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# How a product's design hierarchy shapes the evolution of technological knowledge—Evidence from patent-citation networks in wind power

Joern Huenteler[a,b,*,1], Jan Ossenbrink[a], Tobias S. Schmidt[c], Volker H. Hoffmann[a]

[a] Department of Management, Technology and Economics, ETH Zurich, Switzerland
[b] Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, USA
[c] Department of Humanities, Social and Political Sciences, ETH Zurich, Switzerland

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## ABSTRACT

We analyze how a product's design hierarchy shapes the focus of inventive activity and the expansion of the underlying body of knowledge, building on the complex-system perspective on technological evolution. This perspective suggests that the design hierarchy of a product can have an ordering effect on the evolution of commercialized artifacts, in particular when product design decisions on high levels of the design hierarchy set the agenda for subsequent variation and experimentation on lower levels. We extend this literature by analyzing the design hierarchy's effect on the evolution of the industry's knowledge base, using the case of wind turbine technology over the period 1973–2009. We assess the technological focus of patents along the core trajectory of knowledge generation, identified through a patent-citation network analysis, and link it to a classification of technological problems into different levels in the design hierarchy. Our analysis suggests that the evolution of an industry's knowledge base along a technological trajectory is not a unidirectional process of gradual refinement: the focus of knowledge generation shifts over time between different sub-systems in a highly sequential pattern, whose order is strongly influenced by the design hierarchy. Each of these shifts initiates the integration of new domains of industry-external knowledge into the knowledge base, thus opening windows of competitive opportunity for potential entrants with strong knowledge positions in the new focus of inventive activity. We discuss implications for the understanding of the competitive advantage of specific knowledge positions of firms and nations and technology policy for emerging technologies.

## 1. Introduction

High-technology capital goods, such as cars, power plants, and manufacturing equipment, are a key entry channel for new technology into the economy (Rosenberg, 1963). Some consider them the 'frontier' of the economic development of nations (Hidalgo et al., 2007). They also underpin those sectors – manufacturing, energy, trade, and transport – that are at the heart of the world's environmental challenges. Technological change in such products often takes the form of long periods of incremental innovations along established technological trajectories, interrupted only by the emergence of new technological paradigms (Clark, 1985; Constant, 1973; Dosi, 1982; Frenken, 2006). Understanding the factors that shape the 'natural' trajectories of technological evolution in high-technology capital goods is therefore critical for business strategy as well as economic and environmental policy (Acha et al., 2004; Davies and Hobday, 2005; Nelson and Winter, 1977).

A number of qualitative studies emphasize the 'guiding' influence of the technology-inherent hierarchy of design decisions – or *design hierarchy* – on the focus of innovative activity along technological trajectories (e.g., Hughes, 1983; Clark, 1985; Vincenti, 1990). In particular, evidence suggests that industry-wide movement *along* a common technological trajectory is associated with movement *down* the design hierarchy, in two principal ways: First, after a new trajectory has emerged, decisions about the overall product design often 'set the agenda' for subsequent change in sub-systems and individual components (Clark, 1985; Murmann and Frenken, 2006; Murmann and Tushman, 2002). Second, changes in sub-systems that perform the core functions of the product tend to

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[*] Corresponding author at: Littauer 331A, 79 John F. Kennedy Street, Mailbox 53, Cambridge, MA 02138, USA.
*E-mail addresses:* jhuenteler@worldbank.org, joern_huenteler@hks.harvard.edu (J. Huenteler).

[1] Present address: 701 18th St NW, J6-006, Washington DC 20433, USA.

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precede changes in more peripheral sub-systems (Abernathy and Clark, 1985; Lee and Berente, 2013; Murmann and Frenken, 2006).

The movement along technological trajectories and down the design hierarchy implies change in the universe of commercialized designs – i.e., *evolution in the space of artifacts* – and in the underlying technological understanding and engineering heuristics—i.e., *evolution in the space of knowledge* (Dosi, 1982; Martinelli, 2012). The knowledge and artifact spaces are inextricably linked, as knowledge is embodied in artifacts, and the manufacturing and use of artifacts generates new knowledge (Rosenberg, 1982). But they are far from congruent: significant leaps in the design of artifacts may be the result of incremental gains of knowledge, and seemingly small changes in artifacts may require large changes in the underlying knowledge base (Funk, 2009; Martinelli, 2012). Despite the differences between evolutions in the two spaces, quantitative work on the guiding influence of the design hierarchy on technological trajectories has focused primarily on innovation and the evolution of artifacts (e.g, Saviotti and Trickett, 1992; Frenken et al., 1999; Frenken, 2006; Castaldi et al., 2009; Mendonça, 2012). With few exceptions (Lee and Berente, 2013; Rosenkopf and Nerkar, 1999), the influence of the design hierarchy on invention and the evolution of knowledge has received little attention.

To address this gap, we analyze how a product's design hierarchy influences the trajectory of knowledge generation. We do so in order to investigate the prevalent assumption that the development of an industry's knowledge base along the trajectory is predominantly a process of incremental growth and refinement, without abrupt shifts in the focus of inventive activity and changes in the importance and composition of industry-external knowledge. This assumption has shaped the innovation literature in two important ways. In particular, it is commonly assumed that movement down the design hierarchy leads to *the entrenchment of existing knowledge positions,* thus enhancing the competitive advantage of incumbent firms and nations through incremental knowledge growth and refinement. In contrast, movement up the hierarchy – through the creation of new trajectories – is associated with novel skills and expertise, thus opening windows of opportunity for new entrants (Abernathy and Clark, 1985; Bekkers and Martinelli, 2012; Henderson and Clark, 1990). A better understanding of how an industry's knowledge base evolves along the trajectory can thus contribute to improved managerial and policy decisions.

In analyzing how a product's design hierarchy influences the trajectory of knowledge generation, this paper links two streams of literature: research on dominant designs and technological evolution in systemic artifacts on the one hand (e.g., Frenken and Nuvolari, 2004; Murmann and Frenken, 2006; Mendonça, 2012) and research on trajectories of knowledge generation on the other hand (e.g., Fontana et al., 2009; Barberá-Tomás et al., 2011; Epicoco, 2013). In particular, we develop a novel methodology that combines the manual, *categorical analysis of commercialized designs*, as employed in studies of dominant designs and technological evolution in systemic artifacts, with *patent-citation network analysis,* as employed in the literature on knowledge trajectories. This methodology allows us to bridge the artifact and knowledge dimensions by studying the influence of the design hierarchy, which derives from relationships between elements of the physical artifact, on the trajectory of knowledge generation in the industry. We apply this novel methodology to the case of wind turbine technology in the period 1973–2009.

The paper makes several distinct contributions to theory and methodology. *Theoretically*, we contribute to the literature on knowledge positions and competitive advantage (Bekkers and Martinelli, 2012; Choi and Anadón, 2014; Epicoco, 2013). Our findings suggest that the evolution of an industry's knowledge base along the technological trajectory is not a unidirectional process of gradual refinement but a sequential process that is structured by the design hierarchy: the focus of knowledge generation shifts over time between different sub-systems, with each shift initiating the integration of new domains of industry-external knowledge into the knowledge base—a pattern we call *creative sequences. Methodologically*, our analysis contributes to recent efforts to identify linkages and linking mechanisms between the evolution of knowledge and the evolution of artifacts (Bakker et al., 2012; Barberá-Tomás et al., 2011; Ethiraj, 2007; Martinelli, 2012). We extend the methodology developed by Verspagen (2007) and others to study the knowledge and the artifact dimensions of technological trajectories in an integrated way, which may facilitate a deeper understanding of the interaction between the two domains.

In the following, Section 2 lays out the paper's theoretical perspective and reviews the literature on technological evolution in systemic artifacts. Section 3 introduces the case of wind turbine technology and Section 4 presents the data sources and methodology. The results are presented in Section 5 and discussed in Section 6. Conclusions are summarized in Section 7.

## 2. Theoretical perspective

We use the word "technology" in the tradition of the literature on technological trajectories (e.g., Barberá-Tomás et al., 2011; Bekkers and Martinelli, 2012), to encompass physical artifacts (we focus on commercialized product designs in particular) as well as the underlying technological knowledge (i.e., the engineering practices, rules, heuristics, and formalized pieces of knowledge), not all of which is embodied in the physical artifacts. In line with the empirical literature on technological trajectories, in this paper we approximate knowledge with patented inventions and artifacts with commercialized product designs.

Technological products are conceptualized in this paper as *complex, systemic artifacts* (Murmann and Frenken, 2006; Saviotti, 1986; Tushman and Rosenkopf, 1992), consisting of interdependent subsystems and components that jointly enable the system to perform a number of functions, or *service characteristics*. The sub-systems and components are organized by a *product architecture,* which allocates system functions to the individual components and defines the interfaces between them (Baldwin et al., 2014; Clark, 1985; Simon, 1962).

Technological evolution in high-technology capital goods is understood as proceeding predominantly along technological trajectories through refinement within, and extension of, existing product architectures, interrupted from time to time by fundamental (or 'paradigmatic') changes in the product architecture (Constant, 1973; Dosi, 1982; Frenken, 2006). When discussing the influence of the design hierarchy on technological evolution in the following subsections, we are concerned with the design hierarchy's impact on the *focus of incremental innovative activity along technological trajectories* and *the direction of evolution* in the spaces of knowledge and artifacts.

### 2.1. The sequential pattern of innovation in systemic artifacts

Historians of technology have long noted the existence of sequential patterns of innovation in the evolution of technological artifacts (Constant, 1980; Hughes, 1983; Rosenberg, 1969; Vincenti, 1990). In this context, *sequential* means that technological progress is concentrated in only a small fraction of a product's components and possible directions of change, and that the focus of this concentration shifts over time between technological problems. The observed sequential pattern also implies that the focus of innovative activity is at least partly *collective,* in the sense that it can be observed on the level of communities of practitioners rather than individual problem-solvers or firms.

Langes (1969) observed that since the industrial revolution, innovations in technological systems have followed a challenge-response pattern in which technological breakthroughs *call forth* further, complementary innovations. He described for instance how Kay's flying shuttle (1733), which allowed the development of automatic looms, was followed by rapid development of new spinning devices from the 1750s to the 1770s that supplied yarn more rapidly (Langes, 1969 Langes, 1969; p. 84).[2] More generally, several studies have observed that the focus of innovative activity is often on those elements that keep other parts of the system from exploiting their full performance potential, and that new bottlenecks can arise in related components once such performance bottlenecks are resolved (Dedehayir and Mäkinen, 2011; Ethiraj, 2007; Hughes, 1992, 1983; Sahal, 1985). Rosenberg (1969, p. 111) used the term *compulsive sequences* to describe this self-generating, sequential nature of problem-solving in systemic artifacts.

### 2.2. The influence of the design hierarchy on the evolution of artifacts

While many had observed the sequential nature of technological change, Clark (1985) first described in detail what determines the focus of innovative activity among the elements of a systemic artifact and how it changes over time. The sequence of innovations in the automotive and semiconductor sectors in their early decades, he argued, can be understood as the outcome of two factors: the hierarchical organization of design decisions rooted in the product's architecture and the gradual refinement of consumer preferences. These two factors can be understood as the supply side (i.e., technology-driven or 'technology-push') and demand side (demand-driven or 'demand-pull') influences that jointly determine the sequence of technological changes in the industry. Murmann and Frenken (2006) integrated these two influencing factors into one model that applies a complex-system perspective on innovation in technological products, and uses the term *design hierarchy* to capture the joint effect of technology-push and demand-pull influences on the *trajectory of technological evolution* in systemic artifacts.

The design hierarchy locates each element in the system in two hierarchies (see Fig. 1): the *hierarchy of nested parts*, which locates the element in the hierarchy of systems, sub-systems, components, sub-components, and so on defined by the product architecture; and the *hierarchy of control*, which orders the elements on each level of the hierarchy of nested parts according to their relative importance for the demanded *service characteristics*—i.e., the principal categories of variables that underpin consumer choices, such as the speed, cost, noise, and visual appearance of a car.

How the hierarchy of control and the hierarchy of nested parts relate to the product architecture and service characteristics is shown in Fig. 2. The Figure further shows how technology-inherent (the product architecture) and demand-driven (service characteristics) factors *jointly affect* the direction of change in the evolution of artifacts and the evolution of knowledge, and are in turn affected by feedback from knowledge generated from the manufacture and use of novel artifacts on the product architecture and the service characteristics.

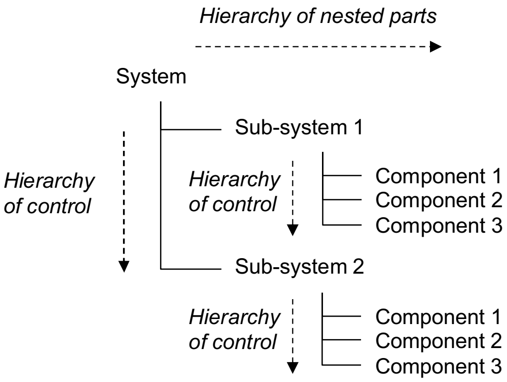

**Fig. 1.** Two dimensions of the design hierarchy of systemic artifacts: the hierarchy of nested parts and the hierarchy of control.

