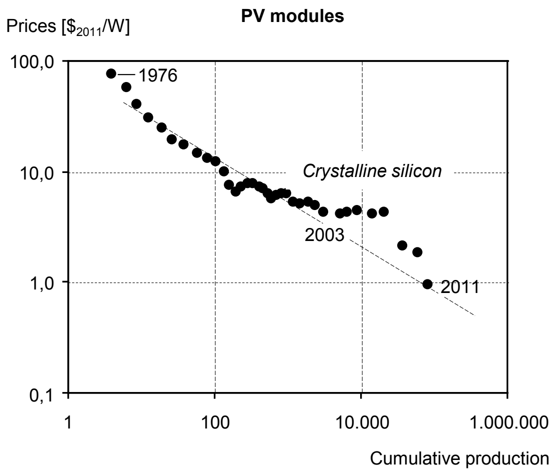
[3] The design data for the wind industry do not track design changes, i.e., in the database firms are assigned the design they entered the industry with. The displayed evolution therefore underestimates the rise of variable-speed turbine models, which was later adopted by many firms who began with the Danish design. (Firms rarely switched between the other designs.)

technological change in electricity technologies are investment cost[5] for new installations (which reflects equipment prices) and efficiency. Both trends are shown in Figure 4 for *crystalline silicon PV modules* and *Danish-design wind turbines*. 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.[6]

a) Investment costs



b) Conversion efficiency

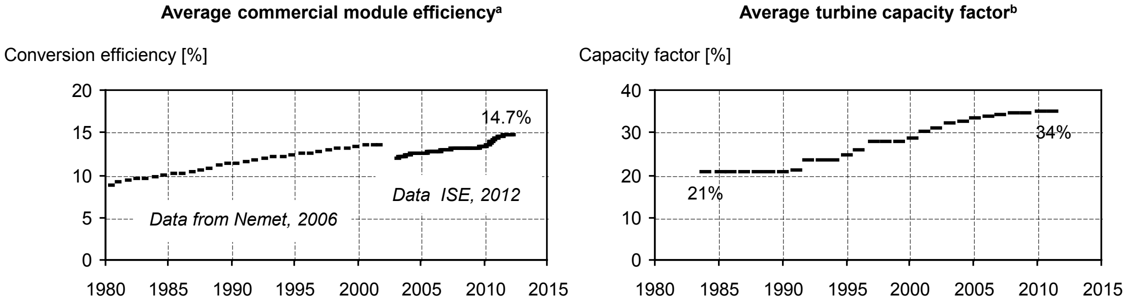


Figure 4: Technological change within the dominant designs in wind power and solar PV: a) Trends in investment cost displayed as 'experience curves,' i.e., logarithmic unit prices over the logarithmic cumulative production [50,51]; the recent plateaus in PV and wind turbine prices do not reflect technological discontinuities; they were mainly driven by imbalances between supply and demand [52,53]; b) Quality indicators commonly used by industry: PV module conversion efficiency [48,54] and wind turbine capacity factors (the ratio of actual power generation to continuous power generation of a wind turbine generator) [50]. The break in the trend for module efficiency is due to different data sources.

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[4] 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 [9].

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

[6] Patent applications grew exponentially in both technologies since the early 1990s and now stand at several thousand per year (see Figure 5 below). This surge in patenting is consistent with typical patterns in the era of incremental change [22,33].

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 wind power and solar PV. Patents have been used extensively to study trends in innovation in technological systems, in part because they are readily available as large empirical datasets [55,56]. 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 [57]. Therefore, researchers have long been searching for ways to identify valuable patents, which can then be analyzed in more detail [58,59].

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 [26–28,60–62]. 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 [63]. 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 [27,64]. 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 [26,65,66]. 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 [67]. 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 [e.g., 69,70].

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 (section 4.3). *Third*, we group the top 1,500 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.[7] The patent data was 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 [67]. First, we compiled a list of relevant keywords extracted from the innovation literature.[8] Then we iteratively curtailed the keyword list by applying it 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 manually checking random samples for irrelevant patents.[9] 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 wind power and solar PV, respectively.[10] 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 [67]. Therefore, after retrieving the citation data of all patents (see below), we extended the database in a second iteration to include those 1,000 outside patents that received the most citations from the patents in the database.[11]

The citation data were extracted from the DWPI and Thompson Innovation databases, which together cover most of the patent offices' data. We cleaned the citation data from duplicate citations

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

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

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

[10] To test for false positives, we randomly tested a total of about 1,000 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.

