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Published in:
Science and Public Policy

DOI (link to publication from Publisher):
10.1093/scipol/scv055

Publication date:
2016

Document Version
Accepted author manuscript, peer reviewed version

Science and Public Policy Advance Access published September 29, 2015

Science and Public Policy, 2015, 1–16
doi: 10.1093/scipol/scv055

Comparing the knowledge bases of wind turbine firms in Asia and Europe: Patent trajectories, networks, and globalisation

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Abstract

This study uses patent analyses to compare the knowledge bases of leading wind turbine firms in Asia and Europe. It concentrates on the following three aspects: the trajectories of key technologies, external knowledge networks, and the globalisation of knowledge application. Our analyses suggest that the knowledge bases differ significantly between leading wind turbine firms in Europe and Asia. Europe's leading firms have broader and deeper knowledge bases than their Asian counterparts. In contrast, the leading Chinese firms, with their unidirectional knowledge networks, are highly domestic in orientation with respect to the application of new knowledge. However, Suzlon, the leading Indian firm, has a better knowledge position. While our quantitative analysis validates prior qualitative studies it also brings new insights. The study suggests that European firms are still leaders in this industry, and leading Asian firms are unlikely to create new pathways that will disrupt the incumbents in the near future.

Key words: patent analysis; wind turbine firms; knowledge base; knowledge flow; network analysis; Asia and Europe.

1. Introduction

The wind power industry plays a key role in the efforts of European and Asian countries to promote renewable energy. Wind energy, as the most commercialised and successful type of renewable energy currently available (Lema et al. 2014), has experienced a stable, high average growth in the past 15 years. Led by European firms for many years, the recent rise of emerging economies has made them significant competitors in the global wind market. There is a debatable assumption that these rising powers might build specific knowledge bases, and even challenge the traditional leaders (most of whom are European firms) through future leapfrogging.

Firms' knowledge bases are considered significant in relation to competitiveness and future pathways (Nesta and Saviotti 2005).[1] Considering knowledge as competitiveness, a strong knowledge position may offer advantages that increase opportunities for sustainable development, market leadership or even leapfrogging (Pavitt et al. 1997). A strong knowledge position may also bring bargaining power and serve as a source of knowledge-based revenue (Bekkers et al. 2002). From an evolutionary perspective, firms' choices regarding key technologies and other settings may influence future pathways (Dosi 1982). Such path dependency may also imply that the knowledge bases of different firms do not necessarily converge toward a single best practice, as the firms' specifics and the contextual embeddedness of such evolutionary processes may result in diverse trajectories (Schmitz and Altenburg 2015, this issue). To date, there has only been limited research on this topic.

These knowledge base concepts can be characterised by various methodologies, and a patent-based lens is frequently used. In recent years, patent profiles have been increasingly employed to understand knowledge trajectories (Ernst 2003; Damrongchai et al. 2010). Others have used essential patents to map or forecast future pathways (Jeong and Yoon 2015). On the other hand, assuming that knowledge reflects competitiveness, some recent research has used patent counts to explicate the core technologies and portfolio strategies (Tseng et al. 2011; Ju and Sohn 2015). In more advanced cases, patent network has been used to analyse the global knowledge flow, such as learning and spillover within industries and across national borders (Bekkers and Martinelli 2012).

Given the success of these patent-based approaches, it may be promising to extend these quantitative methods to explore whether Asian wind firms might build a unique knowledge base for technological leapfrogging. We believe that doing so may offer a unique perspective with quantitative estimates, as other contemporary researchers are exploring international comparisons of wind turbine manufacturers from a qualitative perspective (Lema et al. 2014; Dai et al. 2014). In this study, our goal is to integrate and use a set of patent-based methodologies to address the following question:

> To what extent and how do the patent knowledge bases differ between leading wind turbine firms in Asia and Europe?

We also explore what these differences between knowledge bases tell us about the global competition between the leading firms and the policy implications. This study focuses on three aspects related to examining firms' knowledge bases: the trajectories of key technologies (measured by patents), external knowledge networks for patents, and the globalisation of knowledge applications, with a focus on patenting efforts. Six wind turbine firms serve as representative cases in Asia and Europe: Goldwind (China), Mingyang (China), Suzlon (India), Enercon (Germany), Siemens (Germany), and Vestas (Denmark).

The remainder of this paper is organised as follows. Section 2 provides a narrative of the wind industry and its leading firms. Section 3 discusses our methodology. Section 4 compares the cases. Section 5 discusses the findings and draws conclusions.

2. Wind turbine industry and leading firms: Narratives of key knowledge activities

The wind energy industry has achieved rapid growth, and will continue to grow. The global share of electricity generation from wind could reach 12% by 2050 (International Energy Agency 2009). Initially, for more than 30 years the developed countries led the attempts to develop wind power energy in terms of both the technology and market occupation (Lema et al. 2014). However, in the past decade, the distribution of the world wind energy market has reflected an obvious strong shift in production capacity and scale of deployment. In the late 2000s, emerging economies such as China and India began to catch up and rapidly gained a large market share (Dai et al. 2014; Narain et al. 2014).[2] In 2013, both China and India had wind turbine firms that were listed among the top five market owners (Goldwind was second and Suzlon was fifth) in terms of accumulated installation capacity.[3] Thus, China and India may play more significant roles in wind knowledge activities.

Here, we specifically focus on the key dimensions of knowledge bases that may highlight the knowledge differences: as mentioned above, the differences may imply dissimilar future pathways. First, the trajectories of key technologies are primarily important to a firm's knowledge bases (Lema et al. 2014). They are important because they determine the size, shape and direction of decisions by firms about key technologies and patenting strategies. Second, the external knowledge network and firms' relative position is also a critical dimension, while knowledge transfer (flow) and collaboration activities can reflect network positions (as an innovation leader or follower) and are essential to develop the bases (Bekkers and Martinelli 2012). This is particularly important as China and India have depended for many years on technology transfer and technology collaboration for accessing state-of-the-art wind energy technology, while indigenous innovation is a relatively new phenomenon. In addition, the globalisation attempt is another significant dimension, and the globalisation of knowledge applications can provide insights for interpreting firms' ambitions toward global markets (Dai et al. 2014). This provides evidence about lead markets and firm leadership at an international level. Thus, we will examine these three knowledge dimensions, and the following narratives may provide a reference point for the understanding of lead firms' knowledge bases.

2.1 Trajectories of key technologies

In the wind power industry, the key technologies of wind turbines consist of various aspects (Lema et al. 2014). Wind turbine design may be the most important indicator for studying the technological trajectories, because such designs can be viewed as platforms supporting continuous incremental innovations. There are two major platforms for wind turbines: gear and gearless models. The gear model can be traced back to the early 1900s in Demark as the 'Danish design' (Lema et al. 2014). To date, the gear model still occupies the majority of the wind turbine market share (e.g. 72% in 2013 (BTM Consult 2013)). Vestas maintains the gear model with a platform known as dual-fed induction technology (DFIT). Most wind manufacturers (e.g. Gamesa, Suzlon etc.) are following this path. The other major platform is the gearless or direct drive (DD) model which accounts for a smaller but steadily increasing market share (from 14% in 2007 to 28% in 2013 (BTM Consult 2013)). The development of the DD technology was also driven by European firms (mostly German), and initially developed by Enercon. Based on Enercon's DD design, the permanent magnets DD (PMDD) has also been developed by German companies such as Vensys and Siemens (offshore). China's Goldwind, after collaborating with Vensys, has participated in this group and significantly contributed to the increase in market shares since 2006.

The other recent indicator is the turbine size, mainly due to emerging offshore technologies, and all of the world's leading manufacturers are competing. For example, Enercon developed 126 offshore turbines (7.5 MW capacity) in 2007, and Vestas developed 8.0 MW offshore turbines in 2010. In addition, larger up-scaled turbines (10–20 MW) are being explored by lead companies such as Enercon, Vensys etc. (Lema et al. 2014). Chinese manufacturers have also participated in this race, with prototypes for 8–10 MW turbines since 2011 (Dai et al. 2014).

Other essential technological aspects may be related to those turbine technologies that complement the above platforms' reliability and quality when concerned with deployment, possibly including control technologies and grid connections. In this regard, it has been argued that high-tech firms benefit from diverse technology portfolios whereas low-tech firms need to have higher concentrations (Lichtenthaler 2010). However, there has been limited inquiry into the specific wind sector. Furthermore, it has been argued that Asian wind turbine firms are specialised in developing customised turbines that are high altitude compatible, sand proof etc. (Dai et al. 2014). This also requires empirical examination.