The hierarchy of nested parts reflects the *product architecture* (arrow a in Fig. 2) (Murmann and Tushman, 2002). It captures the tendency of the focus of innovative activity to shift over time from the system-level to sub-systems and components – i.e., from the general to the specific – as certain high-level design decisions set the agenda for incremental problem-solving efforts on lower levels. These high-level design decisions have been referred to in the literature as technological paradigms (Constant, 1973; Dosi, 1982), dominant designs (Utterback and Abernathy, 1975; Anderson and Tushman, 1990), or technological guideposts (Sahal, 1985). For instance, design decisions in the combustion chamber component of a piston-driven internal combustion engine have to build on (and thus succeed) system-level design decisions on the type of energy conversion (internal or external combustion) and energy transmission (piston or rotary internal combustion engines).[3]

The hierarchy of control reflects the *interplay between the product architecture and the service characteristics* (arrows $b_1$ and $b_2$ in Fig. 2). It captures the effect whereby even within sub-systems and within components, some design decisions are more important than others and therefore have a *controlling* influence on them. In particular, when a new trajectory emerges, innovative activity first tends to focus on 'core' sub-systems and components that are most relevant to the service characteristics of a product. Later it shifts toward more 'peripheral' elements that facilitate the adaptation of certain service characteristics to newly emerging market segments (Clark, 1985; Frenken et al., 1999; Lancaster, 1979; Saviotti, 1996; Teubal, 1979). The focus of innovative activity in the early years of the automobile industry, for example, moved over time from the engine and the steering device to the transmission system, the chassis, and other parts of the system, because this was the order of precedence of perceived consumer demand for innovation in these components (Clark, 1985).

The Murmann–Frenken model predicts that the hierarchy of control and the hierarchy of nested parts jointly affect the evolution of artifacts (arrow c in Fig. 2). The (primarily technology-driven) product architecture defines the landscape of technological problems, while the (demand-driven) set of service characteristics determines (together with the product architecture) which problems are perceived as most pressing by the industry and therefore tackled first. The model thus integrates technology-push and demand-pull perspectives on design decisions and on the broader trajectory of knowledge generation, and conceptualizes the relationship between the two as complex and non-linear.

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[2] To explain the challenge-response pattern, some economists have invoked induced changes in the relative prices of component technologies or input factors, e.g. the price of yarn in Kay's flying shuttle (Hayami and Ruttan, 1973). Yet, many others have pointed out that as long as the cost of R&D is uncertain, a change in relative factor prices by itself cannot explain the highly selective focus of innovative activity in technological systems (Dosi, 1982; Mowery and Rosenberg, 1979; Rosenberg, 1969).

[3] In evolutionary theory, this effect is referred to as *downward causation* (Campbell, 1990; Rosenkopf and Nerkar, 1999).

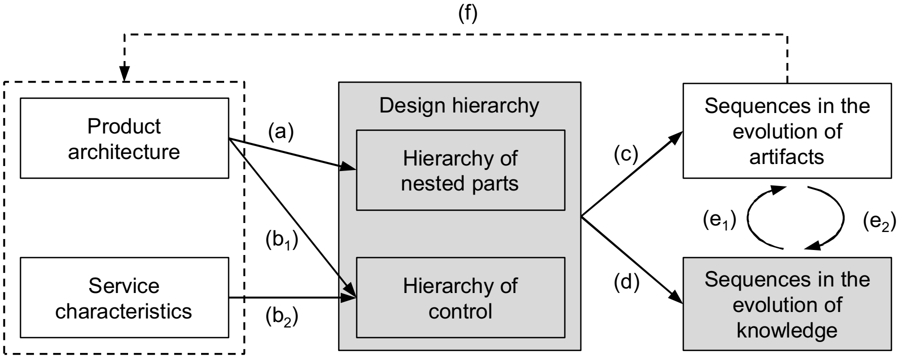

**Fig. 2.** A framework to study the influence of the design hierarchy on sequences in the evolution of artifacts and the evolution of knowledge (the focus of the analysis presented in this paper is marked in grey).

In the long-run, incremental innovations along the trajectory can, endogenously, give rise to new technological paradigms and new trajectories, if innovations and their diffusion in the market alter demanded service characteristics (Levinthal, 1998) or create opportunities to change the prevailing product architecture (Henderson and Clark, 1990). These long-run dynamics, marked by arrow f in Fig. 2, are outside the scope of this paper, but have been studied extensively elsewhere (e.g., Funk, 2009).

### 2.3. *The influence of the design hierarchy on the evolution of knowledge*

Innovation is a process that links the knowledge and artifact dimensions of technological trajectories (arrows $e_1$ and $e_2$ in Fig. 2). However, the literature on the influence of the design hierarchy on technological evolution has treated the underlying body of knowledge mostly as a black box. Below we analyze how the design hierarchy affects the evolution of the knowledge base of an industry (arrow c in Fig. 2)—and thus the value of different knowledge positions relative to the core of the trajectory. In particular, we aim to explore whether the Murmann–Frenken model is useful also in conceptualizing how the focus of *knowledge* generation changes over time as an industry moves along a technological trajectory. In this process, does the trajectory of knowledge move from the general to the specific, and from the core to the periphery?

Recent studies provide fragmented evidence that the trajectory of knowledge evolution does reflect the design hierarchy. On a general level, Martinelli (2012) shows that different 'generations' of technological artifacts are reflected in the evolution of knowledge trajectories. Within one trajectory, Ethiraj (2007) demonstrates that bottlenecks in the artifact affect the allocation of R&D efforts across the computer industry, and Lee and Berente (2013) use the example of particle filters to show that patenting outside the core component increases once a dominant design for the core component is reached. Lastly, Fontana et al. (2009) briefly mention that the knowledge trajectory of the telecommunication network industry points to an 'engineering logic' – which can be interpreted as design hierarchy – governing the sequence of patented inventions, although they do not assess this influence systematically.

However, the trajectory of knowledge generation in an industry may differ from the evolution of commercialized artifacts in three important respects. First, the body of technological knowledge may exceed what is embodied in commercialized products and services, because firms 'know more than they make' (e.g., Brusoni et al., 2001). This means that knowledge generation at any point along the trajectory may not be as focused on specific sub-systems and components as the scope of artifact variation would suggest. Second, firms also make much more than they know, since high-technology capital goods often employ operating principles that are only imperfectly understood (Vincenti, 1990). Third, not all commercialized knowledge is industry-specific, as firms import a significant share of the knowledge embodied in the artifacts they assemble in the form of components from other sectors (Pavitt, 1984). The last two points mean that some changes on the artifact level may not be reflected in the evolution of the underlying knowledge base. For this reason, processes that depend on the knowledge dimension of technological trajectories, such as knowledge-based competitive advantages of firms and nations (Bekkers and Martinelli, 2012; Epicoco, 2013) and the impact of policy-led incentives on the exploration and exploitation of knowledge (Hoppmann et al., 2013; Nemet, 2009), can only be partially explained using data on the evolution of artifacts. These must be complemented by analyses of the knowledge dimension.

## 3. Research case

### 3.1. *Rationale for case selection*

For empirical studies of the impact of design hierarchy on the direction of knowledge generation, the research case should have three specific characteristics.

First, the product needs to be a systemic artifact with a complex product architecture that has multiple levels in the hierarchy of nested parts and several components on each level, which translates into multiple levels in the hierarchy of control. This allows the possible influence of both types of hierarchy. Second, the product should have been produced for as few applications as possible, ideally with relatively stable demanded service characteristics. On the one hand, differences in the demanded service characteristics between applications can lead to the bifurcation of artifact trajectories, making the identification of linkages between knowledge and artifact trajectories difficult. On the other hand, changes in the demanded service characteristics over time can induce changes in the design hierarchy and vice versa (see Section 2.3). Yet in order to allow for the observation of their structuring effect on the production of knowledge, both the service characteristics and the design hierarchy should ideally remain unchanged throughout the observed period. Third, the majority of progress over the observed time period needs to have taken place along one technological trajectory, because the phenomenon we want to observe by definition only applies to this type of technological change. Over time, innovative activity along the technological trajectory should ideally have focused on different parts of the system, enabling the sequence of shifts in the focus of inventions to be compared to the sequence of shifts in the focus of innovations.

We selected the case of wind turbine technology in the period 1973–2009 because it fulfills all three requirements (discussed in detail in Section 3.2–3.4), and because understanding the evolution

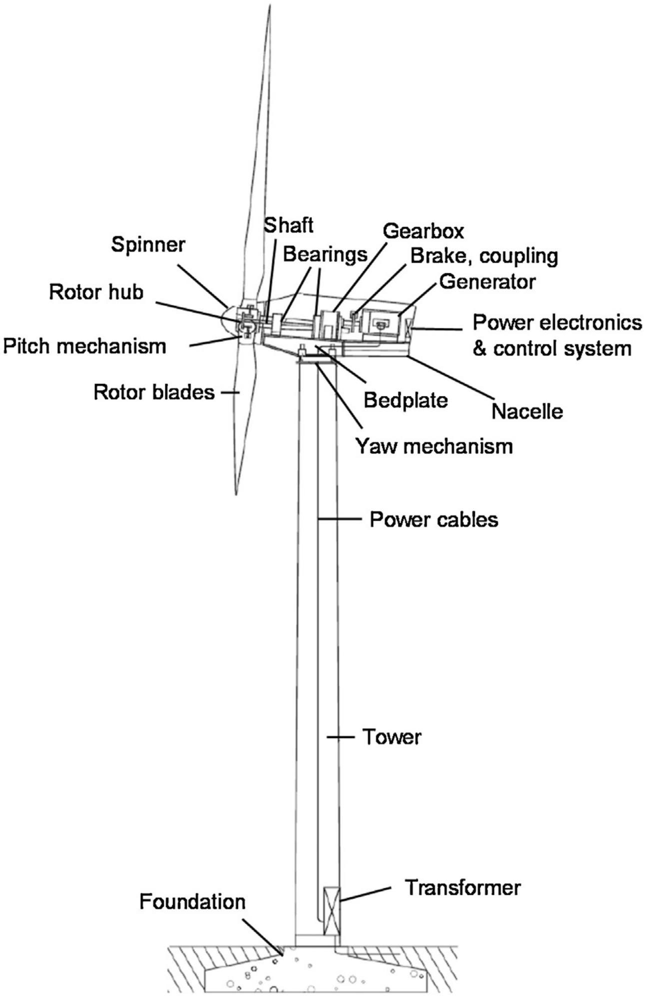

**Fig. 3.** Components of a wind turbine (adapted from Hau, 2013).

of renewable energy technologies such as wind turbines is particularly important for informing public and environmental policy decisions.

### 3.2. Complex product architecture

We use the concept of a shared operational principle to delineate the scope of our research case (Murmann and Frenken, 2006; Vincenti, 1990), and define wind turbine technology as all technologies pertaining to the conversion of wind energy to electricity by means of a rotor, which is driven by wind and drives an electric generator.[4]

Modern wind turbines are large electro-mechanical machines that can reach up to 200 m in size and 8 MW of electric capacity; consist of several thousand components; and cost up to around USD 15 million per unit. The components are organized in a complex product architecture, as can be seen in Table 1 and Fig. 3 (Section 4.2 describes the derivation of this representation of the product architecture). Virtually all wind turbine designs feature a product architecture containing the following four groups of components, which we will refer to as *sub-systems*: (i) a rotor, (ii) a means of converting rotational energy into electrical energy (the power train), (iii) some form of mounting and machine encapsulation (typically the foundation, the tower, and the nacelle), and (iv) some form of grid-connection (or electricity storage unit in the case of off-grid generation). As an illustration of the diversity of engineering challenges and design choices within this common product architecture, Table A1 in the Appendix A summarizes the main engineering tasks involved in wind turbine design (including the main underlying knowledge domains), and Table A2 illustrates the scope of design decisions for each sub-system and most of the components.

This common product architecture has multiple levels of nested parts: each of the four main sub-systems contains components, which are made up of sub-components, and so on. The power train, for example (sub-system ii) contains the mechanical drive-train, which contains a gearbox, which consists of cogwheels, shafts, and a lubrication system, which are all again made up of various smaller parts. And the fact that the product architecture features four sub-systems and three to four components for each sub-system means that the hierarchy of control has multiple levels, too.