[11] 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 sub-systems, such as inverters, generators, transformers, etc.

between different patents in the patent families and excluded circular references.[12] 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 [67]. Therefore, in order to avoid a bias towards older patents, we discarded all citations with a lag between filings of citing and cited patents of more than five years [e.g., 70,71]. 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[13] (55,687 linkages with a lag ≤5 years) and 8,907 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. Figure 5 shows how patents and citations are distributed over time.[14]

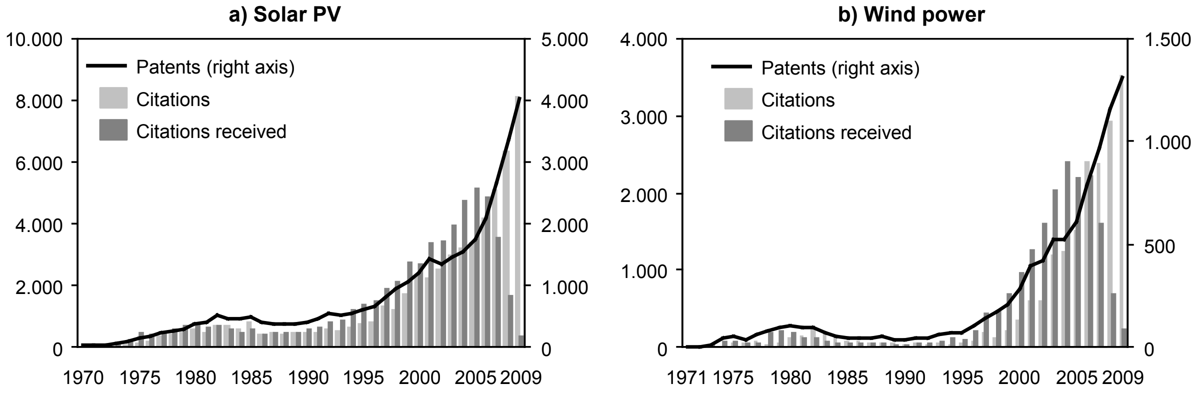

Figure 5: Descriptive statistics for patent filings filed citations and received citations over time. Only citations with a lag of ≤ 5 years are included. The trends in patenting are in line with other studies that find a surge in patenting activity in the era of incremental change [22,33].

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 in order to address two aspects of the broader research question: *In step1*, we identified the current 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

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[12] 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.

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

[14] 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.

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 [26,67,72]. 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 8,907 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 [27,61]. We implemented the algorithms using Pajek [73].

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) [66,67,74]. 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) [75]. 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'.

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 Figure 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.

Table 3: Descriptive statistics of patent data.

	A	**B**	**C**	**D**	**E**	**F**
Technology	**Full network (all linkages)**	**Full network (linkages with lag ≤ 5 years)**	**Critical path (linkages with lag ≤ 5 years)**	**80%-weight network (linkages with lag ≤ 5 years)**	**95%-weight network (linkages with lag ≤ 5 years)**	**Sequential critical paths (linkages with lag ≤ 5 years)**
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 (1,063)	915 (2,069)	3 (2) … 35 (53)
Wind power	11,330 (41,268)	8,907 (18,718)	36 (60)	158 (499)	494 (1,827)	4 (3) … 36 (60)

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-F in order to identify the focus of innovation over the technology life-cycle [67].

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

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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).

between the two coders was 87%. In cases of disagreement, the coders reached a consensus after discussing the patent content in detail.[16]

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 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 (incl. 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)

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[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.