2.2 Knowledge transfer (flow) and collaboration

Knowledge flow and collaboration play key roles in developing knowledge bases (Bekkers and Martinelli 2012). Specifically, in the wind turbine sector, knowledge flow in terms of learning and spillover is prominent. European firms started earlier, in the 1970s, and thus have been first movers in R&D and frontier wind technologies that create spillover knowledge. India started local manufacturing in the mid-1990s and China in the late 1990s. As latecomers, Indian and Chinese wind turbine firms strove to catch up with the learning, and benefited significantly from technology transfer and cooperation in the form of foreign aid, joint ventures, licensing and international acquisitions (Lewis 2013). For example, some researchers have found that most Chinese turbine manufacturers (26) have technological links with European (mostly German) knowledge-intensive firms (Schmitz and Lema 2015). Specifically, Goldwind has conducted joint development with Vensys and received licensing from Jacobs/Repower (Goldwind later acquired Vensys in 2008) while Mingyang engaged in joint development with Aerodyn (Lewis 2013). Meanwhile, Indian firms have also been very active in acquiring external knowledge through the network. In the late 2000s, Suzlon in India bought the Sudwind R&D team in Germany and a blade-manufacturing factory in Amsterdam. Suzlon then produced turbines for the Indian market by leveraging their acquired expertise abroad (Narain et al. 2014). These knowledge activities, however, are rather anecdotal and require empirical data for in-depth inquiries.

Collaboration is also significant for knowledge bases. Innovative firms can leverage alliances to access intellectual resources that promote more efficient R&D in this open innovation era (Chesbrough 2003). Wind firms also collaborate within the networks. According to Lema et al. (2014), the network may be the value chain that produces and assembles a wind turbine's components between major wind manufacturers (e.g. Vestas, Enercon etc.) and specialised component suppliers (e.g. LM Glasfiber is the world's largest manufacturer of rotor blades). Collaboration may also happen beyond component suppliers and may involve project developers. For example in Europe, Ramboll offers engineering and planning services, including structural design, to the offshore wind industry (Lema et al. 2014). This also requires empirical enquiries.

2.3 Globalisation attempts

In this globalisation era, many wind turbine firms are attempting to become, or have already become, international firms with a global reach. For example, Vestas is no longer a 'Danish firm' but rather a global firm that only sells a small fraction of its wind turbines to Denmark (Lema et al. 2014). For Vestas and Enercon, the growth comes from other markets outside Europe and their R&D is organised globally, although firmly coordinated from Denmark and Germany (BTM Consult 2013). Siemens, Gamesa and General Electric are considered to be regional suppliers that produce technologies within their home countries but send active exports to the global markets. Chinese and Indian wind firms are still rather domestic, but are striving to participate in the globalisation activities in addition to their previous efforts toward international knowledge transfer. Suzlon acquired Repower in 2007 for global market access and technologies—a rare acquisition between the mainstream wind turbine manufacturers. Goldwind, however, acquired Vensys (a German design firm) in 2008 and became the largest exporter of wind turbines in China (approximately 90%) in 2011 (Dai et al. 2014).

3. Methodology

3.1 Research design and case selections

Following Yin (2003), we selected six leading firms as representative cases (see Table 1) for our cross-case comparison using a patent-based analysis. The analysis followed the methodological success of prior patent studies (see Section 3.2), focusing on the trajectories of key technologies, knowledge networks (e.g. knowledge flow and collaboration), and globalisation patent families.

The selection process was purposive rather than random. A theoretical sampling procedure applied two case selection criteria: first, the firms are leading wind manufacturers in their home countries with a global reach; and second, they have specific knowledge competitiveness that can be analysed using patents. Hence, we deliberately selected the top five firms in the world (see Section 1.1): Vestas from Denmark, Enercon and Siemens from Germany, Goldwind from China, and Suzlon from India.[4] In addition, we included a specific Chinese private firm (Mingyang, ranked ninth globally) to provide diversity. These selected cases have sufficient heterogeneity (see Table 1) to create a contrast between cases that ensures the internal validity of this research.

3.2 Patent analysis methods

As mentioned, we investigated the six cases through three sets of patent analyses. The first (Section 3.2.1) and third (Section 3.2.3) were based on key patent counts and categorisations and the second (Section 3.2.2) used network-based methodologies to analyse patent citations. We used worldwide patent data for the international comparisons (see Section 3.3 for details) and adopted the Derwent Classification with Manual Code (DCMC) to categorise the key technologies.

3.2.1 First set: Trajectories of key technologies

In recent years, patent analysis has been applied to analyse trajectories and key technologies (Ernst 2003). For example, some researchers have attempted to use key patent data to map technological trajectories (Lee and Lee 2013; Jeong and Yoon 2014) and explore emerging trends (Ju and Sohn 2014). Specifically, in the wind power industry, patent research has been conducted to study wind development at the sectoral level (Dubarić et al. 2011). In this study, we attempt to extend the above methods to study the trajectories of the key technologies (see Section 2.1) of leading wind turbine firms.

Following previous fieldwork and based on relevant concepts (Teece 1986; Ju and Sohn 2015; Phan and Daim 2013), we used four dimensions to analyse key technologies through patents (also see Section 2.1): platform technologies, complementary technologies, emerging technologies and customised innovations (especially for innovation followers).[5] With the assistance of wind experts, we began by defining the generator and drive system technologies as the platform technologies of wind turbine firms, including gearless DD including PMDD, and gear-based dual- or single-fed induction technology (DFIT/SFIT). In addition, the grid connection and control system was viewed as the key complementary technology in improving the reliability and quality of wind turbines. Offshore wind turbine technology was recognised as the most important emerging technology because it is very different from onshore in terms of design, control, grid connection etc. Finally, the customised innovation of wind turbine firms includes designs for niche markets, including: high-altitude, low wind speed, extreme temperature, sand proof etc.

3.2.2 Second set: Knowledge networks (knowledge flow and patenting collaborations)

3.2.2.1 Knowledge flow (learning and spillover). Knowledge networks are significant for knowledge flow (transfer) between firms. Recently, researchers have used patent citation-based methods to examine the knowledge networks for strategic analysis. Specifically, some have used the citation network indicators (e.g. centrality) to identify the key players (so-called nodes) and their knowledge positions (Bekkers and Martinelli 2012), measure knowledge flows between entities (Braun et al. 2010; Ju and Sohn 2015; Li-Ying et al.

Table 1. Sample wind manufacturers in Asia and Europe

	Goldwind	Mingyang	Suzlon	Enercon	Vestas	Siemens
Employment size	4162	4600	10000	13000	17778	370000
Age (years)	16	8	19	30	33	167
Market share (2012)	6.0%	2.7%	7.4%	8.2%	14%	11.0%
Patents (basic, by 2012)	231	200	314	337	1061	294
Patents (family, by 2012)	233	228	1772	4826	5093	453
SCI papers (by 2012)	2	0	14	3	105	156
Country	China	China	India	Germany	Denmark	Germany

For most cases of mergers and aquisitions, we did not include transfer of target firms' patents to acquirers, either because they were not clearly significant (e.g. Flender to Siemens, Hansen to Suzlon etc.), or the acquirers had no exclusive rights on the target firms (e.g. Goldwind and Vensys). For Suzlon, we provided the patent discussion on both 'Suzlon only' and 'Suzlon and Repower'. However, in some circumstances due to data complexity (see Section 4.2, knowledge network part), we only retained the acquirers in the network when cleaning patent assignees by combining the parties to the mergers and aquisitions (e.g. Repower's patents to Suzlon)

2013), and even indicate technological trends (Karvonen and Kässi 2013).

Drawing on the existing approaches, we used patent citation network analysis to assess the importance of the technology attributes of our sample wind firms within the industrial network. In this study, the starting point was the knowledge network of wind turbine patents (4,457 items of raw data, see Section 3.3). Because the patents are owned by the wind firms, we set up a network of cumulative patents at the company level (the top 15 firms plus Vensys and Aerodyn, see Section 4.2). The resulting network revealed an overview of patents and citation links in which the nodes represent key firms (their cumulative patents) and the links are the cumulative citations in-between. The literature has argued that the links can represent knowledge flows (between firms, excluding self-citations), if a patent cites another patent. We call the former a backward citation (citing) and the latter a forward citation (cited). In Fig. 5 (see Section 4.2.1) we set the size of the node to denote the number of patents owned by firms (i.e. the larger the node, the larger number of patents). The thickness of the lines (links) also illustrates the intensity of the citations.