### 3.3. Stable service characteristics

Wind turbines have been produced almost exclusively for onshore, grid-connected electricity generation. Of the roughly 198 gigawatt (GW) installed globally by the end of 2010, only 0.4 GW are small wind turbines (<100 kW), which represent most of the off-grid market (WWEA, 2012), and about 3 GW are installed offshore (GWEC, 2011). This dominance of the onshore, grid-connected market over other segments has prevailed throughout 1973–2009. Therefore, the demanded service characteristics can be approximated as relatively stable in the observed period.[5]

### 3.4. Technological change along one trajectory

Technological change in wind turbine technology over the period 1973–2009 has been predominantly characterized by incremental innovations along the trajectory of scaling-up and refining one overarching system design: a horizontal-axis rotor with airfoil-shaped blades that utilize the lift forces of the wind.

Fig. 4a shows how the price of wind turbines per watt of electric capacity has come down gradually as the technology progressed along the trajectory. The incremental nature of technological change is also visible in Fig. 4b, which shows how the average rotor diameter, turbine capacity, and hub height have all increased gradually since 1980.

Data on design competition suggests that the focus of innovative activity has shifted over time as the technology has moved along the trajectory (Fig. 5a and b). In the late 1970s and early 1980s, firms experimented with different positions of the rotor relative to the tower (upwind, downwind), blade numbers (one, two, three, four, or more blades were all introduced commercially), and rotor control mechanisms. As Fig. 5a shows, it was not before 1986 that more than 50% of the firms in the market had adopted the three-blade, upwind rotor called the 'Danish design,' which is now used in virtually all grid-connected wind turbines.

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[4] This scope includes turbines used for off-grid electricity generation and onshore as well as offshore turbines, but it excludes all wind electricity generators that do not feature a rotor, such as those driven by kites (e.g., as described in patent US 8,319,368). The advantage of applying the shared operational principle to define the scope of analysis is that all included artifacts have a common basic product architecture (Murmann and Frenken, 2006), which allows us to categorize inventions across turbine designs.

[5] The design requirements in different segments *within* the onshore, grid-connected market, which are usually differentiated according to wind conditions at the site (harmonized in the standard International Electrotechnical Commission (IEC) 61400), can be considered relatively homogeneous in comparison to the design requirements for offshore and small wind turbines.

**Table 1**
Product architecture of a typical wind turbine used for grid-connected electricity generation: Sub-systems, and their function in the technological system.

| Sub-systems and components | Function |
|---|---|
| Wind turbine (system-level) | Conversion of wind energy into grid electricity |
| Rotor | |
| Blades | Conversion of wind energy into rotational energy |
| Hub | Transfer of rotational energy to main shaft |
| Rotor control system (pitch and yaw mechanisms), control routines | Adjustment of rotor and individual blades to wind conditions |
| Power train | |
| Mechanical drive-train: Rotor shaft, bearings, gearbox, couplings, brake | Transmission of rotational energy from rotor blades to generator |
| Electrical drive-train: generator, power electronics | Conversion of rotational energy into electrical energy; AC-DC and frequency conversion |
| Power-train control system and routines | Adjustment of drive-train elements to wind & system conditions |
| Mounting & encapsulation | |
| Nacelle, spinner, and bedplate | Load carrying; machinery enclosure |
| Tower | Support turbine at designated height; load transfer to foundation |
| Foundation | Load transfer into ground |
| Climate & vibration control system and routines | Regulate operating conditions & minimize system vibrations |
| Grid connection and/or storage | |
| Transformer/substation and power cables | Transfer of electrical energy to grid |
| Storage (if applicable) | Storage of electrical energy |
| Grid-impact and wind-farm control system and routines | Reduce impact of grid-side disturbances; ensure grid-friendly wind farm output |

The focus of innovative activity then shifted within the Danish rotor design toward more efficient power train concepts, as can be seen from the adoption of variable-speed power trains starting from the early 1990s (see Fig. 5b). The most intense period of design competition on the power-train level was in the late 1990s and early 2000s, when the variable-speed power train with a partial-scale converter emerged as dominant design. It has held more than 50% market share since around 2003.

Data on artifact evolution such as those presented in Fig. 5 cannot reveal trends in the underlying knowledge base. One can only speculate, for example, whether the surge in variable speed turbines in the 1990s (see Fig. 5b) was based on industry-internal refinement in the understanding of wind-specific drive-train requirements or was based on 'imported' advances in standardized drive-train components used in other industries. However, these trends directly affect the competitive position of firms and nations, and they have implications for the assessment of innovation policies in the wind industry. Below we proceed to open this black box.

## 4. Data and methodology

### 4.1. Empirical strategy

In this section, we develop a systematic approach to determining the impact of the design hierarchy on the trajectory of knowledge generation in high-technology capital goods.

Recent studies of the *knowledge dimension of technological trajectories* have made significant advances by applying citation-network analysis to patent data (Barberá-Tomás et al., 2011; Epicoco, 2013; Fontana et al., 2009; Martinelli, 2012; Verspagen, 2007). This approach allows researchers to trace the trajectory of knowledge generation over time, by making use of the information on 'knowledge inheritance' between patents that is contained in patent citation data (Martinelli and Nomaler, 2014). External validations show that this approach can reduce a large patent dataset to a small selection of patents that were highly relevant for technological progress around the time of filing (Barberá-Tomás

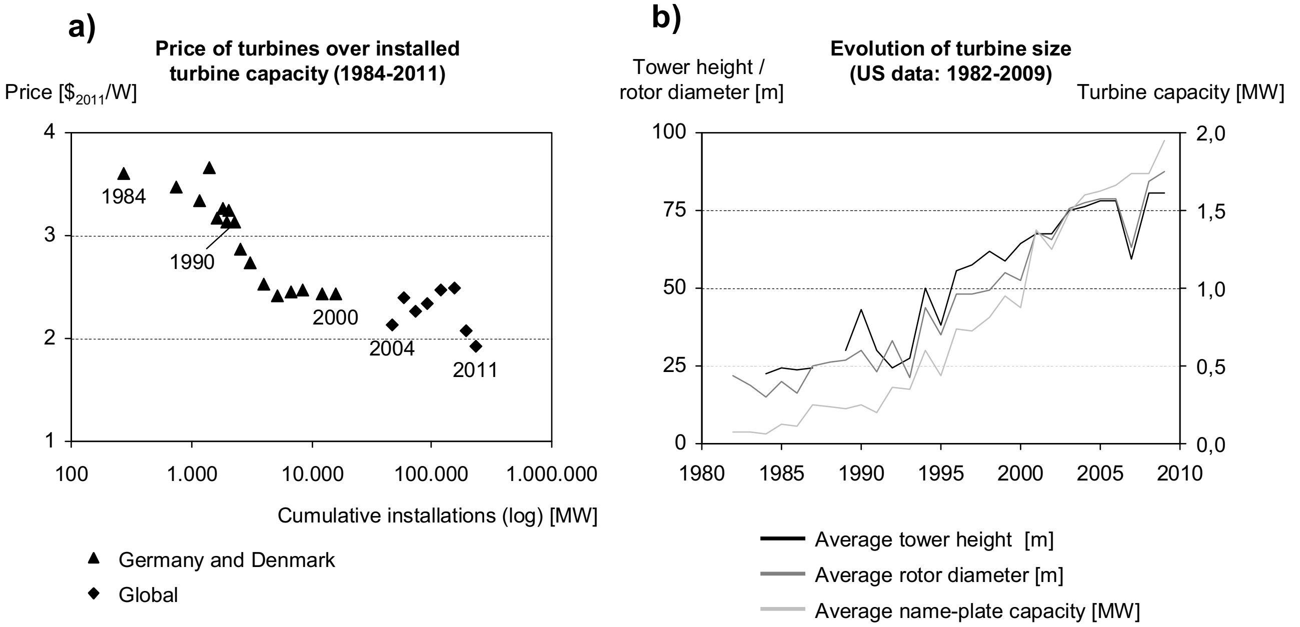

**Fig. 4.** (a) Price development of wind turbines over cumulative installations; data from BNEF (2012). (b) Size trajectories of modern wind turbines: rotor, name-plate capacity, and tower height; data from USGS (2014).

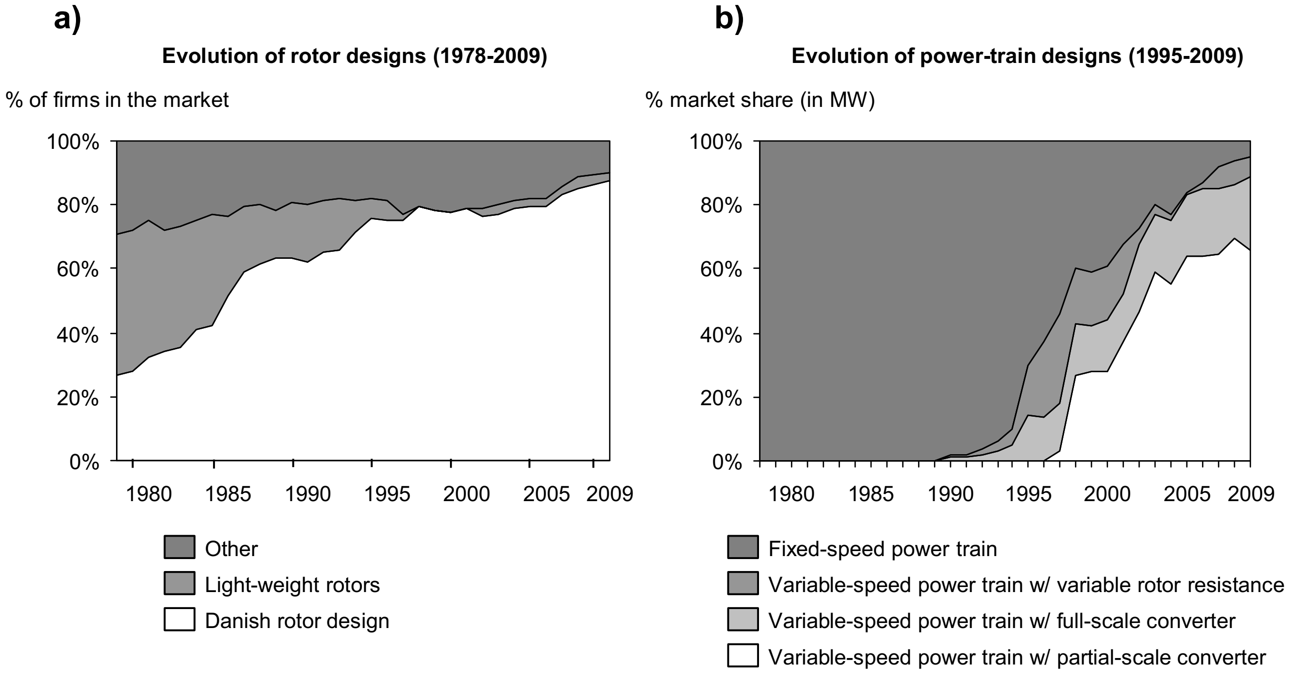

**Fig. 5.** Evolution of wind turbine designs: (a) The number of firms with different rotor designs in 1978–2009; data from Menzel and Kammer (2011). (b) Market share of different power-train designs in 1978–2009; data for 1978–1994 is approximated based on firm-level data from Menzel and Kammer (2011), data for 1995–2009 based on top 48 turbine manufacturers, from Hansen (2012).

et al., 2011; Fontana et al., 2009). The identified sequence of key inventions thus provides insights on how the focus of significant innovative activity changed as the technology evolved over time (Huenteler et al., 2014). However, because patents often lack a clear connection to specific designs, results of patent-citation network analyses cannot easily be linked to the evolution of artifacts and dominant designs (Barberá-Tomás et al., 2011). Studies of the *artifact dimension of technological trajectories*, on the other hand, have traditionally relied on categorical analysis of product designs available in the market (Fixson and Park, 2008; Frenken and Nuvolari, 2004; Mendonça, 2012; Rosenkopf and Nerkar, 1999). This approach is useful for analyzing the influence of the design hierarchy on the evolution of artifacts, but does not allow identification of developments in the underlying knowledge base. Combining these two approaches allows us to identify the influence of the design hierarchy on the trajectory of knowledge generation and thus to bridge the knowledge and artifact dimensions of technological trajectories.

Our empirical strategy was as follows: We first used a combination of desk research and expert interviews to identify the product architecture, relevant service characteristics, and design hierarchy of wind turbines (Section 4.2). Second, we analyzed the network formed by wind turbine patents and patent citations in order to characterize the core trajectory of knowledge generation (the data is described in Section 4.3 and the algorithms in Section 4.4). Third, we manually categorized the core patents on the trajectory of knowledge generation, identified in step two, according to their focus in the design hierarchy (4.5). In a fourth and final step, we then analyzed the sources of knowledge drawn upon by the inventions in the different sub-systems in order to characterize the process of knowledge generation in the wind industry and the different involved knowledge domains (4.6).

## 4.2. Design hierarchy

The design hierarchy was identified through a qualitative assessment of the product architecture, the relevant service characteristics, and the linkages between the two.

We first developed an initial understanding of the product architecture from the technical literature. Then this initial understanding was iteratively refined through five semi-structured telephone interviews with two industry professionals. The resulting product architecture is shown in Fig. 6 in Section 5.