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 (Figure 6a and b) allow us to characterize the current stage of the life-cycle, including 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 in PV remains focused on the cell, with only two module patents as exceptions, whereas innovative activity in wind power is spread much more evenly 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 trajectory, in particular the relative emphasis on product and process innovations. As can be seen from the color-coding in Figure 6a, the current innovative activity in solar PV is 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 Figure 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 weight (network E) relate to the production or installation process.[17]

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

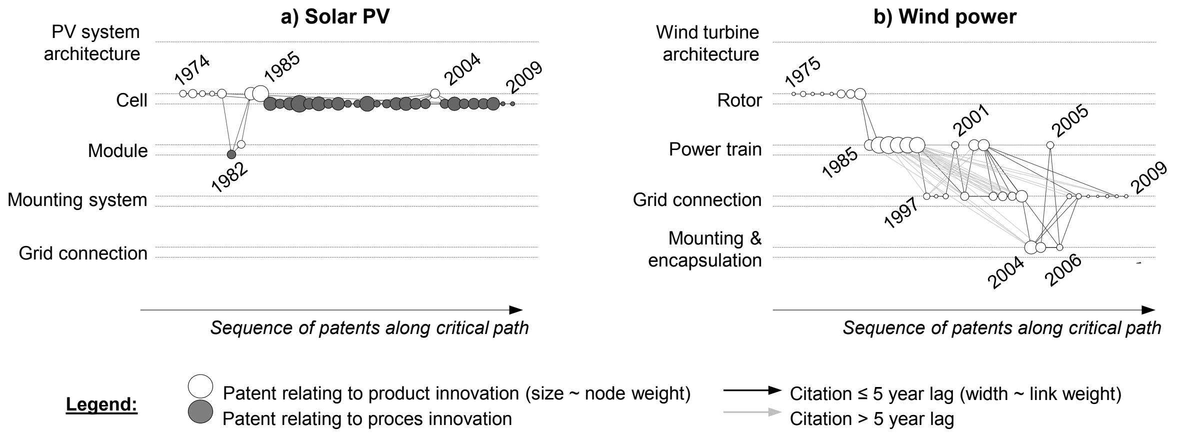

Figure 6: Critical path in full networks (network C in Table 3) showing the currently dominant trajectory of innovative activity. Citations with a lag of more than 5 years were not included in the connectivity analysis but are nonetheless shown in Figure 6 to illustrate the multitude of linkages between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

The patterns observed in Figure 6 allow us to draw conclusions about the innovation process in the 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 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. Figure 7a and b show 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 Figure 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 Figure 8b. Systemic patents are defined here as patents that received more than half of their citations from patents in other sub-systems.[18] Their share increased from 25% in 1975-1979 to 63% in 1990-94 and 58% in 2005-09. This, again, illustrates the systemic nature of innovation in wind power, as do the patterns of citations seen in Figure 6b.

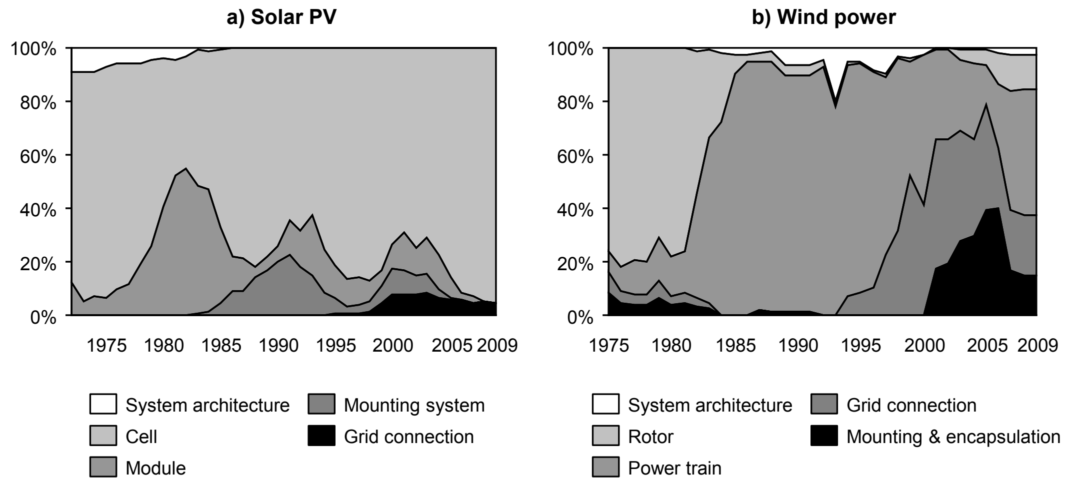

Figure 7: Share of innovative activity in different parts of the technological system (based on patent-content categorization of 95%-weight networks D, which are shown as graphs in Figure A1 in the appendix).