To study the knowledge network structure, we applied several indicators such as density, average distance, fragmentation, hybrid reciprocity and out- and in-degree centrality.[6] This allowed us to analyse the cohesion and centrality of the network while creating descriptive statistics for the entire network, based on three indicators, as shown in Table 2. The network diagram based on the citation matrix between patent assignees analyses the position of a particular firm in each network. The network contains two types of companies: one is at the obvious core of the network (knowledge spillover as leaders) while the other is at the periphery (learners). The black circles indicate the (core) leading spillovers and the white squares indicate the peripheral learners. Analysing each company's network structure provides a better understanding of their roles within the network. We also used betweeness centrality to measure the degree of resources controlled by the core firms (see Table 3).

3.2.2.2 Patenting collaboration: R&D collaboration between entities can expedite the innovation process by providing diverse opportunities and ensuring that resources are used efficiently (Chesborough 2003). Specifically, some recent research has explored specific sectors (e.g. nanotechnology, photovoltaic etc.), arguing that R&D collaboration positively affects R&D output in terms of patenting (Luciano et al. 2014; Li et al. 2015). Following this, we used the co-patenting relationships to indicate the collaborative innovations. Based on the patent data of sample firms (see Section 3.3), we used data mining techniques to build the co-patenting matrix of relevant patent assignees, based on which we studied the co-patenting activities between the six firms and their collaborators in patenting.

3.2.3 Third set: Globalisation intent

Limited studies have used patents to probe wind firms' globalisation efforts, particularly when firms may have strategic options regarding global competition with standardised innovative products (with considerable international patents) or are competing in the domestic market by using customised technologies (with more domestic and limited international patents). Gosens and Lu (2014) made one of the few attempts to explore this issue in the wind sector, arguing that global intellectual property is critical for sustainable competitiveness in a global sense. Following this, we used the counts of the patent family (a series of patents taken in various countries to protect the prior basic patent) to understand the global market diffusion efforts of the leading wind firms. In general, more family patents indicated the firms' strategic intentions with regard to going global.

3.3 Patent data

We needed appropriate patent data to compare the international cases. The first and third analyses required a dataset that covered worldwide patent applications and patent families across different regimes. The second network-based analysis required another dataset that contained citation relations between these patents. Below, we briefly describe the patent databases and both datasets.

Following de Rassenfosse et al. (2013) and Nepelski and De Prato (2015), we used worldwide patent data (across various offices) to compare firms from developed and developing economies (see Section 4.4). We retrieved the worldwide patent data from the well-recognised Derwent World Patents Index (DWPI) and Derwent Patents Citation Index (DPCI) databases through the Thomson Innovation (TI) search engine. The DWPI and DPCI are integrated databases with patent and citation data from 50 patent-issuing authorities around the world,[7] rewritten by experts at Thomson Reuters for better interpretation, standardisation and error reduction. The DWPI and DPCI are viewed as better choices than other world patent databases in terms of comprehensiveness, accuracy and consistency across countries for both patent counts and citation

Table 2. Changes in knowledge network: Descriptive comparative data

Indicators	Time		
	1993–2006 network	2007–12 network	Full-time network
Density (containing self-citations)	19.6758	12.2872	29.5121
Density (excluding self-citations)	17.9792	10.8162	26.511
Average distance	1.153	1.485	1.441
Fragmentation	0.423	0.225	0.206
Hybrid reciprocity (percentage of reciprocated total links)	0.4767	0.4808	0.4775
Out-degree centrality	0.22671	0.17632	0.20337
In-degree centrality	0.13248	0.15408	0.15192

Table 3. Centrality indicators for 17 firms (including our six sample firms)

Firm/indicators	1993–2006				2007–12			
	Betweenness	Out-degree centrality	In-degree centrality	Net citations	Betweenness	Out-degree centrality	In-degree centrality	Net citations
Enercon	2.531	1087	325	762	6.123	535	155	380
Vestas	2.763	615	727	−112	26.825	441	658	−217
Siemens	4.346	563	635	−72	24.123	301	607	−306
Suzlon	2.181	269	645	−376	4.434	327	340	−13
General Electric	4.346	972	695	277	9.123	728	446	282
Gamesa	0.905	159	467	−308	2.634	279	202	77
Nordex	1.208	169	474	−305	9.303	127	240	−113
Aerodyn	4.346	374	77	297	1.277	106	46	60
Vensys	0.375	101	22	79	1.401	51	13	38
XEMC	0	7	81	−74	44.404	23	50	−27
Goldwind	0	0	28	−28	0.451	8	25	−17
Shanghai	0	0	21	−21	0.111	6	10	−4
Mingyang	0	0	12	−12	1.336	4	38	−34
Envision	2.531	0	24	−24	0.011	2	40	−38
Sinovel	0	0	52	−52	0.458	2	40	−38
Dongfang	0	0	0	0	0	1	5	−4
Guodian United	0	0	0	0	0	0	31	−31

data. In addition, the DCMC system provides good data consistency across regimes and application-oriented codes.

Our first dataset for worldwide patent counts was retrieved from the DWPI database for the analyses of trajectories (see Section 4.1) and globalisation (see Section 4.3). Overall, we searched the patent data of the six cases (see Appendix 4), with the patenting year (the priority year of submissions) during the period 1993–2012 (1993 was the earliest year of our patent records of the six cases). For the first set of the analysis (see Section 4.1), we used the basic patent applications for analysis as they were a better indicator of the original inventive activities. We only considered 'priority patent applications'. In order to avoid double-counting all patent family members, only the first filing of the basic patent application was considered and all possible successive filings of the same invention to different patent offices were discounted. As a result, 2,437 basic patents were collected for the six firms after the data cleaning process. For the third set of the analysis (see Section 4.3), we used patent family members instead, also drawn from the DWPI database. In this case, we searched 12,605 patents for the six firms as family members in more than 20 countries.

The second dataset for the global network analysis (see Section 4.2) also used worldwide patent citation data, following Karvonen and Kässi (2013) and Bekkers and Martinelli (2012). Citation data across different regimes was again used in order to reduce the bias of using a single-office patent, especially when considering developing economies (see Section 4.4). We used the DPCI database because it was highly integrated and aligned with the DWPI database under the TI framework (data matching is more than 99.9% for the six cases), with the standardised patent data and classifications. The DPCI citation data also included citations from patent family members when eliminating the double counts by TI experts. This was one of the most significant advantages of the DPCI, which was comprehensive yet with limited duplicates, especially compared with other citation databases (e.g. EPO Worldwide PATSTAT). In this study, we searched 4,457 patent data records for a citations network (see Appendix 2) containing 17 international firms, with 2,435 for the six sample wind firms. Further, using the 2,435 patents, we developed the collaboration networks (see Fig. 8 in Section 4.2.2) between the six sample firms and their collaborators (see Section 4.2).

4. Empirical analysis: Trajectories, networks and globalisation

In this section, we present the findings of our empirical analyses performed according to the methodologies discussed above. We begin with the analyses of the trajectories of the key technologies and continue with the knowledge networks in terms of knowledge flow and collaboration before presenting the results of the globalisation patenting efforts.

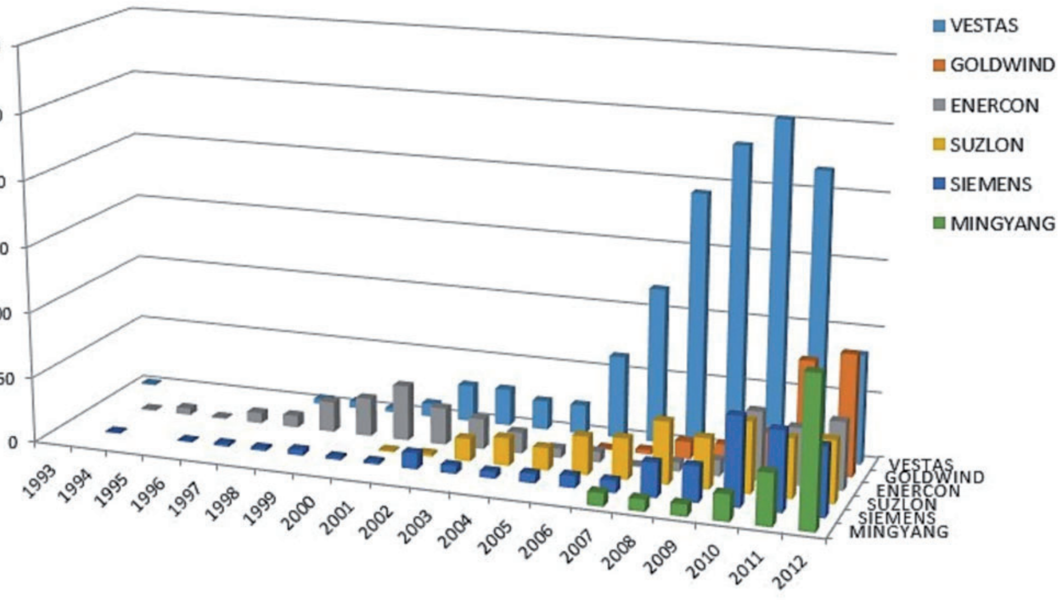

Figure 1. Patent submissions (basic) of sample firms alongside growth

Table 4. Patent citation information for sample firms

	Total patents				Top 10 cited patents	
	Total forward citations	Average forward citations	Total backward citations	Average backward citations	Total forward citations	Average forward citations
Goldwind	33	0.14	107	0.46	20	2.0
Mingyang	43	0.21	92	0.46	24	2.4
Suzlon	75	1.23	213	3.49	43	4.3
Suzlon and Repower	1195	3.84	1292	4.15	297	29.7
Enercon	1952	5.76	1616	4.76	503	50.3
Vestas	4001	3.77	5479	5.16	592	59.2
Siemens	1059	3.48	1875	6.16	420	42.0