The list of relevant service characteristics was identified through a series of nine structured interviews,[6] in which we asked for characteristics that determine model choice. From the resulting long list of criteria we removed turbine model-specific characteristics such as the availability of upgrades and spare parts as well as purely organizational characteristics such as warranty time, contract flexibility, reaction time, etc. We further aggregated some criteria to reduce complexity. (The final selection is shown in the column headers of Table A4 in the Appendix A)

Lastly, the design hierarchy, which is determined by the linkages between the product hierarchy and the service characteristics, was developed through structured interviews with two industry professionals, in which we asked them to link sub-systems and components of a wind turbine to the identified list of service characteristics. We contacted the interviewees a second time to clarify inconsistencies between the two and removed linkages where disagreement could not be resolved.

## 4.3. Patent and patent citation data

We used patents as indicators of knowledge generation in the wind industry (Nemet, 2009) and citations as indicators of technological relatedness (Von Wartburg et al., 2005).

For the underlying patent database, we compiled wind patents, filed between 1963 and 2009, from the Derwent World Patent Index (DWPI) database.[7] The patent database was compiled by applying

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[6] For this step we interviewed professionals (by telephone and on-site) from two wind turbine operators and wind turbine experts from one insurance company, one engineering service provider, one bank, one consultant and one project developer.

[7] Even though our focus is on the time period 1973–2009, the database includes patents from 1963 to 1972 in order to improve the results of the connectivity analysis

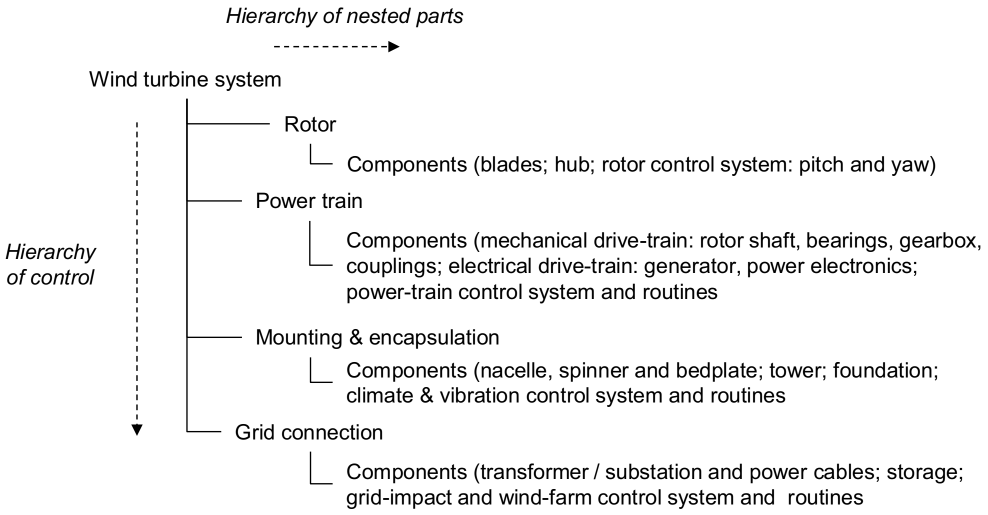

**Fig. 6.** Design hierarchy of a wind turbine. Based on product architecture presented in Table 1 and pleiotropy map presented in Table A4 in the Appendix.

a list of keywords to the titles, abstracts, and claims of patents in 20 four-digit International Patent Classification (IPC) classes. We extracted an initial list of relevant keywords from the technical literature (four industry experts provided feedback on the identified keywords) and an initial set of wind-related IPC classes from the 'Green Inventory' of the World Intellectual Property Organization. We then iteratively curtailed the keyword list and IPC classes by manually checking random samples of patents for irrelevant keywords; and we added further IPC classes by analyzing in which IPC classes relevant patents in the database were co-filed. The combination of keywords and IPC classes yielded a total of 25,512 patent families (including applications and granted patents). After retrieving the citation data of all patents; we extended the database in a second iteration to include those 1000 outside patents that received the most citations from the patents in the database (almost all of these are wind patents). Tests indicate the presence of about 6% false positives and 9% false negatives in the final dataset.[8]

The citation data was extracted from the DWPI and in addition from the Thompson Innovation database. Neither of the two databases alone provides citation data for the full period from all patent offices that we deemed important for the case of wind power, but taken together the coverage is satisfying.[9] We cleaned the citations of duplicates and excluded all patents that were not connected to other patents in the network. Finally, we reversed the citations to transform them into indicators of knowledge inheritance between nodes in the network, and we excluded circular references[10] (Martinelli and Nomaler, 2014). The final database contains 11,330 patent families with 41,268 citations between them (network A in Table 2).

### 4.4. Patent-Citation network analysis

Connectivity analysis of networks created from patents (as vertices) and patent citations (as arcs) has emerged as a standard approach for analyzing the knowledge dimension of technological trajectories (Barberá-Tomás et al., 2011; Bekkers and Martinelli, 2012; Epicoco et al., 2014; Fontana et al., 2009; Mina et al., 2007). We employed connectivity analysis with two objectives: to investigate how the core trajectory of knowledge production *evolved* over time as more and more patents are added to the network, and to analyze the *foundations of the currently dominating technological trajectory* in detail to determine how the focus of inventive activity along this trajectory shifted over the course of the last four decades. For both objectives, we used connectivity algorithms to extract sub-networks that could then be categorized manually (see Section 4.5).

To address the first objective, we extracted a series of gradually growing sub-networks that allowed us to analyze how the core trajectory of knowledge generation in the wind industry varied and converged over time. This approach reflects the fact that the core trajectory of knowledge generation identified in an industry's knowledge base at any point in time, represented here by a set of patents, changes *ex-post* when new knowledge is added over time: the (patented) roots of what the industry is working on today may have been *outside* the industry's focus of knowledge generation at the time they were filed, and patents *inside* the focus in the 1980s may have become obsolete by now.

We began by specifying a series of gradually growing networks $N_t$, in which each $N_t$ contains all patents filed between 1963 and the year $t = 1975...2009$ and the citations between them (network set B in Table 2).[11] We only included citations with a lag between the application dates of the citing and cited patents of no more than five years so as not to disproportionately weigh older patents that

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for the earliest patents. We chose DWPI because it facilitated the assessment of patent content by providing expert-generated abstracts of all patents (see Section 4.5), including translated abstracts for non-English entries from 48 patent-issuing authorities worldwide. The search was conducted in early 2013 in order to account for the time-lag between patent filing and publication of patents filed in 2009. We used patent families as the unit of analysis to avoid double-counting of multiple filings.

[8] To test for false positives, we extracted a random sample of 50 patents from each of the 20 four-digit IPC classes used in the search string and manually screened each patent for relevance (in total we screened 1000 patents). For false negatives, we checked how many of the patents filed by the top 10 wind turbine manufacturers (in 2010 by market share, excluding the two conglomerates GE and Siemens) were included in our database.

[9] We considered as important the 12 countries with the most successful turbine manufacturers (by market share) in the observed period as well as the multilateral patent offices (in country codes of the World Intellectual Property Organization): BE, CN, DK, DE, ES, EP, GB, IN, IT, JP, KR, NL, US, and WO. Gaps that remained even after combining citation data from both databases are: BE before 1987, CN, ES before 1992, IN, IT before 1986, KR before 2008.

[10] 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.

[11] The year 1975 was chosen as a starting point because at that time the cumulative number of patents exceeded 100.

**Table 2**
Descriptive statistics of (sub-) networks and their role in the analysis.

| (Sets of) Networks | Content | Number of networks | Time period | Patents (citation links) | Manually coded (y/n) | Analysis steps |
|---|---|---|---|---|---|---|
| A | All patents | 1 | 1963–2009 | 11,330 (41,268) | No | – |
| B | Sequential full networks, citation links ≤5 years | 35 | 1963–1975 . . .<br>1963–2009<br>(in year-steps) | 111 (43) . . .<br>8907 (18,718) | No | Calculation of vertex and arc weights to determine critical paths (see set C) |
| C | Sequential critical paths | 35 | 1963–1975 . . .<br>1963–2009<br>(in year-steps) | 4 (3*) . . .<br>33 (32*) | Yes | Variation of core trajectory over time (Fig. 7) |
| D | Patents with top 80% of vertex weight | 1 | 1963–2009 | 158 (499) | Yes | Analysis of focus of inventive activity along the currently dominating technological trajectory (Fig. 8) |
| E | Patents with top 95% vertex weight | 1 | 1963–2009 | 494 (1827) | Yes | Robustness check for analysis of dominant knowledge trajectory |
| F | Patents with top 80% vertex weight (all citations) | 1 | 1963–2009 | 158 (817) | Yes | Analysis of knowledge flows between patents on the currently dominating technological trajectory (Fig. 8) |

had more time to get cited. For each $N_t$ we applied the search path link count (SPLC) algorithm[12] (e.g., Hummon and Doreian, 1989; Verspagen, 2007). This allowed us to determine vertex and arc weights, which represent the importance of patents and citation linkages for the cumulative evolution of technological knowledge represented by the network, and act as input to the connectivity algorithms described below.

We then used the critical path method[13] to identify the ‘backbone’ of each network $N_t$, which can be understood as a core trajectory of knowledge generation in the observed period (Barberá-Tomás et al., 2011; Bekkers and Martinelli, 2012; Epicoco et al., 2014; Fontana et al., 2009; Mina et al., 2007). Thereafter, we extracted each resulting critical path as a separate sub-network – one for each $N_t$ (network set C in Table 2) – and categorized all contained patents according to their content (see Section 4.5). By displaying the sub-networks individually and identifying change and stability over time, we were able to observe how the core trajectory of knowledge evolution varied and converged over time.

To address the second objective – investigating in detail the focus of inventive activity along the currently dominating technological trajectory over the last four decades – we started with the full network (1963–2009) and again used the SPLC algorithm to weigh vertices and arcs. Instead of using the critical path method, however, we extracted the two sub-networks containing 80% and 95% of the total vertex weight, respectively (networks D and E in Table 2). Because the weight of patents in the network is highly skewed, with a few patents holding most of the aggregate weight, this vertex-cut algorithm (Batagelj and Mrvar, 2004) reduces the number of patents in the network significantly. This means we can characterize the main stream of knowledge through the network, and the weighted average of the focus of inventive activity at any point in time, a relatively small number of patents—in our case from 8907 to 494 for 95% of the aggregate vertex weight and 158 for 80% (see Table 2).

### 4.5. Patent-Content analysis

We manually coded the abstracts and claims of the patents in the sub-networks extracted in Section 4.4 to identify how the industry’s knowledge base evolved over time (networks C–F in Table 2). One mechanical engineer and one electrical engineer independently coded each of the patents according to the abstracts’ focus, and located them in the design hierarchy.

The coding scheme we used in the analysis, shown in Table 3, has three levels in the hierarchy of nested parts (system, sub-system, and component) and four levels in the hierarchy of control on the sub-system level (rotor, power train, mounting & encapsulation, and grid connection).[14] The agreement between the two coders was 89% in the hierarchy of nested parts and 92% in the hierarchy of control. We cross-checked the resulting focus of knowledge generation along the trajectory in a final round of interviews with four academic experts on the wind industry. All four confirmed the trends displayed in the data.[15]

### 4.6. Characterization of knowledge generation in different sub-systems

In a last step, to shed more light on how the knowledge base of the wind industry evolved over time, we characterized the source

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[12] The SPLC algorithm assigns to each vertex (patent) a weight which is equal to the number of ‘search paths’ running through the vertex. A search path is any path from a sink vertex (a patent that only has backward citations in the network) to any other vertex in the network.

[13] The critical path method algorithm sums up all SPLC weights along the arcs of any path from a source vertex (patents that only have forward citations in the network) to a sink vertex (patents that only have backward citations in the network) and determines the path with the largest total sum of weights on the arcs.

[14] The initial coding scheme also had a sub-component level. However, the agreement between the two coders was not high enough to justify a distinction between the component and sub-component level (<70%), and in all but one component the agreement between the two coders on the distinction between different sub-components (such as between generators and power electronics) was also insufficient (<80%).

[15] We were further able to test the robustness of the coding by assessing whether or not the categorization of sub-systems is reflected in the citation data, because previous research has shown that patent citations are more likely to link patents within than across sub-systems and components (Rosenkopf and Nerkar, 1999). $\chi^2$ tests for the randomness of the distribution of citations from each of the four sub-systems indicate that the results of the coding do indeed correspond to relational patterns in the citation data (see Table A3).