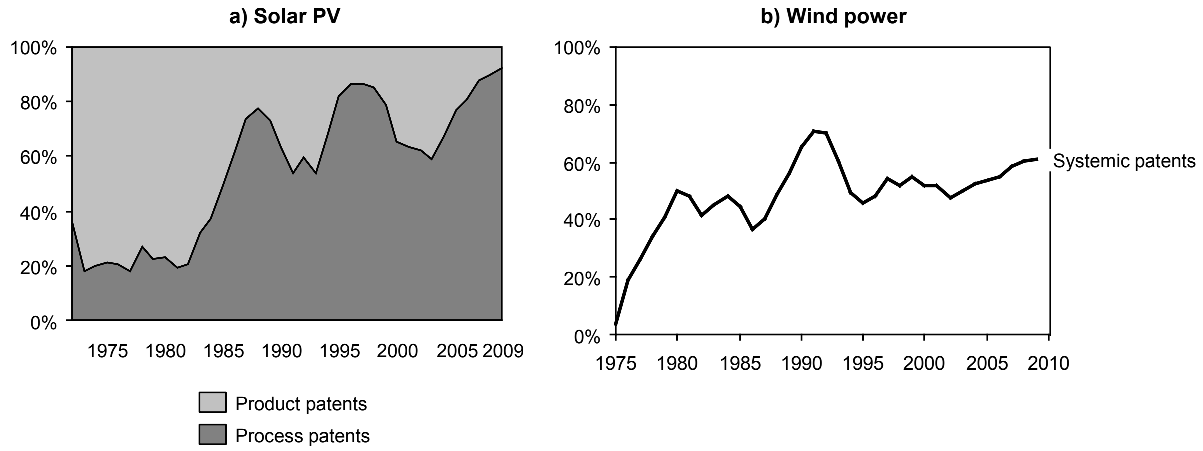

Figure 8: a) Shift from product to process innovation along life-cycle in solar PV, b) Share of 'systemic patents' in wind power over time, defined as patents that received more (>50%) citations from patents in other sub-systems than from their 'own' sub-system. Both graphs based on patent-content categorization of 95%-weight networks D, which are shown as full graphs in Figure A1 in the appendix.

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

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

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 Figure 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 [67]. 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 Figure 3 as well as qualitative accounts of the emergence of dominant designs in the two technologies [76,70,77].

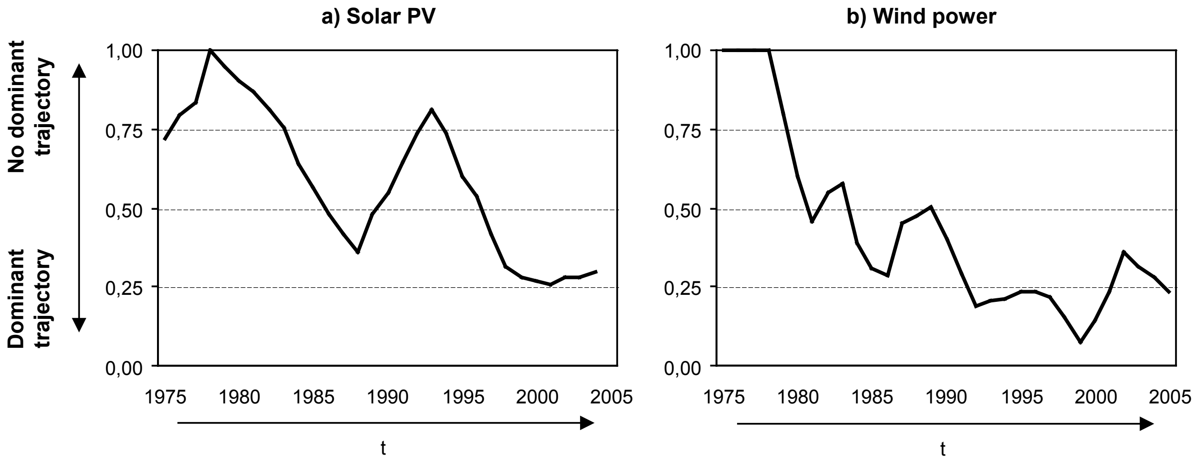

Figure 9: Hazard rates of patents on the critical path, indicating share of patent that is still on critical path after five years of new patent filings have been added to the network.

The second set of more detailed observations is contained in Figure 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 a different shade of grey, 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*, Figure 10 allows one to analyze how the overall focus of innovative activity in the two technologies evolved in 'real time.' Unlike in Figure 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, Figure 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 Figure 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 Figure 6. In wind power, Figure 10 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, Figure 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 Figure 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

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[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 Figure 10.