4.1 The trajectories of key technologies

Following the methods outlined in Section 3.2.1, we now use patent counts to examine the trajectories of the key technologies of the sample wind turbine firms. From the DWPI database, we searched the basic patent applications of 2,437 in numbers (see Section 3.3). Within this dataset, we further categorised the patents into platform technologies, emerging offshore technologies, complementary technologies and customised innovations through the data mining methods.[8] We then collated all of the related patents (in Appendix 1) to generate the following figures.

From Fig. 1, we can argue that Vestas, Enercon and Siemens have been leading in terms of patent submissions since the 1990s whereas Suzlon, Goldwind and Mingyang have been catching up rapidly in recent years. However, considering the quality of the patents using citations (see Table 4), Asian firms are currently falling far behind the European leaders. For example, Vestas' top-cited patents each have 59.2 forward citations on average, which is almost 30 times that of Goldwind's patents. In addition, from the information in these top-cited patents, European firms appear to have wider portfolios of key technologies, as their top-ten cited patents involve broad domains ranging from wind turbine generators and rotor blades to wind power systems and installation methods. In contrast, Asian firms' top-ten cited patents are mainly limited to minor turbine design improvements.

4.1.1 Platform technologies

As mentioned in Section 2.1, there are two major platforms: gear-based DFIT/SFIT and gearless DD technology. Enercon and Goldwind follow the DD pathway whereas Vestas, Siemens, Suzlon and Mingyang use gear-based systems like DFIT. Fig. 2 shows that DFIT remains dominant from a patent view, with Vestas leading (823 patents on DFIT) and newcomers such as Suzlon and Mingyang actively joining in since the late 2000s. Thus far, there has been no sign that DFIT will face threats of being disrupted, as it still accounts for the majority of the existing patent pool. In contrast, the patent submissions for DD have been led by Enercon since the late 1990s with 117 highly cited patents, although the others have begun to catch up, especially after Goldwind participated in 2008. However, this does not indicate any sign of a convergence of two existing platforms. From a patent knowledge perspective, we argue that these two dominant designs may co-exist for some time into the future, which enriches the observations from market data in Section 2.1.

Despite the differences in design, the European firms are leading in terms of the patented platforms, with more patents and higher citations. They also have higher portfolios of drive/generator technologies among their patents (calculated from Appendix 1). However, Asian leading firms are catching up quickly. Chinese firms have been striving to develop indigenous platform technologies since 2006, in both PMDD (Goldwind, acquired from Vensys) and DFIT

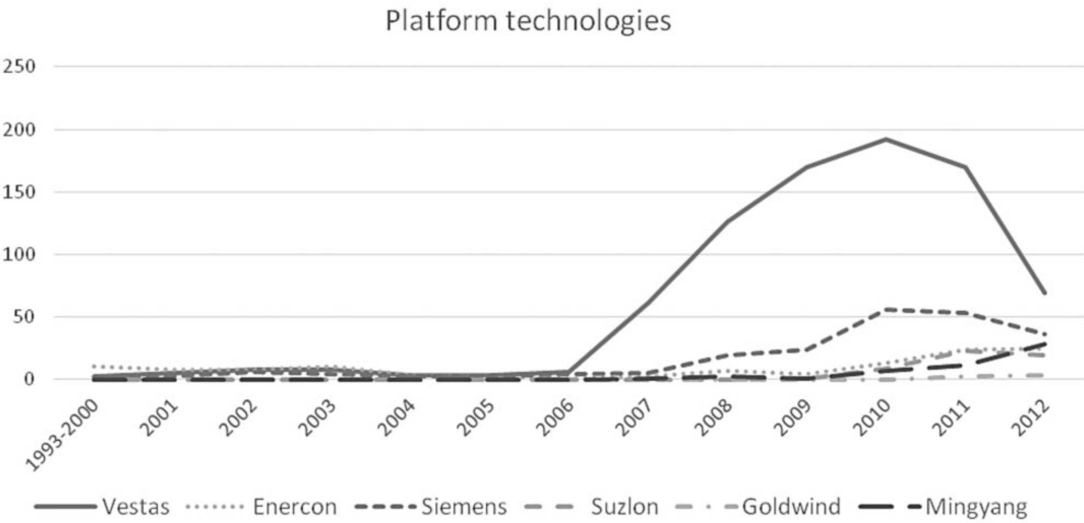

Figure 2. Patent counts of platform technologies in six leading firms

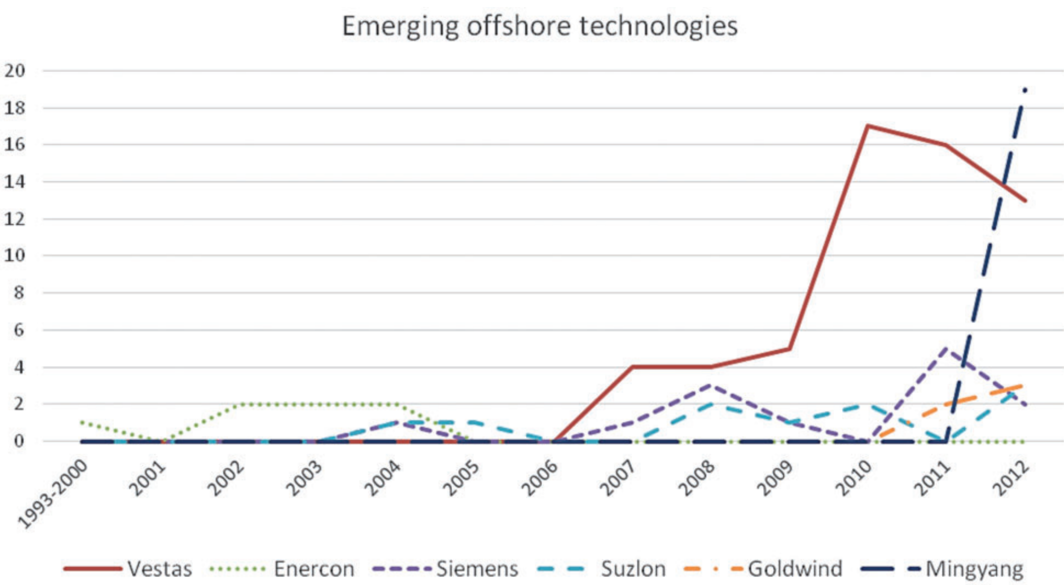

Figure 3. Patent counts of emerging offshore technologies in six leading firms

(Mingyang, acquired from Aerodyn), regarding firm-level preferences. The invention patents of Goldwind and Mingyang related to platform technologies outnumbered those of Enercon in 2011 and 2012, respectively (see Appendix 1), and these platforms have enabled the leading Chinese firms to keep on track for incremental innovations in the following years. [9] This is a sign that the Chinese wind firms are starting to challenge the existing leaders of the current trajectory, leveraging their capacity for manufacturing innovation, similar to Huawei in the telecom sector or Lenovo in the personal computer sector. In contrast, Suzlon (without Repower) has limited patents with regard to platform technology, which echoes the fact that they only started to use DFIT in their recent product (S9x). However, Suzlon was greatly strengthened by Repower's patents after the acquisition in 2007.

4.1.2 Emerging offshore technologies

Asia's leading firms have paid close attention to catching up with the existing platform technologies, but they may have neglected the emerging offshore knowledge until very recently (see Fig. 3). Goldwind had no offshore patents until 2011 while Mingyang only started obtaining offshore patents in 2012 (although with a sudden burst of 19 submissions). Suzlon has also been lacking in this field, although Repower can compensate for this. In contrast, leading European firms started much earlier. Enercon is also one of the leaders in offshore technologies. Its patent submissions for offshore turbines date back to 2001, making it the earliest entrant worldwide. Vestas and Siemens followed soon after, as they started patenting offshore technologies in 2003, and Vestas owns the largest number of patents among these firms. This contrasts with the narrative that the leading Chinese firms are significantly focusing on offshore technologies, and are challenging their European counterparts in this aspect. From the patent perspective, leading Asian firms are paying less attention to offshore knowledge compared to the existing platform designs, and are falling far behind after a very late start. The leading European firms, however, have acted as innovation leaders and first movers in this new technological trajectory.