**Table 3**
Coding scheme for patent focus.

| Content code | Content | Example |
|---|---|---|
| Wind turbine (system-level) | 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 (sub-system level) | Novel rotor design in which novelty has to do with the design of at least two components (blades, hub and/or rotor control) | Rotor arrangement with teetering hub and rotor control mechanism (US 4,201,514) |
| Rotor (component level) | Novel rotor design in which novelty has to do with the design of one component (blades, hub and/or rotor control) | Sectioned rotor blade (US 4,389,162) |
| Power train (sub-system) | Novel power-train design in which novelty has to do with the design of at least two components (mechanical transmission system, generator, power electronics, power-train control) | Compact, gearless power train (US 6,921,243) |
| Power train (component) | Novel power train design in which novelty has to do with the design of one component (mechanical transmission system, generator, power electronics, power-train control)C | Planetary gearbox (US 6,420,808) |
| Mounting & encapsulation (sub-system) | Novel mounting & encapsulation design n which novelty has to do with the design of at least two components (nacelle, spinner, bedplate, tower, foundation, climate & system-vibration control) | Novel tower-nacelle arrangement in which transformer is mounted inside the top of the tower (US 7,119,453) |
| Mounting & encapsulation (component) | Novel mounting & encapsulation design in which novelty has to do with the design of one component (nacelle, spinner, bedplate, tower, foundation, climate & system-vibration control) | Tower consisting of pre-fabricated modules (US 7,770,343) |
| Grid connection (sub-system) | Novel grid-connection design in which novelty has to do with the design of at least two components (mechanical transmission system, generator, power electronics) | Novel electrical connection of wind turbines in a wind farm, including substation, individual transformers and cabling (US 7,071,579) |
| Grid connection (component) | Novel power train design in which novelty has to do with the design of one component (transformer, substation, cabling, storage, wind-farm integration control, grid-fault control) | Control system for wind farm that optimizes voltage and reactive power output (US 7,119,452) |

of knowledge utilized by patents in the different sub-systems of the wind turbine.

We first analyzed the degree to which patents drew upon *network-external knowledge*, by counting the number of backward citations from patents in the different sub-systems to patents *inside* and *outside* the wind patent network. For each sub-system, this analysis yields a trend over time in the relative importance of industry-internal and industry-external knowledge. These trends allow us to identify at what point in time, and in which part of the system, external knowledge was integrated into the wind industry's knowledge base. In a next step, we took a closer look at network-internal citations, by analyzing the *patterns of cross-citations* between patents in the different sub-systems. This allowed us to better understand to what extent inventive activity in the different sub-systems was interdependent, and which sub-systems built upon each other with regard to technological knowledge. In a last step, we characterized *the fields of knowledge* underlying the different sub-systems, to identify commonalities and differences between the sub-systems. To that end, we compared the scientific fields in which scientific articles pertaining to the different sub-systems were published in the period 1973–2009. The bibliometric datasets for the four sub-systems were created by applying the keywords we used for the patent analysis (see Section 4.3) in combination with keywords for each sub-system to the Web of Science, and extracting information on the scientific articles relating to the rotor (2362 articles), power train (882), mounting & encapsulation (718), and grid connection (644).

## 5. Results

### 5.1. Design hierarchy

The design hierarchy, displayed in Fig. 6, is derived from the interplay of the product architecture and the service characteristics. The product architecture directly yields the hierarchy of nested parts, with the turbine system on the system-level, the rotor, power train, mounting & encapsulation, and grid connection on the sub-system level, and all other elements on the component level.

The hierarchy of control is determined on the sub-system level by assessing the influence of each sub-system on the service characteristics. Specifically, each sub-system's position in the hierarchy of control is calculated from the number of service characteristics affected by the sub-system. The underlying relationships between system elements and service characteristics are presented in Table A4 in the Appendix (Murmann and Frenken, 2006). Our results suggest that the hierarchy of control of a wind turbine follows the order (from core to periphery) (i) rotor, (ii) power train, (iii) mounting & encapsulation, and (iv) grid connection, as indicated by the vertical order of the sub-systems in Fig. 6.[16]

### 5.2. Gradual stabilization of knowledge trajectory

The evolution of the core trajectory over the last four decades was analyzed iteratively by determining the core trajectory as increasingly more years of data are added to the patent-citation network. Fig. 7a–h shows how the core trajectory meanders through the design hierarchy for eight networks representing network growth in 5-year steps. It can be seen how the knowledge trajectory in the industry varies substantially from 1974, the year when the earliest core trajectory begins, until 1990, but stabilizes thereafter. This result is quantified in Fig. 7i, which displays for each year *t* the percentage of the patents on the core trajectory of network $N_t$ (i.e., the network with data until year *t*) that are no longer on the core trajectory of $N_{t+5}$. Only by 1991 does this hazard rate, which is a measure of variation of the core trajectory, remain consistently below 50%. Accordingly, our analysis is able to describe the competition between fundamentally different engineering approaches in the 1970s and 1980s as well as the subsequent convergence on the 'Danish' bottom-up approach to wind turbine design (shown in Fig. 5 above). This convergence in the knowledge trajectory is well documented in the literature, but so far only by qualitative studies (e.g., Karnøe, 1993; Gipe, 1995; Bergek and Jacobsson, 2003; Garud and Karnøe, 2003; Nielsen, 2010).

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[16] The resulting design hierarchy is in line with the prominent role that rotor and power-train designs assume in historical accounts of wind turbine engineering (Garrad, 2012; Gipe, 1995; Karnøe, 1993).

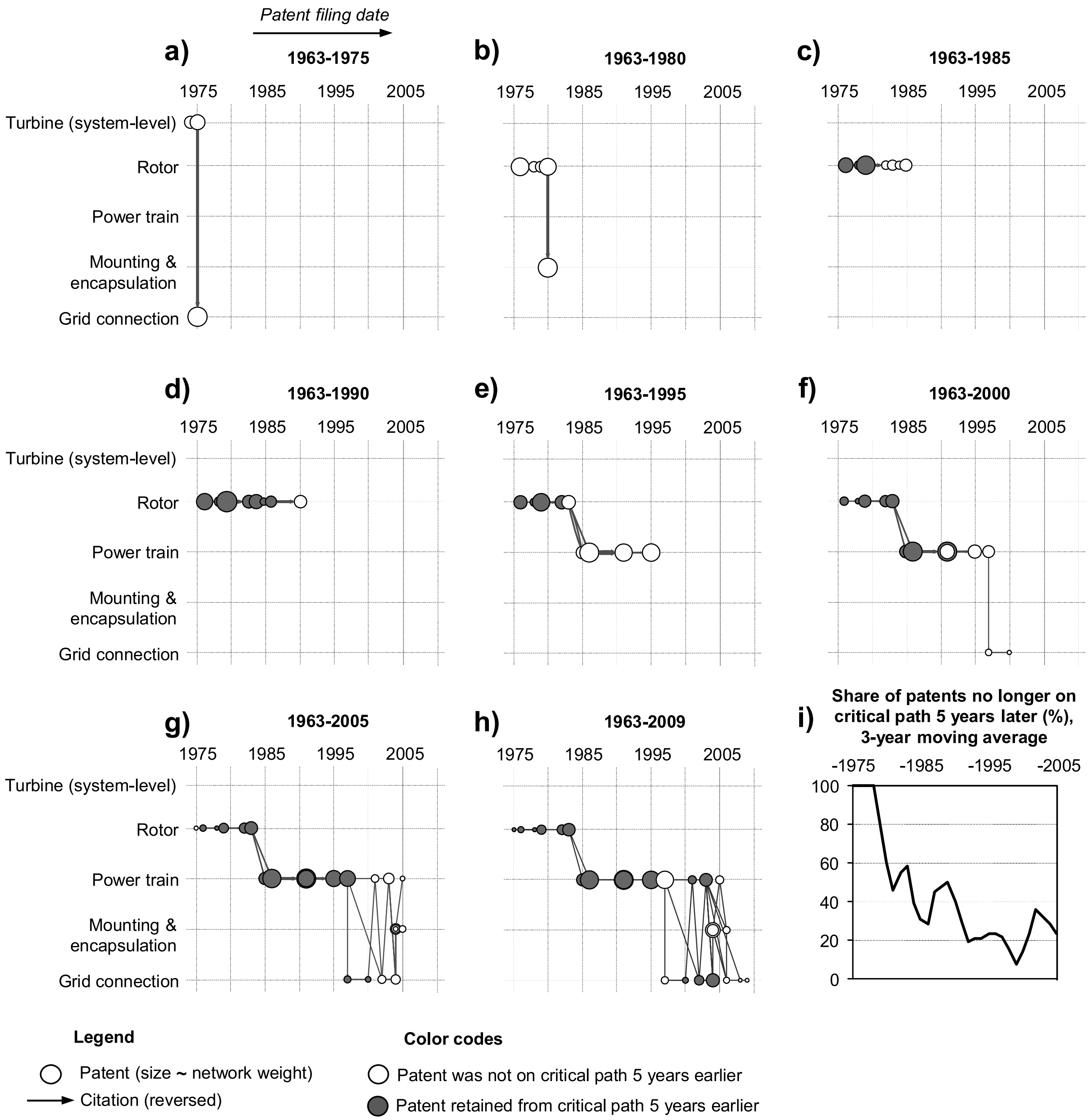

**Fig. 7.** Variation of core trajectory over time. (a)–(h) display the critical paths in a series of gradually growing networks (time periods are given in parentheses). The color of each vertex in $N_t$ indicates if it was also on the critical path of $N_{t-5}$. figure (i) shows the five-year hazard rate for patents on the core path, indicating how the core trajectory gradually stabilizes over time. The size of vertices and arcs represents their weight.

The sequence of core paths in Fig. 7 indicates that the knowledge trajectory stabilized as soon as the core patents on the rotor stabilized: while there is much variation between the rotor-level patents in the networks $N_{1975}$–$N_{1990}$, there is no significant change on the rotor level from $N_{1995}$ on, which coincides with the stabilization of the knowledge trajectory overall. This demonstrates empirically that the dominant rotor design reduced variation on the highest level in the hierarchy of control, but set the agenda for further developments and thus allowed for much innovation on lower levels of the design hierarchy (as suggested, among others, by Clark, 1985; Sahal, 1985; Frenken, 2006; Murmann and Frenken, 2006).[17]

### 5.3. The current dominant technological trajectory

The analysis of the networks with patents that represent 80% and 95% of the vertex weight in the network (networks D and E) confirms the overall trend shown in Fig. 7h, while adding further depth and detail. Fig. 8 shows network D which contains those

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[17] Table A5 in the Appendix provides details on content and assignees of the patents along the top path of the core trajectory.

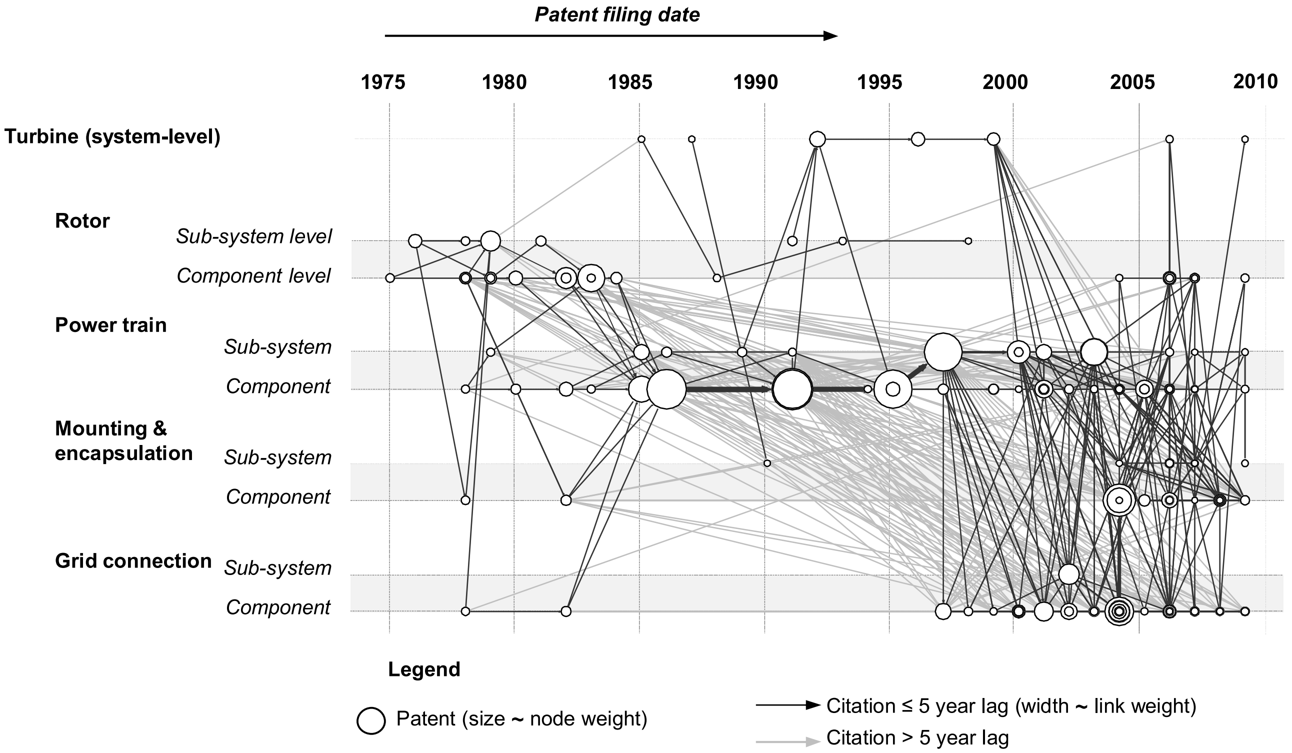

**Fig. 8.** The current dominant trajectory of knowledge evolution in the wind industry in detail (represented here by the network containing 80% of the total vertex weight (Network D), sorted by patent filing date). Citations with lag > 5 years were not used in analysis, but are displayed here to indicate actual technological linkages.

patents that account for 80% of the vertex weight. Significant inventions along the trajectory can be found in all four sub-systems and across all levels of the hierarchy of nested parts, underlining the systemic character of the product architecture of wind turbines. However, the focus of inventive activity shifted through the system in a clearly *sequential* way: from the rotor to the power train, grid connection and lastly mounting & encapsulation. The full sequence through all sub-systems took more than 30 years (from 1975 to around 2005, when the last sub-system was reached).