[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., [90]. 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].

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 Figures 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 Figure 6b.

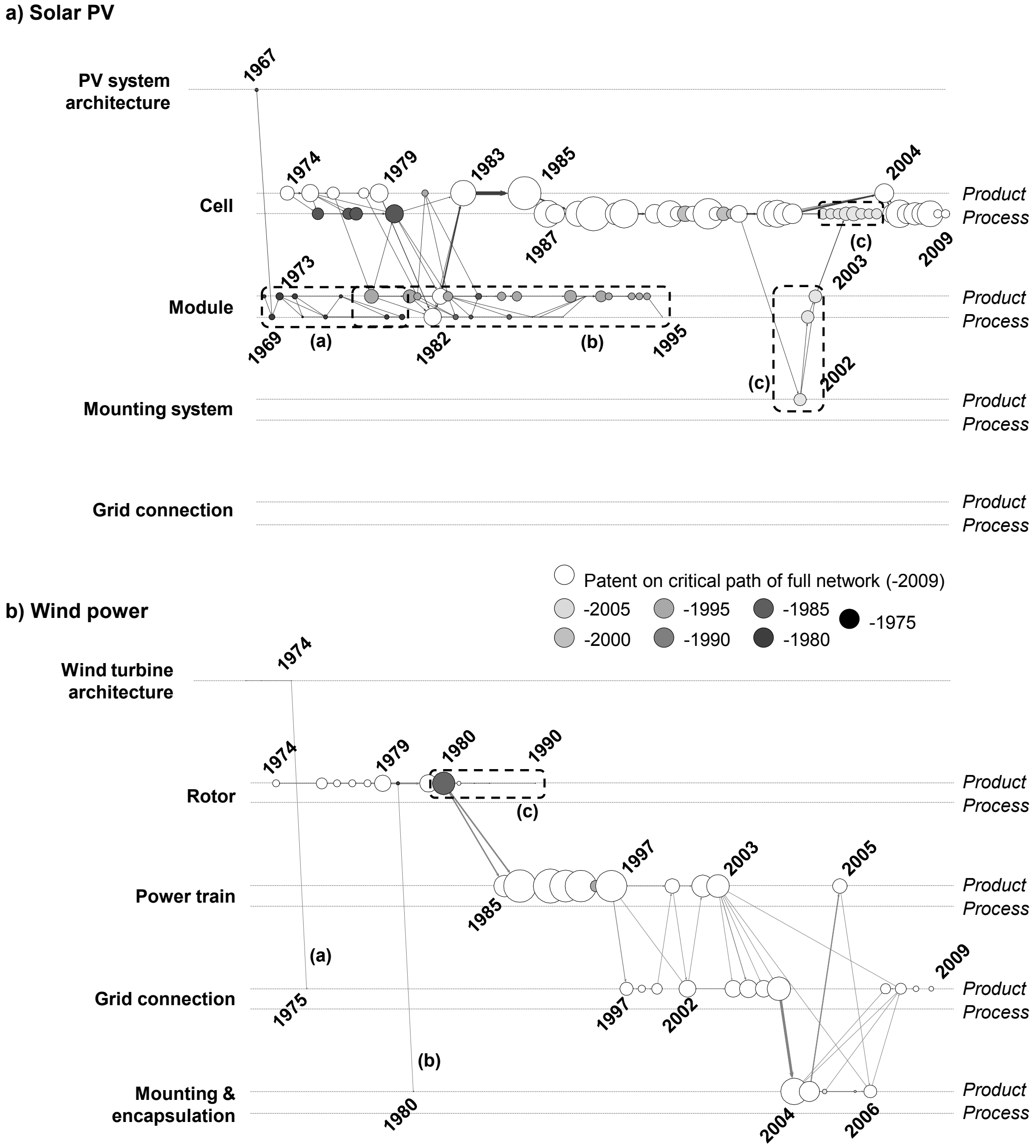

Figure 10: Networks for solar PV and wind power which combine patents from the 8 critical paths of networks N_{1975}, N_{1980}, N_{1985} … N_{2009} to illustrate competing trajectories and emergence of currently dominant trajectory. The color of each patent (node) indicates the year of the last critical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

Table 6: Technological details on the abandoned trajectories in solar PV and wind power visible in Figure 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, 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 Figure 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., Figure 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 is now standard throughout the industry.