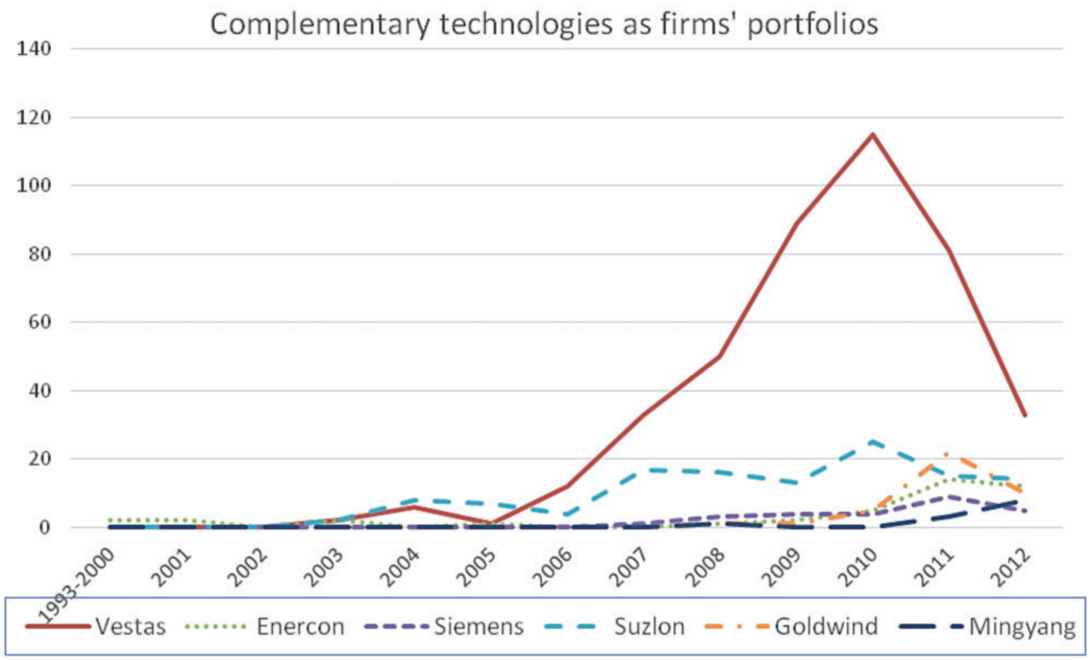

Figure 4. Patent counts of complementary technologies as firms' portfolios

4.1.3 Complementary technologies as firms' portfolios

Complementary technologies are essential to firms' competitiveness in profiting from innovation (Teece 1986; Zhou et al. 2015). However, several recent inquires have maintained that the significance of complementary technologies (as portfolios) to firms may vary and depend on the sectoral and firms' characteristics. In particular, high-technology firms may enhance their performance by having diversified portfolios while low-technology firms cannot do this (Lin et al. 2006; Lichtenthaler 2010). When we extended this argument to the wind turbine industry, we realised that the leading European firms are continuously emphasising portfolio-complementary technologies (control and grid connection) for reliability and quality from a patent perspective. Appendix 1 shows that they have a higher portfolio rate of complementary technologies than their Asian counterparts.

As Fig. 4 shows, Vestas, Enercon, and Siemens have all exhibited a strong interest by filing patents on these aspects since the 1990s. The Repower side of Suzlon has also demonstrated a strong patent knowledge base since the early 2000s. In contrast, leading Asian firms may have problems in this regard. For example, only after 2011 did both Goldwind and Mingyang start to file patents for complementary technologies. Suzlon, without Repower, owned very limited relevant patents by the end of 2012. This opposes the argument that the leading Asian firms are on par with the European leaders in terms of knowledge position. In fact, the leading Asian firms must devote more effort to enhancing their complementary technologies. This may also explain the 'curtails' in China that are partially due to the less reliable grid connection and control technologies of domestic turbines. It also adds empirical evidence about the wind sector to the literature on how high-technology firms more successfully consider diversified portfolios.

Finally, Appendix 1 shows that the leading Asian firms have advantages thanks to customised innovations, but due to the small numbers, we do not present those details here. Based on the analysis, we argue that the leading European firms are still leading from a patented knowledge perspective, in terms of platform trajectories, emerging offshore technologies, and portfolios for reliable and quality products. Some leading Asian firms have developed their indigenous platforms so that they are able to challenge the existing leaders. However, when considering other technological aspects, the leading Asian firms are still rather weak despite their slight edge on customised products. In addition, they place less emphasis on platform/complementary technologies in terms of percentage of patents at the firm level. This is in contrast to the perception that Chinese and Indian firms are growing significantly and have come to account for a large share of the global wind market since 2007. Based on this contrast, we argue that leading Asian firms may have inferior knowledge competence for creating new trajectories, but may have successfully used other strategies for competing (Zhou and Minshall 2014), such as low-cost manufacturing, agile followers' strategy, or customised designs for domestic markets.

4.2 Knowledge networks: Knowledge flow and collaboration

4.2.1 Knowledge flow (learning and spillover)

Following the methods outlined in Section 3.2.2, we created the knowledge network for wind turbine patents (see Figs 5–7) based on the mining of patents and citation data and using the visualisation software UCINET. To develop a better overview, we included all of the patents of the top 15 global wind turbine firms and two key design firms (Vensys and Aerodyn) who were significantly involved in knowledge transfer to Asia's leading firms. Based on Section 4.1, we divided the period (1993–2012) into two phases, making 2006 the cut-off year, to construct two sub-networks (1993–2006 and 2007–12) and a full network (1993–2012). This allowed us to research the firms' growth changes over time. Detailed data about the citations and the frequency statistics of the three networks are given in Appendixes 2 and 3.

Table 2 shows the evolution of the network structure's key indicators for the different periods. We investigated the density and cohesiveness (e.g. average distance, isolated point and reciprocity) of