An analysis of the 95%-weight network (network E), shown in Fig. 9, provides further quantitative evidence for (i) the highly sequential pattern of knowledge generation along the trajectory, and (ii) the structuring effect of the hierarchy of control on the underlying sequence.

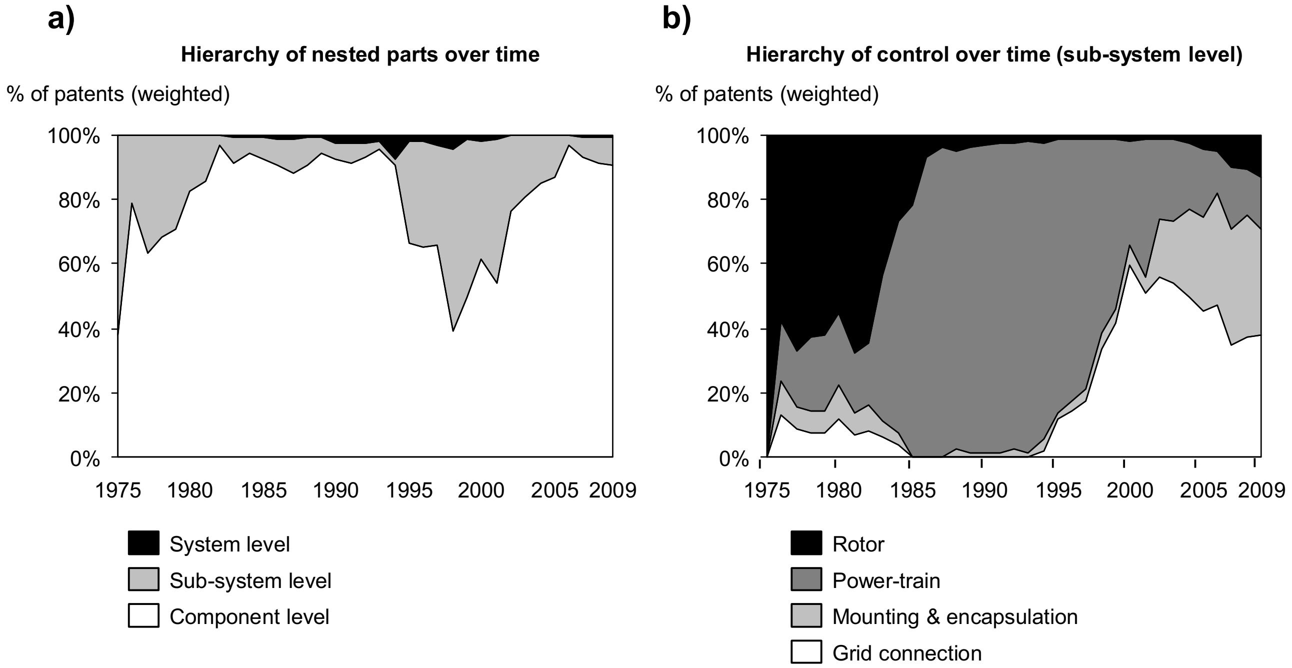

**Fig. 9.** Weighted-average of the focus of patents over time: (a) hierarchy of nested parts and (b) hierarchy of control; data from network E, which contains the patents representing 95% of vertex weight in the full network (determined through a search path link count algorithm). Data displayed as 5-year moving averages.

**Table 4**
Cross-citation patterns between sub-systems (data based on the 494 patents in network E); citations per patent are given in parentheses.

| Entry in row i and column j indicates sum of citations from sub-system in column j to sub-system in row i | Wind turbine (system-level) | Rotor | Power train | Mounting & encapsulation | Grid connection |
|---|---|---|---|---|---|
| Wind turbine (system-level) | 9 (0.5) | 9 (0.5) | 29 (1.61) | 32 (1.78) | 3 (0.17) |
| Rotor | 14 (0.12) | 233 (2.06) | 92 (0.81) | 77 (0.68) | 52 (0.46) |
| Power train | 4 (0.03) | 88 (0.6) | 537 (3.68) | 215 (1.47) | 356 (2.44) |
| Mounting & encapsulation | 9 (0.1) | 46 (0.49) | 90 (0.97) | 252 (2.71) | 48 (0.52) |
| Grid connection | 0 (0) | 36 (0.29) | 151 (1.22) | 55 (0.44) | 477 (3.85) |

In the hierarchy of nested parts, across the observed period, most inventive activity is on the component level (Fig. 9a), while there is no clear trend in the inventions on the system- and sub-system levels.

In contrast, the hierarchy of control is well reflected in the sequence of inventive activity along the trajectory (see Fig. 9b and Table A6 in the Appendix A): Rotor patents account for 77% of the total vertex weight in 1975–1979 and for 76% in 1980–1984, but only for an average of 3% in the two subsequent decades. Power train patents, on the other hand, surge from 16% in 1980–1984 to 91%, 87% and 78% in the three periods after that, before falling to 34% in 2000–2004. The last two periods are dominated by grid connection patents, with 46% in 2000–2004, and mounting & encapsulation with 32% in 2005–2009, two categories that both had 0 patents in the 95%-weight network in 1985–1989.[18] Toward the end of the observed period, the focus of knowledge generation seems to diffuse.[19] Replacing network weight by patent forward citations, a classical measure of patent value, yields almost identical results, as shown in Table A7 in the Appendix A (Table 3).

The product architecture and the design hierarchy also clearly leave their mark in the patterns of citations between patents. As the cross-citation matrix in Table 4 shows, over half of all citations between patents in the 95%-network are on the diagonal (i.e., within one architecture element). And almost twice as many citations from patents on lower levels of the hierarchy of control to higher levels (913) than the other way around (493), indicating how knowledge flows between sub-systems point predominantly downward in the design hierarchy.

The presented results suggest that the design hierarchy had a structuring effect on the trajectory of knowledge evolution in the wind industry, albeit with two qualifications. First, although the earliest patents in the field of mounting & encapsulation precede those in grid connections in Network D (Fig. 8), *substantial* activity in the latter field occurred earlier (after 1995) in all networks (Figs. 7, 8, and 9). Second, the hierarchy of nested parts appears not to be a good predictor of the sequence of knowledge generation along the current dominant knowledge trajectory. On the one hand, inventive activity did not start on the system level (a least not in patents filed from 1963).[20] On the other hand, in all four sub-systems the earliest inventive activity is on the component level, rather than on the sub-system level. And in all but the rotor, which features significant patents on the sub-system level early on, the vertices on the component level appear much more important than those one level higher. One possible explanation for this second qualification is that inventors had network-external knowledge on the system-level and sub-system level to build on, for example in the form of standardized generators, towers and transformers available in other industries, and thus could focus immediately on wind-specific improvements on the component-level. To shed more light on this possible explanation, we analyze below the relative importance and composition of network-external knowledge over time.

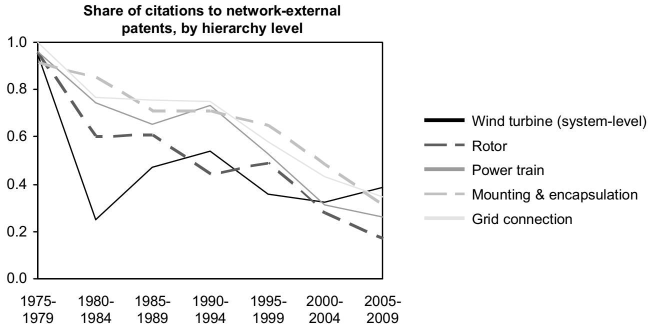

**Fig. 10.** Weighted average share of citations to patents outside the network over time (data based on the 494 patents in network E; missing values are interpolated).

### 5.4. *Sources of knowledge for inventive activity in different sub-systems*

We set out to investigate the assumption that the development of an industry's knowledge base along the trajectory is predominantly a process of incremental growth and refinement, without abrupt shifts in the focus of inventive activity and changes in the role of industry-external knowledge. The results presented in Sections 5.1–5.3 demonstrated that the focus of inventive activity shifted through the technological system in a highly sequential way. But how significant were these shifts from a knowledge perspective?

Our data suggests that shifts in the focus of inventive activity were accompanied by shifts in the *importance and composition of network-external knowledge*. To illustrate the shifts in *importance*, Fig. 10 plots the relative importance of external knowledge, measured by the weighted-average share of citations to patents outside the network, over time for the system-level and the four sub-systems. For each element of the system the influx of industry-external knowledge consistently declined over time. But the decline occurred in the order of the design hierarchy – and thus in the order of the focus of inventive activity – rather than uniform across the system: The importance of external knowledge first fell on the system-level, as wind-specific knowledge had been developed in that area, then the rotor and the power train, and lastly in mounting & encapsulation and grid connection. The trends converge in the late 1990s and early 2000s, but before that the lag in the decline between the curves is up to 20 years. Due to this pattern on the sub-system level the importance of network-external knowledge for the industry as a whole temporarily increased when the

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[18] An ordered, bivariate ordinal regression of the hierarchy of control on the logarithmized cumulative number of patents in the network confirms that inventive activity gradually shifts downwards on the hierarchy as the knowledge base grows ($\beta = 0.60$; $t(494) = 6.53$; $p < 0.001$, AIC = 1437).

[19] This observation might be partly due to the fact that patents had lower chances of being cited in the last four years.

[20] However, system-level inventions did have some impact later. The patents on the system-level in the late 1990s as well as the recipient patents on lower levels relate to direct-drive technology, a specific type of power train that does not need a gearbox.

**Table 5**
The knowledge base of the different subsystems: Top Web of Science categories of literature pertaining to wind turbine rotor, power train, mounting & encapsulation, and grid integration (percentage of articles assigned by Web of Science to each category shown in parentheses).

| Rank | Rotor | Power train | Mounting & Encapsulation | Grid integration |
|---|---|---|---|---|
| 1 | Mechanical engineering (34.41) | Electrical/electronic engineering (72.87) | Civil engineering (28.51) | Electrical/electronic engineering (64.10) |
| 2 | Electrical/electronic engineering (15.08) | Automation/control systems (12.73) | Mechanical engineering (27.39) | Automation/control systems (8.43) |
| 3 | Mechanics (11.37) | Mechanical engineering (9.50) | Materials science multidisciplinary (14.25) | Mechanical engineering (5.977) |
| 4 | Materials science multidisciplinary (10.70) | Industrial engineering (4.71) | Construction/building technology (11.58) | Materials science multidisciplinary (4.07) |
| 5 | Applied physics (7.08) | Computer science/artificial intelligence (4.28) | Mechanics (11.14) | Thermodynamics (3.85) |

focus of inventive activity shifted between elements of the system. Fig. 11 depicts the relative importance of external knowledge for the full patent network, illustrating that the temporary increase in importance was most pronounced when the industry shifted from focusing on the rotor to the power train in the late 1980s.

The shifts in the focus of inventive activity also represent changes in the *composition* of relevant network-external knowledge, because each sub-system draws on different domains of external knowledge. Table 5 shows the main Web of Science categories to which the scientific articles are assigned for each sub-system (Table A1 in the Appendix shows further detail on the knowledge domains of the different sub-systems and components). The bibliometric data shows that the sub-systems share certain knowledge areas – e.g., mechanical engineering is part of all four categories' top 5 – but the relative importance and the combination of fields are quite different. A shift in the focus of inventive activity can therefore have quite significant impact on the value of technological knowledge held by firms or nations. The only exception is between the power train and grid integration sub-systems, which show significant overlap and share the top three categories. This shared knowledge base, which is also indicated by the larger number of citations between the two sub-systems (see Table 4), helps explaining why the focus of inventive activity shifted from the power train immediately to grid integration, skipping mounting & encapsulation: Solving the problems in grid connection may have been a 'logic' next issue to work on for the industry after a significant body of relevant knowledge had been established by working on the power train.