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 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, as discussed in section 6.1. The different innovation and learning processes imply the need to tailor technology policy to technological characteristics (6.2). The findings further help conceptualize previously inconclusive evidence about the impact of technology policies in the past (6.3).

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. Figure 17 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 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 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.

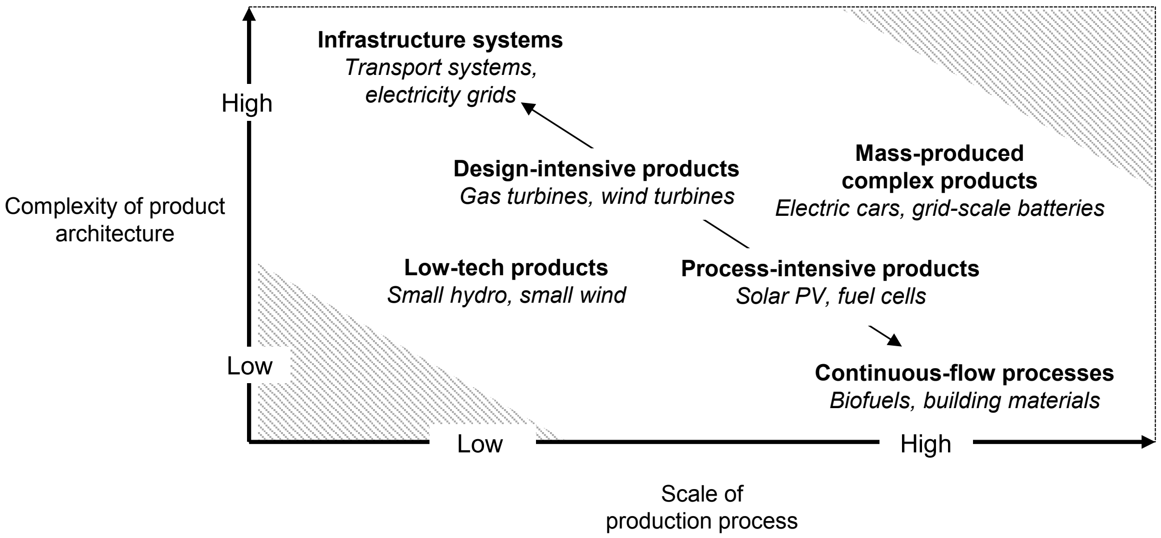

Figure 11: Stylized classification of different energy technologies according to scale of production process and complexity of product architecture.

6.2. Implications for Technology Policy

The life-cycle patterns identified in this paper point toward very different sources of relevant experience and potentials for innovation in the two analyzed technologies and the energy technology space in general. This section explores the implications of these differences for technology policy. A particular focus is on the design of so-called 'deployment policies,' because in recent years, rather than focusing purely on public investment in R&D, many countries have provided public resources for the deployment of relatively mature clean technologies in order to induce innovations and 'buy-down' cost [78,79]. Much of the policy debate on the function of such 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. [22] However, our analysis shows that the energy sector comprises technologies that do not conform to this model of the technology life-cycle.

The two contrasting models of the technology life-cycle discussed in section 2.1 suggest that technological trajectories in the energy sector differ in three respects that affect the role of deployment – and thus, the potential role of deployment policies – in the innovation process in later stages of the technology life-cycle. *First*, economies of scale in manufacturing, and thus *the absolute*

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[22] For example, the German feed-in tariff for solar power (a form of subsidized electricity tariff), which with about USD 10bn 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" [92]. 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" [93].

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. 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 [e.g., 80]. 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.

These three characteristics can serve as guideposts for technology policies that aim to make use of deployment to stimulate innovation (see Figure 12 and Table 7). 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. 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 [7]: 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).