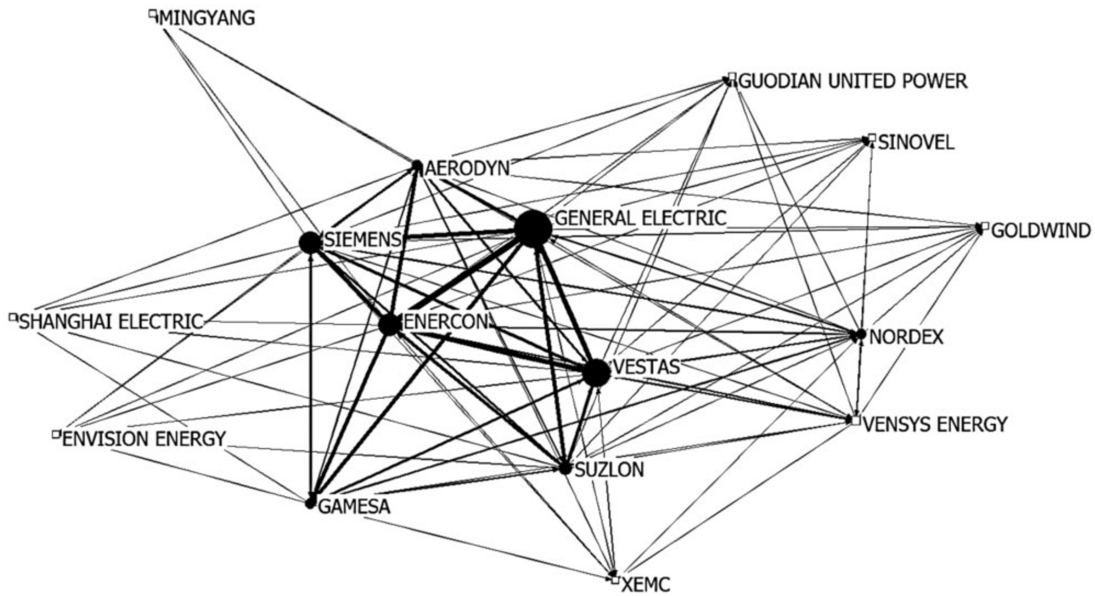

Figure 5. Firms' network 1993–2006

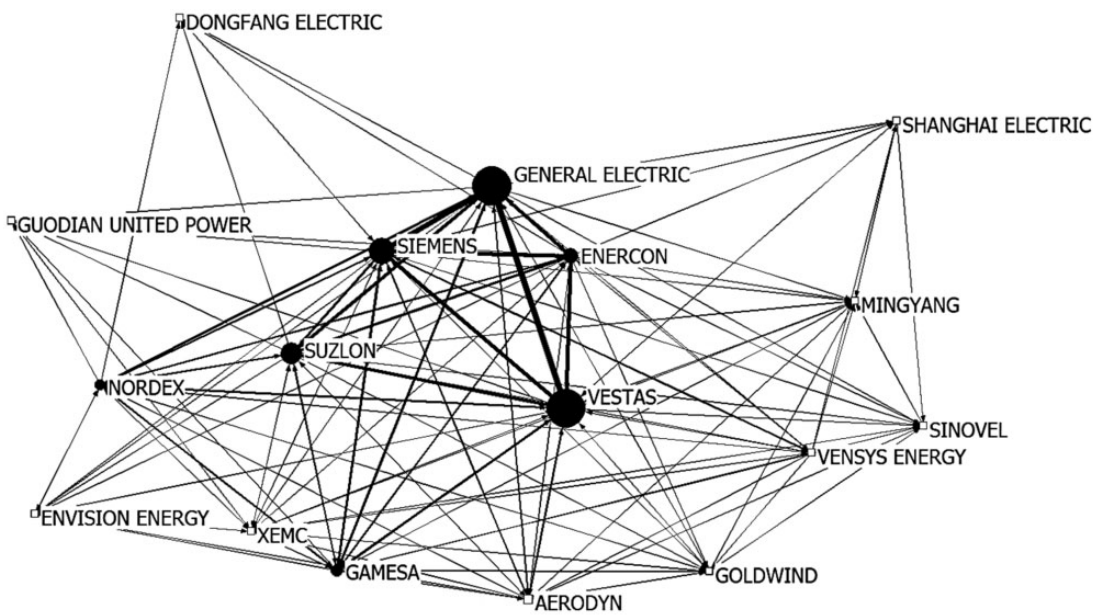

Figure 6. Firms' network 2007–12

the network that grows over time (see Section 3.2.2). We discovered some interesting features. For example, the decrease in network density (total patents/total citations) may mean that patent citations between firms grew exponentially after 2007, given that the total number of patents is also increasing, as knowledge flows (citations) appear to increase within the network. In addition, the decrease in fragmentation (proportion of firms/nodes that cannot reach each other) shows that there are fewer and fewer isolated islands within the wind knowledge network. The reciprocity has remained stable, which may indicate that the producers and consumers of knowledge have not changed significantly over time in the wind turbine industry, as the innovation leaders are still spilling over knowledge and the latecomers are still learning and absorbing. There is no clear sign of leapfrogging by latecomers in terms of knowledge.[10] The centrality degree measures the number of links (citations) that a node (firm) has. The decreasing out-degree and increasing in-degree centrality (see Table 2) may indicate that more companies' patents were less highly cited, and while there is no sign of dominant leaders emerging, there is still fierce knowledge competition in the wind industry, which has not yet matured and stabilised.

Figs 5–7 illustrate the resulting network of wind firms. The lines represent the cumulative citations in both directions: the thicker the line, the more citations between the two firms. The size of the nodes is determined by the number of self-citations. The core/periphery structure of the three network diagrams represents each company's position in the network. As mentioned in Section 3.2, the black

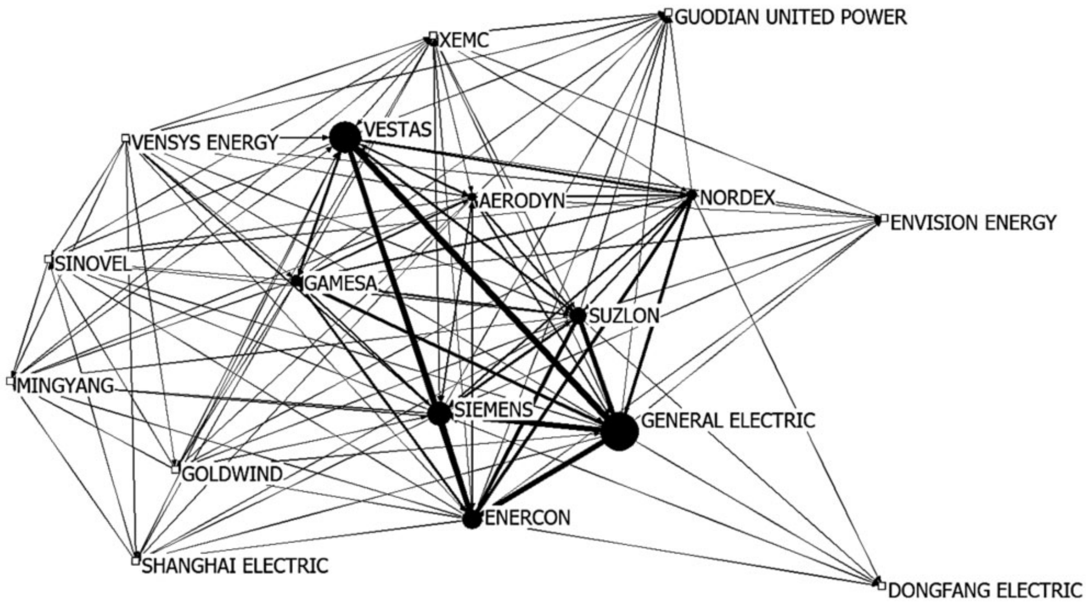

Figure 7. Firms' network, full period 1993–2012

circles represent the companies in the core position, while the white squares indicate firms at the periphery of the network (less important). Through the algorithms (UCINET software), the core/peripheral positions are determined by the thickness of the links (citations) and their distance from the other nodes (paths). Firms with higher citations and shorter paths are positioned at the centre and defined as core positions.

First, we observed that the core companies (black circles) in all three networks included traditional European leading companies such as Vestas, Siemens, Enercon etc. Suzlon (with Repower) also appeared to be a core firm, which may be attributed to Repower's rich knowledge base. Design firms such as Aerodyn also appeared in the earlier network (1993–2006) and the full one, suggesting that they also played significant roles in knowledge flow. In contrast, the Chinese firms were all at the periphery, even in the later network (2007–12), which may indicate that they have yet to play a key role in knowledge flows. Second, the circles representing the companies in the core positions were generally larger (more self-citations), indicating that they depended considerably on their own in-house knowledge. From Section 4.1, we know that these European firms had larger patent portfolios, which may explain why they frequently self-cited. This may be a unique phenomenon associated with the wind turbine sector (high-technology and still young). Third, the network figures also revealed that those firms in core positions were closer to each other, suggesting that similar nodes were closer. Thus, we argue that the leading European firms were similar to each other due to knowledge spillover (Suzlon benefits from Repower), whereas the Chinese firms were clearly the learners.

Table 3 shows the key indicators for the 17 firms, in 1993–2006 and 2007–12, respectively. The citation net count indicates the net knowledge producers (positive) and net knowledge consumers (negative). Enercon, in this case, contributed significantly to the world, with by far the highest number of net citation counts. In addition, the design firms (Aerodyn and Vensys) also acted as net knowledge producers, with high positive net counts. In contrast, many of the core firms (e.g. Vestas, Siemens and Suzlon) were net consumers but had a high number of both backward (out-degree) and forward (in-degree) citations, which meant that they were very active in knowledge flows, and engaged in spillover knowledge on a considerable scale while also absorbing knowledge (a good open innovation model). The leading Chinese firms played a very limited role in the knowledge network, as they had a very limited presence in terms of both citing and being cited (Goldwind had the highest out-degree and had only been cited eight times). Thus, they remained mainly the learners (knowledge consumers) in recent years.[11] The betweenness centrality, which indicates the control of resources and positions in the knowledge network, also echoes the above observations.