## 6. Discussion

### 6.1. Creative sequences in the evolution of an industry's knowledge base

Our results shed light on how the knowledge base in wind turbine technology emerged and in which direction it grew over time. Building on this case, this paper provides a model that explains how the focus of inventive activity shifts along the technological trajectory of a high-technology capital good, and how the importance and composition of external knowledge evolves over time along with the shifting focus. In contrast to extant conceptualizations of technological trajectories, this model holds that the evolution of an industry's knowledge base along a technological trajectory features sequential changes in the focus of inventive activity, and changes over time in the importance and composition of industry-external knowledge, rather than a more or less linear process of incremental growth and refinement. The model relates the order of sequential changes in the focus of inventive activity to the joint influence of technology-driven and demand-driven influences – the product architecture and the service characteristics, respectively – and

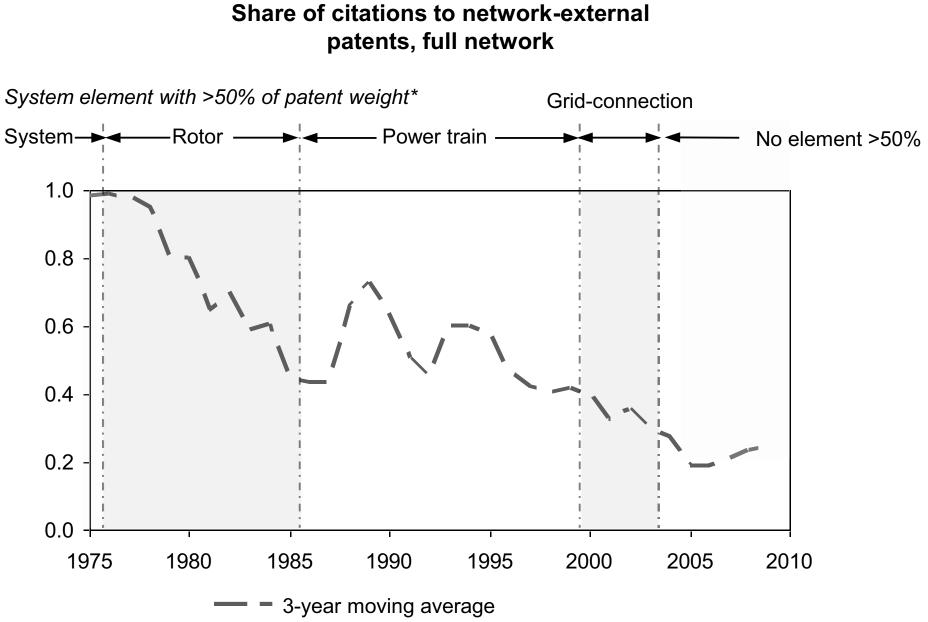

**Fig. 11.** Weighted average share of citations to patents outside the network over time for full network and shifts in focus of inventive activity (based on the 494 patents in network E).

links the direction of any shift in the focus of inventive activity to influences from both sides.

### 6.1.1. *Sequential change in the focus of inventive activity*

The principal finding of our paper is that the focus of knowledge generation shifts in a highly sequential way through the clusters of technological problems that pertain to different sub-systems of a systemic artifact. The order underlying this creative sequence is strongly influenced by the core-periphery dimension of the design hierarchy: Our findings suggest that if a systemic artifact has many different sub-systems, inventive activity will focus first on the (core) sub-systems that are most important for the demanded service characteristics. The knowledge trajectory in the industry will stabilize once the understanding of the design of this sub-system has reached some degree of saturation. It will then gradually proceed, along the sequence defined by the design hierarchy, toward more peripheral sub-systems.[21] Exceptions to this general sequence seem possible only when different sub-systems are very close in terms of the underlying knowledge base. In the analyzed case, inventive activity shifted directly from the power train to grid connection issues (skipping mounting & encapsulation). This shift was likely facilitated by the fact that the two sub-systems share an almost identical underlying knowledge base, although changing regulations may also have played a role (the shift to grid connection coincided with the first regulations on grid-compatibility in the industry in the late 1990s). The observed patterns mean that design hierarchy defines not only the physical interaction of sub-systems and components *in the artifact space of technological evolution*, but also 'guides' the focus of inventive activity in the process of knowledge generation along the trajectory.

The model of creative sequences reconciles technology-push and demand-pull perspectives on the focus of inventive activity by relating each step in the sequence to the *joint influence* of the (technology-driven) product architecture and the (demand-driven) service characteristics. The space of technological problems relating to wind turbines is defined by the product architecture. For example, the fact that engineering problems relating to rotor blade were among the first to be tackled by the industry is determined in part by the fact that a turbine typically contains one or more rotor blades. Yet the prioritization of problems at any point in time can only be understood from the interplay of factors relating to the product architecture (e.g., how fundamental the choice of rotor materials is for the design of the turbine, and how many other engineering problems depend on it) and the demand characteristics (e.g., how important the rotor blade material is for the characteristics that users base their purchase decision on).

### 6.1.2. *Changes over time in the importance and composition of network-External knowledge*

Our second finding is the evolving role of outside knowledge along the trajectory. This finding helps explaining why the nested-parts dimension of the design hierarchy appears to have no influence on the trajectory of knowledge generation. Every time the focus of knowledge generation shifts to a new sub-system, network-external knowledge from new domains is integrated into the knowledge base, with potentially significant impacts on the competitive landscape of the focal technology.

A deeper look at the sources of knowledge of the inventions on the trajectory suggests that the industry built upon two sources of network-external knowledge on the system and sub-system levels: industry-internal knowledge that pre-dates our observation period, and industry-external knowledge. Drawing from industry-external knowledge allows knowledge generation to skip levels in the hierarchy of nested parts.

The first source, industry-internal knowledge that pre-dates our observation period (which spanned roughly 50 years), explains the lack of system-level patents on the current dominant knowledge trajectory. Due to the necessarily limited time period that our database covers, the fundamental system design of horizontal axis, lift-based wind turbines, was well-established at the beginning of the observed period (even though its application to large-scale electricity generation was a novelty in the universe of artifacts). The fact that our database begins in 1963 means that system-level inventions such as US 2,037,528 (filed in 1934) or US 2,622,686 (1948) cannot be located on the trajectory.

The second source, industry-external knowledge, explains the lack of patents on the sub-system level before patenting begins on the component level. The knowledge base of the wind industry builds on knowledge transferred from a number of adjacent sectors, including aerospace, electrical engineering, ship building and agricultural machinery (a list of the main involved knowledge domains is given in Table A1). Knowledge from these adjacent sectors entered the wind industry in the beginning in the form of sub-system assemblies – the power-train of a wind turbine is in principle not much different from that of a hydro turbine – as well as standardized components such as gearboxes, generators, and towers. The adoption of these components in the wind industry meant an innovation in the universe of artifacts, but not necessarily novelty in the evolution of knowledge. When the focus of inventive activity later shifted toward these components (e.g., to the power train in the late 1980s), the generation of wind-specific knowledge did not start with the sub-system level, but with specific adaptations of standard components to the operational requirements of a wind turbine. Indeed, on each sub-system, the earliest patents on the core trajectory are component-level inventions that – in addition to wind-turbine patents – draw significantly on conceptual patents from other sectors. For example, MAN's rotor patent US 4,297,076 cites water wheels (such as US 2,152,984), United Technologies' power-train patent US 4,703,189 builds on technology from aircraft engines (US 4,330,743) and ABB's grid-connection patent US 6,670,721 references many generic grid-related patents (such as US 6,429,546).

## 6.2. *Implications for technology strategy and public policy*

Our model of creative sequences has implications for technology strategy and public policy aimed at stimulating innovation in high-technology capital goods.

The focus of an industry's inventive activity directly affects the competitive value of knowledge held by firms and nations. Our model of creative sequences suggests that movement along the trajectory does not preclude abrupt shifts in the value of knowledge positions of firms and nations. Our findings suggest that, first, at any point in time, the knowledge that has a long-lasting impact on the trajectory of knowledge generation focuses on only a very narrow set of technological problems. Second, this narrow focus shifts over time between sub-systems, which depend on significantly different knowledge bases. For example, while the rotor of a wind turbine requires understanding of mechanics, aerodynamics and materials, the power train requires knowledge of electrical engineering and electronics. This pattern may help explain sudden shifts in an industry's competitive landscape that occur without major shifts of the technological trajectory, such as the sudden rise of large electrical engineering conglomerates in the wind industry in the early 2000s (including GE, Siemens, Alstom and Areva) that coincided with a shift in the focus of inventive activity toward grid integration issues.

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[21] Our data did not allow us to analyze the trajectory on the component level, but we would expect a similar pattern there.

The notion of creative sequences may also have implications for technology policy. Many governments are attempting to steer technological change in capital goods to improve the competitive and environmental performance of high-technology sectors. In the context of climate change, there is an ongoing debate about the rationale for government support for proven clean technologies with established technological trajectories, such as wind power and solar PV, compared to government support for more basic research and development. A prominent argument *against* supporting proven technologies has been that further deploying existing technologies predominantly leads to the exploitation and refinement of the *existing knowledge base*, rather than the exploration of novel solutions with the potential for breakthroughs in performance and that this may not be enough to achieve long-term policy goals (Hoppmann et al., 2013; Menanteau, 2000; Nemet, 2009; Sandén and Azar, 2005). While our empirical research does not allow us to draw conclusions about the impacts of specific types of policy intervention, our results nonetheless hint at a more nuanced understanding of the trade-off between R&D and deployment: movement along the trajectory does not preclude the exploration of novel solutions, based on industry-external knowledge, *on the sub-system and component levels*. The development of direct-drive power trains on the sub-system level (power train) is a good example of this: although they constitute a development along the trajectory, direct-drive power trains involved the integration of industry-external knowledge of permanent magnets and full-scale power converters, and facilitated a step-change in performance (especially in terms of grid behavior). Numerous other historical examples, which include jet engines in airplanes, automatic transmissions in automobiles, the computer mouse and random access memory, also indicate that sub-system level innovations can drive major system-performance improvements. The potential for governments to stimulate such developments through subsidies or other forms of policy support should be explored through further research.

### 6.3. *Interaction of artifact and knowledge dimensions along technological trajectories*

Our extension of the methodology introduced by Verspagen (2007) and others allows to study the knowledge and the artifact dimensions of technological trajectories in an integrated way. We believe that the presented methodology can yield particularly valuable insights in two directions.

First, it can be used to study the interaction between the knowledge and artifact dimensions of technological trajectories in greater detail. If data on the knowledge trajectory is systematically compared to data on product designs and market shares, further conclusions may be drawn about the mechanisms of influence between the two. In particular, future research could investigate the relative timing of shifts in the knowledge trajectory and the emergence of dominant sub-system designs in the market. Our results for the case of wind turbines suggest that different modes of innovation were prevalent in different parts of the trajectory. Interestingly, there is variation on the rotor-level of the core trajectory until 1991, while the dominant rotor design in the market (>50% from 1986) had emerged about five years earlier (cf. Figs. 5 and 7). This points to a non-linear model of innovation in the design of wind-turbine rotors and an important role of learning by doing and using in the early years of the industry. The shift away from the power-train level (around 1997), however, took place long before the dominant design had been established in the market (>50% from 2003). This indicates a more linear model of innovation in this period. The shift from a non-linear to a more linear relationship between knowledge production and artifact commercialization in the 1990s corresponds well with qualitative accounts of the wind industry (Garrad, 2012; Garud and Karnøe, 2003; Hendry and Harborne, 2011). This means that differences in learning mechanisms can be observed when comparing the evolution of knowledge and the evolution of artifacts. It also means that shifts in the predominant mode of innovation might be rooted not only in the maturation of the industry, but also in differences in the technological nature of the two sub-systems, in this case the rotor and the power train.

Second, our results suggest that the methodology can be used as a meaningful *proxy for the evolution of artifacts* along the hierarchy of control. In many cases this can facilitate a deeper look into a technological trajectory's inner dynamics, since many technological developments may be concealed when only data on design specifications in the market is examined. Patent data is relatively easy to access and process, whereas data on commercialized designs may not always be available in standardized form and sufficient detail. For example, our analysis allowed us to analyze how knowledge generation shifted across intangible components such as wind-farm integration strategies and power train control systems.[22] Our results also point toward the ability to approximate the emergence of a dominant design in a specific component that cannot be easily observed statistically by analyzing the shift of the *knowledge* trajectory away from that component. Furthermore, the richness of patent data may facilitate detailed analyses of the role of different types of actors along the trajectory, as well as spatial aspects of technological evolution.