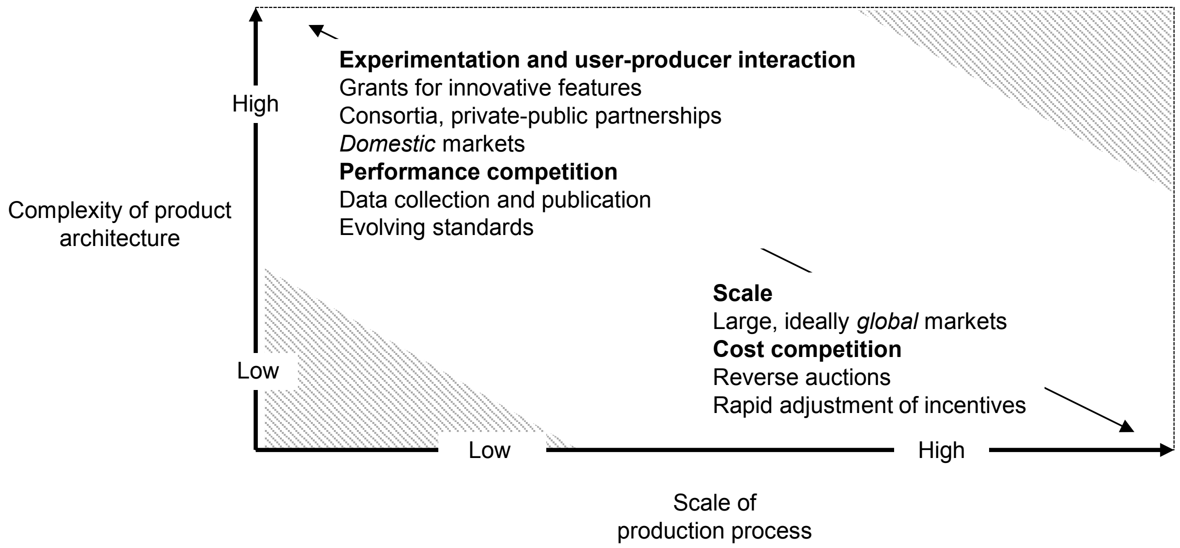

Figure 12: Characteristics of deployment policies if tailored to the characteristics of the two life-cycle models.

	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

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

6.3. Reconciling Empirical Evidence

Our analysis provides quantitative evidence for systematic differences between solar PV and wind power. This evidence helps reconcile two areas of conflicting evidence about the impact of technology 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 [54,70,81]. 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 [10,81] and cost reductions through economies of scale [54]. In wind power, by contrast, experience generated in government-supported markets was a key driver of product innovation [82]. However, a very large market alone was not sufficient to stimulate innovation in wind turbines, as experience with the early US wind policies suggests [70]. 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 [83,84].

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 technology life-cycle patterns revealed in this study suggest 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. 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 [85,86], research on solar PV has found such a relationship between domestic markets on and innovation and firm competitiveness only in the early years of the industry [87,88]. Comparing the evidence between the two cases, Barua et al. [89, p. 2-3] 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."[23]

6.4. 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*, using patents as indicators for innovation introduces a bias against process innovations. Since much of the relevant information is to be revealed anyway, a product innovation is more likely to be patented than a process innovation, which inventors may appropriate by other means, most notably secrecy. 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. This makes careful interpretation of the results necessary. However, because this bias 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

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[23] 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 protectionist actions by governments [89]. 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 [e.g., 90].

patterns. *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 Figure 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 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 sub-system 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.

Differing roles of large-scale deployment in the innovation process imply different, technology-specific policy instrument designs. These stand in contrast to 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 uniform mandates for *all* kinds of alternative vehicle drive-trains. For *mass-produced goods*, such as solar cells, biofuels, LEDs, batteries or fuel cells, large, ideally internationally coordinated markets are needed to enable the necessary economies of scale and the learning-by-doing in production – a small market, even if supported over a long time frame, will not overcome the 'chicken-and-egg' problem of low production volumes and high production costs. For *complex products and systems*, such as wind turbines, geothermal systems, nuclear power plants, and transport systems, deployment policies have to go beyond simply subsidizing more-of-the-same in order to fully realize their potential innovation impact. For these technologies, deployment policies should take the form of 'performance-driven niche markets,' because these policies are most useful if they generate valuable experience from learning-by-using and can enable user-producer interaction, not if they only enable economies of scale and learning-by-doing.

In conclusion, 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.

Acknowledgements

Previous versions of this paper have been presented at the School of Science and Technology Policy at KAIST, South Korea, the Energy Policy Consortium Seminar at Harvard University, USA, the ECN/ETH Zurich side event at UNFCCC COP 18 in Doha, Qatar, the International Sustainability Transitions 2012 conference in Copenhagen, Denmark, and the International Schumpeter Society Conference 2012 in Brisbane, Australia. We are grateful for the feedback received from the conference and workshop participants. All errors remain our own.