The analysis, which distinguished between true innovators and catch-up learners in different periods (1993–2006 and 2007–12), offered some interesting insights which echo the qualitative narratives (see Section 2) with estimates of quantities or provide contrasts. In this case, leading European firms were still leading in the knowledge networks and behaved as knowledge producers. Enercon was still a (distinguished) net knowledge producer while Vestas and Siemens remained active in knowledge inflow and outflow. The leading Chinese firms, despite their remarkable market success, were still far from being significant in this knowledge network. However, they began participating in knowledge production (though still limited as forward citations) in the period 2007–12. Suzlon, however, successfully grew from a net knowledge consumer (net citations −376 in 1993–2006) into an ambidextrous innovator (−13 in 2007–12), which may be attributed to its successful integration of Repower.[12]

4.2.2 Patenting collaborations

In this study, we developed a co-patenting matrix (see Appendix 4) to create patenting collaboration networks (see Fig. 8) for six leading firms and between other collaborators, following the method/data in Section 3. From Fig. 8, we can tell that there was limited joint patenting between these leading firms, which may be the rationale in high-technology industries in an open innovation era. The leading firms were competitors, and thus were more comfortable collaborating with patenting partners within specific ecosystems (e.g. universities) or value chains (e.g. component suppliers or project developers, as mentioned in Section 2). From Fig 8, we can see

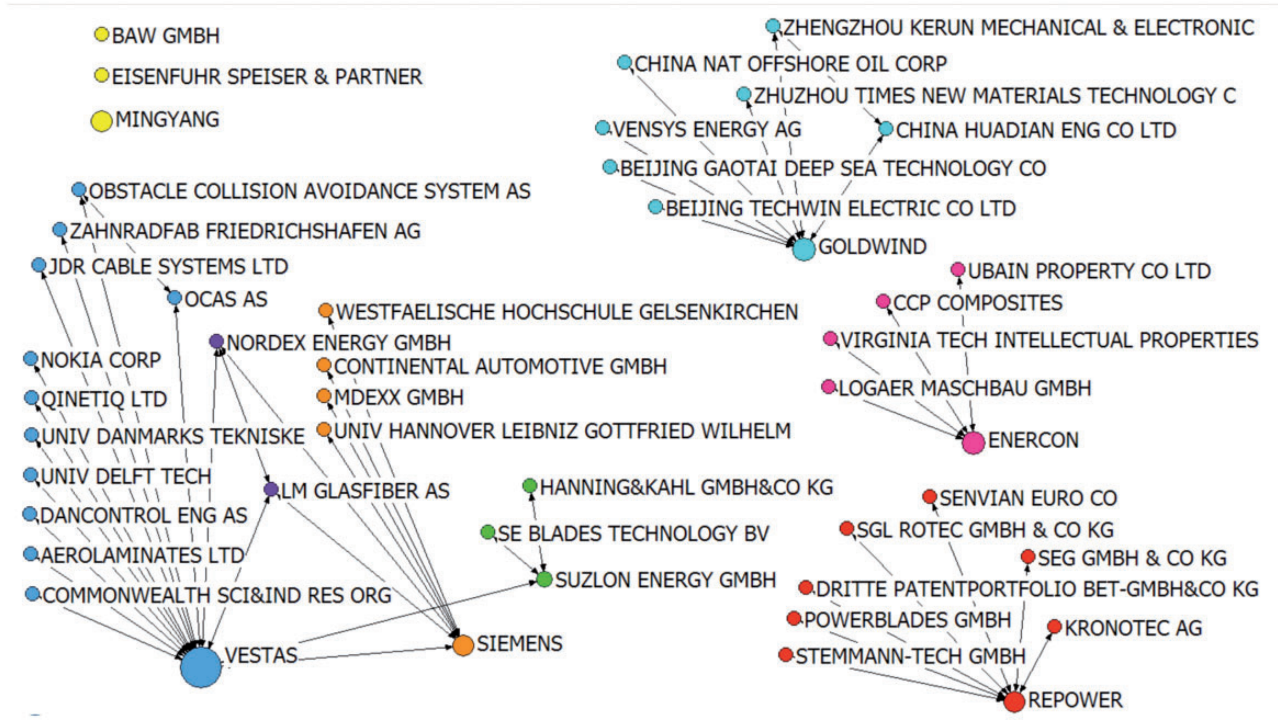

Figure 8. Patenting collaboration activities of sample wind firms

that Vestas and Siemens both collaborated with LM (the largest wind blade supplier) over patenting, which validates the above theory and echoes the narrative in Section 2. In addition, China's Goldwind had links with China Ocean Oil over the exploration of offshore technologies.

As Fig. 8 shows, the leading European firms engaged in a considerable amount of intensive collaboration in patenting. Vestas and Siemens were very active in joint patenting activities, with more than 20 patenting partners, respectively. Enercon, however, was less active regarding patenting collaboration, possibly due to its unique business strategies.[13] In contrast, the leading Asian firms made very limited open innovation efforts in terms of joint patenting. For example, Goldwind had fewer than six patenting collaborations (one with Vensys) while Mingyang had none. This may have weakened their long-term technology exploration capabilities. India's Suzlon was also less active in terms of R&D collaboration, but was better placed compared to the Chinese firms through its ability to leverage its full acquisition of Repower's network. As such, we argue that existing active collaboration may have strengthened the knowledge competitiveness of the leading European firms, which may, in turn, have given them advantages in exploring new knowledge and opportunities. Leading Asian firms, especially those in China, should strengthen their links with their R&D partners (including overseas organisations such as Vensys and Aerodyn) to create new opportunities.

4.3 Globalisation intentions

Following Section 3.2.3, we searched for the patent families of the sample firms. The findings are shown in Figs 9 and 10, which show that the leading Chinese firms were still rather domestic from a knowledge perspective, as they mainly filed patents in the domestic markets (99%). For example, Goldwind had only one international patent while Mingyang had three by the end of 2012. We argue that Chinese firms may face difficulties when developing global products and competing in the global market with regard to technological competitiveness. This phenomenon contradicts the narratives (based on qualitative interviews) that leading Chinese firms such as Goldwind and Mingyang have strong ambitions to achieve a global reach in terms of not only the market but also technology leadership. It seems that their collaboration with Vensys and Aerodyn mainly helped them to file domestic patents. However, it does support the existing arguments that the globalisation of Chinese wind turbines is leveraging lower costs (or higher cost/performance) and other non-intellectual resources such as financial loans.

In contrast, Indian firms are culturally closer to Western firms, and thus may be better able to integrate global innovation networks. For example, Suzlon (with Repower) was far more active in terms of filing international patents than its Chinese counterparts (see Fig. 10). Similarly, the leading European firms were all very active in submitting international patents in diverse markets. For example, Vestas had 5,093 international filings (patent family) in more than 20 countries based on 1,061 basic patents. Enercon, in particular, emphasised international patents with more than 4,000 international filings (patent family) in more than 20 countries based on 337 base patents, possibly due to their aggressive globalisation strategies. They had the most international patent submissions and the highest rate of family patents in different countries (see Fig. 10). This may indicate that Enercon devoted more effort to international market exploitation than to R&D exploration (as indicated by the basic patents) in recent years. This finding echoes the previous narratives that the leading European firms have set out to become multi-nationals.

4.4 Validity of analysis and methodological limitations

To validate the above findings, we conducted follow-up interviews with wind experts (including China Wind Energy Association, Dr Qin Haiyan etc.). Most of the interviewees had no objection to the analyses on platform/complementary/customised technologies.