### 6.4. *Limitations and future research*

Two assumptions that limit the generalizability of our findings are worth noting. First, we assumed that the hierarchy of design decisions is stable over time and across countries. This assumption could be relaxed for a more detailed analysis of specific regions or time periods. On the one hand, service characteristics may not always be equally important, and their weighting may depend on characteristics of customers, institutions, and geographies. On the other hand, service characteristics and their weight may change over time as customers learn about technology and their needs. These limitations offer fruitful avenues for future research. Second, in identifying the trajectory of knowledge generation, we approximated knowledge with patented inventions. This introduces a bias against knowledge that is openly shared, tacit, or protected through means other than patenting. In the case of wind turbines, the knowledge pertaining to blade production in particular is typically not patented but protected as a trade secret. The fact that we found very few process patents along the trajectory may be due to a bias against process knowledge in general. Furthermore, many small wind turbine manufacturers did not patent much in the early years of the industry, possibly causing our analysis of the variation of core trajectories over time (Fig. 7) to underestimate how early the industry converged on the current dominant knowledge trajectory.[23] Future research could apply qualitative methodology to capture the evolution of knowledge more holistically along the trajectory.

## 7. Conclusion

Studies of technological evolution provide ample evidence that a product's hierarchy of design decisions, or *design hierarchy*, influ-

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[22] Patent-citation data may also serve to identify the product architecture itself, in a methodology similar to that of Baldwin et al. (2014).

[23] Our analysis of the current dominant knowledge trajectory, shown in Fig. 8, should be unaffected by this bias because the algorithm identifies the foundations and history of the current core trajectory ex-post.

ences the evolution of artifact designs available in the market. Much less is known about the design hierarchy's effect on the evolution of the knowledge base of an industry. To address this gap, this paper employed the case of wind turbine technology over the period 1973–2009. We developed a methodology by linking a recently developed, quantitative approach to studying the knowledge dimension of technological trajectories to methods for studying the evolution of systemic artifacts. This novel approach allows us to relate systemic relationships between sub-systems and components in the physical artifact to patterns in the direction of knowledge generation, and it may facilitate a better understanding of the interaction between the knowledge and the artifact dimensions of technological trajectories.

Our results unmask a sequential pattern in the emergence of an industry-specific knowledge base along the technological trajectory, structured by the product's design hierarchy: The trajectory of knowledge generation is marked by *creative sequences*, the focus of which shifts over time between different sub-systems, with each shift initiating the integration of new domains of industry-external knowledge into the knowledge base.

These findings have implications for the literature on knowledge positions and competitive advantage. Whenever sub-systems of an artifact depend on different knowledge domains, windows of competitive opportunity for firms and nations with knowledge in adjacent sectors can arise *along the trajectory*, if the adjacent sector is related to the sub-system that moves into the focus of innovation. In other words, what constitutes a good knowledge position to enter a specific industry may change significantly over time. This may help explain – and even anticipate – shifts in the competitive landscape that occur in the absence of discontinuities in the trajectory.

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## Appendix A.

**Table A1**
Wind-specific engineering tasks and main involved knowledge domains.

| Components | Engineering tasks | Main knowledge domains |
|---|---|---|
| Rotor | | |
| Blades | Aerodynamic and structural design of rotor to capture wind energy | Aerodynamics; structural dynamics (mechanics) |
| | Design of non-destructive testing equipment and procedures | Optics; robotics; mechanical engineering |
| | Development of tailored structural materials and coating | Materials science; chemistry |
| | Processing of large-scale composite components and core materials | Chemical, mechanical and thermal process engineering; automation engineering |
| | Design of equipment and routines for transport and installation of rotor blades | Logistics, mechanical engineering |
| Hub | Structural design and integration of O&M and control features | Aerodynamics; structural dynamics (mechanics) |
| Rotor control system (pitch and yaw mechanisms), control routines | Design of rotor control strategy and software | Aerodynamics; control engineering, software engineering |
| | Design and integration of electric motors, gears, hydraulics and power sources | Electrical, mechanical, and control engineering |
| Power train | | |
| Mechanical drive-train: Rotor shaft, bearings, gearbox, couplings | Design of drive-train architecture | Mechanical engineering |
| | Dimensioning and material selection for hub, bearings, shafts, brakes, gearbox, lubrication, joints and couplings | Material science; structural dynamics (mechanics) |
| Electrical drive-train: generator, power electronics | Design of generator topology | Electrical engineering, electronics |
| | Design and dimensioning of generator, power electronics, and cooling systems | Electrical engineering; electronics, thermodynamics |
| Power-train control system and routines | Design of rotor control strategy and software | Aerodynamics; control engineering, software engineering |
| | Design and integration of switch board, sensors, actuators (e.g., brakes) and power sources | Electrical, mechanical, and control engineering |
| Mounting & encapsulation | | |
| Nacelle, spinner and bedplate | Design of load transfer, noise insulation and thermal management | Mechanics; acoustics; thermodynamics |
| | Aesthetic and aerodynamic design | Industrial design; aerodynamics |
| Tower | Choice of tower shape, modularity, and structural materials | Materials science |
| | Dimensioning against bending and fatigue | Structural dynamics (mechanics); mechanical engineering |
| Foundation | Dimensioning for static and dynamic load transfer | Mechanics; civil engineering |
| Climate & vibration control system and routines | Design of control strategy and software | Thermodynamics; structural dynamics; control and software engineering |
| | Design and integration of dampers, sensors and climate conditioning system | Thermodynamics; control engineering |
| Grid connection | | |
| Transformer/substation and power cables | Design of wind-farm circuitry, voltage transfer, electrical insulation | Electrical engineering |
| Storage | Choice and design of storage technology | Electrical engineering, electronics |
| Grid-impact and wind-farm control system and routines | Design of control strategy and software | Electrical, control and software engineering |
| | Design and integration of control system elements | Electronics; control engineering |

**Table A2**
Design options within the product architecture of horizontal axis wind turbines operating on the lift principle.

| Salient design features | Design options (today's most common design in bold) |
|---|---|
| Wind turbines (system-level) | Vertical axis, **horizontal axis**; drag-based, **lift-based** energy extraction |
| Rotor | |
| Rotor position relative to power train and tower | **Facing the wind (upwind)**, facing away from the wind (downwind) |
| Rotor size | 5–160 m diameter (~**100 m**) |
| Number of blades | 1, 2, **3**, many |
| Rotor speed control | Aerodynamic ('stall-controlled"), rotation of blades around own axis to control lift ('**pitch**"), hybrid forms |
| Rotor orientation control | **Yaw drive**, positioning vane |
| Rotor material | **Glass fiber reinforced plastics**, carbon fiber reinforced plastics, wood composites, aluminum, steel |
| Rotor fixation | **Fixed,** hinged, teetered |
| Power train | |
| Number of bearings | 1, **2**, 3 |
| Mechanical transmission | **Gearbox**, without gearbox ('direct drive') |
| Number of transmission ratios ('speeds') | 1–5 fixed speeds, **variable speed** |
| Number of generators | **1**–4 |
| Generator size/type | 5 kW–7.5 MW (~**3 MW**)/**asynchronous** (**wound rotor**, squirrel cage), synchronous (permanent, wound rotor) |
| Power converters (rectifier & inverter) | Full, **partial**, none |
| Mounting & encapsulation | |
| Nacelle/spinner | None, reinforced-plastic cover |
| Tower structure/height | **Tubular**, lattice/20–130 m (~**100m**) |
| Foundation | Concrete slab, pile |
| Grid connection | |
| Storage | **None**, battery storage, compressed-air storage |
| Grid-integration control | None, fault ride-through capability, power control capability |

**Table A3**
Goodness-of-fit test of distribution of patent citations from sub-system i to sub-systems j = 1. . .4 with a null hypothesis that the distribution of citations follows the distribution of possible recipient patents (citations to system-level patents were excluded).

| Citations from patents categorized into sub-system. . . | N | Degrees of freedom | $\chi^2$ | p |
|---|---|---|---|---|
| Rotor | 400 | 3 | 271 | <0.001 |
| Power train | 885 | 3 | 318 | <0.001 |
| Mounting & encapsulation | 651 | 3 | 458 | <0.001 |
| Grid connection | 886 | 3 | 555 | <0.001 |

**Table A4**
Design hierarchy, as determined by relationship between components (rows) and un-weighted service characteristics (columns).

| System/sub-systems/components | Initial cost | | Reliability & durability | | Electrical characteristics | | Environmental impact | | Others | | Pleiotropy[b] | Hierarchy of nested parts/Hierarchy of control[c] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Turbine cost | Cost pf transport, installation & disassembly | Availability& O&M cost | Lifetime | Power curve | Grid behavior | Visual impact | Noise emissions | Operational safety | Suitable climate conditions | | |
| Wind turbine (system-level) | X[a] | X | X | X | X | X | X | X | X | X | 10 | 1 |
| Rotor | X | X | X | X | X | X | X | X | X | X | 10 | 2/A |
| Rotor blades | X | X | X | X | X | X | X | X | X | X | 10 | 3 |
| Hub | | X | X | X | X | | | | | X | 5 | 3 |
| Rotor control | X | | X | X | X | X | | X | X | X | 8 | 3 |
| Power train | X | X | X | X | X | X | | X | X | X | 9 | 2/B |
| Mechanical drive-train | X | X | X | X | X | X | | X | X | X | 9 | 3 |
| Electrical drive-train | X | X | X | X | X | X | | X | X | | 8 | 3 |
| Power-train control | | | X | X | X | X | | X | X | X | 7 | 3 |
| Mounting & encapsulation | X | X | X | | X | | X | X | X | X | 8 | 2/C |
| Nacelle, spinner & bedplate | | X | X | | X | | X | X | | X | 6 | 3 |
| Tower | X | X | | | X | | X | | | | 4 | 3 |
| Foundation | | X | | | X | | | | | | 2 | 3 |
| Climate and vibration control | | | X | | | | | X | X | X | 4 | 3 |
| Grid connection | X | | X | | X | X | | X | X | | 6 | 2/D |
| Transformer/substation and power cables | X | | X | | X | X | | X | X | | 6 | 3 |
| Storage (if applicable) | X | | X | | | X | | | X | | 4 | 3 |
| Wind-farm and grid-integration control | | | X | | X | X | | | X | | 4 | 3 |

[a] Each x marks an influence of the sub-assembly or the individual component (in rows) on the main service characteristic (in columns).

[b] The pleiotropy is the count of influences per row.

[c] The number of the design hierarchy indicates the hierarchy of nested parts (1 = system, 2 = assembly of components, 3 = component); the capitalized letter indicates the hierarchy of control on each level (A = highest pleiotropy, B···D sorted accordingly).

**Table A5**
Patents along critical path of wind-patent citation network 1973–2009.

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

**Table A6**

Shifting focus in hierarchy of control along trajectory of knowledge generation, indicated by share of vertex weight in 95%-weight network in different elements of the system (number of patents in each category in parentheses).

| | 1975–1979 | 1980–1984 | 1985–1989 | 1990–1994 | 1995–1999 | 2000–2004 | 2005–2009 |
|---|---|---|---|---|---|---|---|
| Wind turbine (system-level) | 0.02 (2) | 0.00 (1) | 0.04 (3) | 0.07 (3) | 0.08 (3) | 0.00 (2) | 0.01 (4) |
| Rotor | **0.77 (12)** | **0.76 (17)** | 0.05 (7) | 0.04 (2) | 0.01 (3) | 0.02 (11) | 0.18 (60) |
| Power train | 0.13 (5) | 0.16 (5) | **0.91 (8)** | **0.86 (7)** | **0.78 (14)** | 0.34 (39) | 0.23 (67) |
| Mounting & encapsulation | 0.04 (1) | 0.05 (3) | 0 (0) | 0.02 (2) | 0.03 (8) | 0.18 (20) | **0.32 (67)** |
| Grid connection | 0.04 (1) | 0.04 (1) | 0 (0) | 0.01 (1) | 0.10 (6) | **0.46 (34)** | 0.25 (75) |

**Table A7**

Shifting focus in hierarchy of control, indicated by number of forward citations of top 100 most highly cited patents in the database (number of patents in each category in parentheses). Note that there are only very few patents toward the end of the observed time period because these patents had comparatively little time to get cited.

| | 1975–1979 | 1980–1984 | 1985–1989 | 1990–1994 | 1995–1999 | 2000–2004 | 2005–2009 |
|---|---|---|---|---|---|---|---|
| Wind turbine (system-level) | 75 (2) | 83 (2) | 75 (1) | 64 (1) | 37(1) | 121 (3) | 0 (0) |
| Rotor | **303 (6)** | **220 (5)** | 59 (1) | 78 (2) | 233 (4) | 472 (11) | **42 (1)** |
| Power train | 0 (0) | 109 (3) | **191 (4)** | **372 (5)** | **507 (8)** | 451 (9) | 0 (0) |
| Mounting & encapsulation | 42 (1) | 92 (2) | 0 (0) | 44 (1) | 272 (6) | 252 (6) | 0 (0) |
| Grid connection | 43 (1) | 0 (0) | 0 (0) | 0 (0) | 124 (3) | **469 (11)** | 0 (0) |

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