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Appendix

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

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 grey).

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

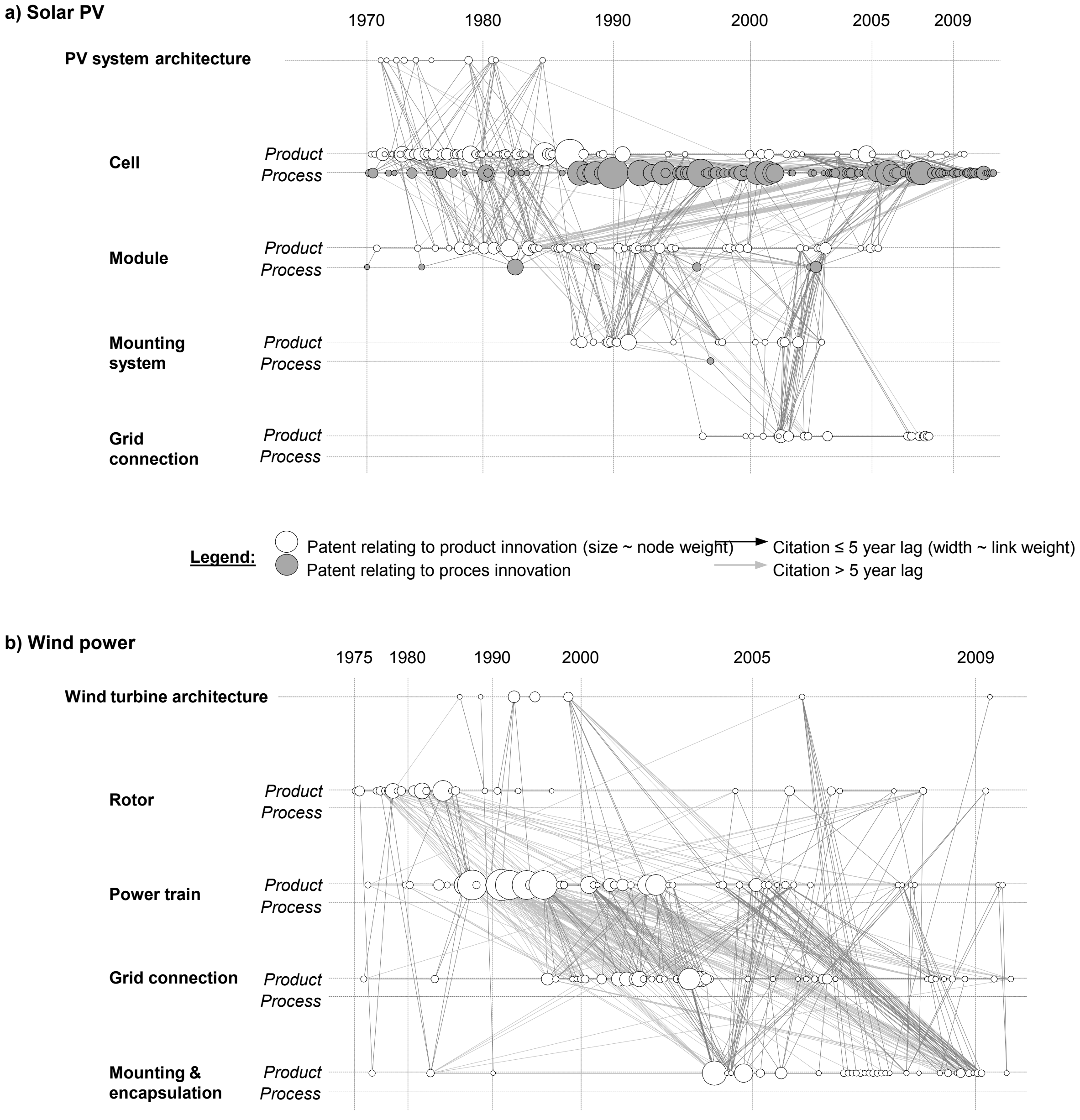

Figure A 1: Patents in 80%-weight network (full networks D in Table 4) ordered by time of patent filing and their focus in the technological system; linkages indicate citations.