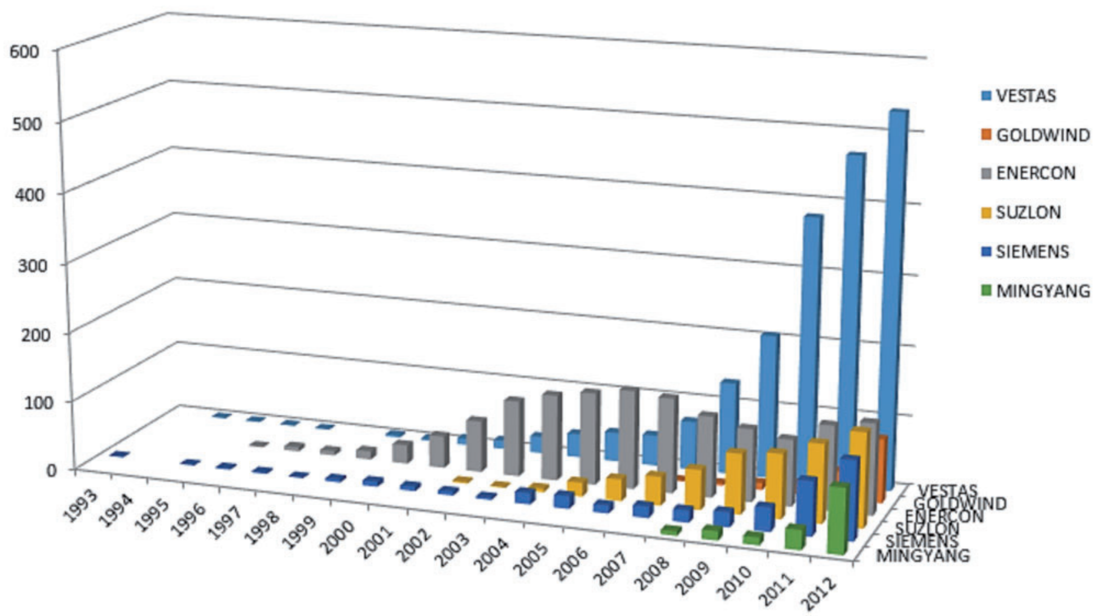

Figure 9. International patents: patent family counts

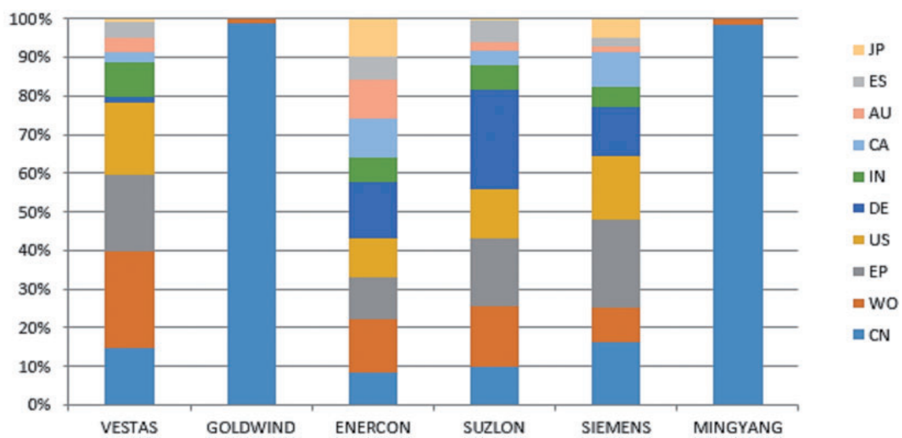

Figure 10. International patents: patent families in percentages

Some of them expressed concern for China's offshore wind power situation and argued that it may be worse than the patent results indicate. We also checked for the international knowledge flow, and many maintained that the patent results seemed to be consistent (in principle) with their field knowledge. However, some raised concerns regarding patent data bias (e.g. overheated Chinese patent filing) that must be handled carefully.

Thus, we collated the possible data bias that might influence our analysis (see Table 5). Following de Rassenfosse et al. (2013) and Frietsch and Schmoch (2010), transnational patent analysis may have issues such as: uneven patent values, geographic bias and institutional bias. We would argue that such data bias, despite leaving much room for improvement in future studies, did not cause significant distortion of the results.

First, in the analysis of key technologies (see Section 4.1), we used worldwide patent counts to reduce the geographic bias caused by the propensity to file patents in local offices, which is more obvious in developing economies (e.g. Chinese firms usually have the most filings in SIPO). Single-office (e.g. USPTO, EPO etc.) data are subject to geographic bias and the international patent (PCT) count may mask the local nature of inventive activities. By contrast, the worldwide patent data can better capture these dimensions, especially when covering both developing and developed countries. However, this global coverage eliminates the geographic bias while raising the institutional bias due to the peculiarities of individual patent systems, as the patent values are uneven across regimes so that simple counts may cause bias.[14] These biases can be partially reduced by using basic (priority) patent counts (see Section 3.3) to reduce double counts of all applications. Moreover, advised by industrial experts, we used invention patent counts (higher value compared to other patents) to reduce bias when examining Chinese firms' platform technologies (see Section 4.1). Using patent value conversion rates can fairly alleviate bias (de Rassenfoss et al. 2013); however, due to length limits this method will be left to future studies.

Second, for the globalisation analysis (see Section 4.3), although counting patent family members may have an institutional bias in evaluating inventive activities, it can effectively indicate the global

Table 5. Comparison of analyses with data descriptions

Analyses	Data sources	Patent data types	Patent/citation value	Geographic bias	Institutional bias
First set (see Section 4.1)	DWPI	Worldwide basic patent	Varying	Low	Medium
Second set (see Section 4.2)	DPCI	Worldwide citation	Varying	Low	Medium
Third set (see Section 4.3)	DWPI	Worldwide family members	Varying	Low	Medium to low
Other single-office data-based studies	USPTO as an example	Single-office basic patent/citation	Medium to high	High	Low

diffusion of a single invention across different regimes. In this sense, we argue that the inconsistency of patent value (e.g. as a rule of thumb, three patents in Japan are equivalent to one at the EPO) does not significantly affect the observation of globalisation trends by tracing family members.

Third, for the knowledge network analysis (see Section 4.2), we used transnational patent citation data following some existing studies (see Section 3.3). As Table 5 shows, single-office citation data can create geographic bias that may affect validity: specifically, Goldwind only had two patent applications (out of a total of 233) outside China. If we used the USPTO or PCT data in this case then the relevant citation data would have suffered severe bias (citations of 2 vs. 233). However, this created institutional bias due to the different regulatory requirements of patent offices. For example, for USPTO it is mandatory to cite all related prior patents by applicants, whereas for EPO the citations are made by examiners. In addition, China's patent office only requires mandatory citation after 2005 and examination of all global previous arts after 2009. Thus, in China, the backward citations may be less than expected before 2009 due to lack of enforcement by that jurisdiction. For example, until 2012, Goldwind only had three patents that cited Vensys. Due to cultural and language gaps, the patents in developing countries are less cited by those in developed economies. However, these institutional biases have been reduced for the data after 2009, with the development of jurisdiction (e.g. China complying with international standards). However, the use of a professional database can also help reduce the abovementioned institutional bias. The DPCI has integrated missing citation data that are not disclosed in the public SIPO database, and it provides an expert-translated platform so that non-English patents can be understood. A data bias also exists for co-patenting analysis. Not all collaborations can lead to the co-filing of patents. In many cases, collaborators negotiate licensing terms in advance and then only one of partners files the patent.

5. Discussion and conclusions

In this study, we conducted an empirical comparison of the patent knowledge bases of global wind turbine firms in Asia and Europe. We used a set of patent-based methods to analyse the specific wind turbine firms in terms of the trajectories of key technologies, knowledge networks and globalisation intentions. We believe that integrating these patent methods allows for a robust assessment of firms' knowledge competitiveness. Using quantitative methods, our systematic analyses generated interesting insights that provided some surprising contrasts to the conventional wisdom about wind technology development and partly provide empirical validation for some prior arguments (see Section 2). Our main conclusions are as follows.

First, by examining the firms' patent trajectories of key technologies over time, we revealed the differences in the knowledge profiles between these leading firms. In addition to the firms' specifics, we argue that the leading European firms have similar knowledge profiles over time to those of the global leaders, whereas the Asian ones are more similar to each other, as followers. Although the two existing wind turbine technology platforms (DFIT and DD) co-exist as the core of the sectoral trajectories, the analyses of knowledge bases show no signs that the leading Asian firms will create new paradigms that may disrupt the existing ones. From the patent perspective, we argue that the leading European firms continue to lead with regard to the existing trajectories, in terms of platforms and portfolios for reliable quality products. They are also first movers in the emerging offshore technologies, which means they may also lead the next generation of technologies. However, some leading Asian firms have developed proprietary platforms within the existing paradigms. These platforms allow them to challenge the technological leaders by leveraging cost–performance capabilities and customising innovations for domestic needs. This may explain why the Chinese and Indian firms have enjoyed considerable market success in recent years.

Second, the patent analysis of wind knowledge networks and network activities (transfer and collaboration) revealed the innovator–follower dynamics in the sector. Specifically, we found that the leading European firms are far more active within the knowledge flow activities as knowledge spillovers (producers) than their Asian counterparts. In addition, we found that some European firms are even net knowledge producers (e.g. Enercon), whereas others are active in terms of both knowledge inflow and outflow (e.g. Vestas and Siemens). Suzlon benefits from ties with Repower. Chinese firms, however, are weak in terms of knowledge outflow, but demonstrate strong learning capacities (knowledge inflow), which echoes the narratives and earlier findings about their endeavours over indigenous platforms. Leading European firms engage in much more patenting collaboration with their value chain partners, whereas leading Asian firms are still adopting the traditional in-house R&D approach with limited patenting collaboration (including collaboration with international partners such as Aerodyn and Vensys).

Third, our analysis of international patents (patent family) revealed the globalisation attempts of lead firms. Leading Chinese firms, despite their ambitious globalisation strategies, have limited knowledge resources for global technology competition. This supports the argument that Chinese firms are not primarily leveraging broad research-based knowledge resources, but other resources such as capabilities for rapid catching up, producing heavy-industry products at scale and driving down cost. The leading European firms and Suzlon have better intellectual property portfolios for addressing diverse markets.

Based on these patent analyses, we argue that the leading Asian wind firms have less developed knowledge bases, which limits their chance of leapfrogging to new technological paradigms in the near future. However, regarding the existing trajectories, the leading Asian firms are catching up very rapidly on both indigenous platforms and in terms of market shares. When leveraging specific resources and business strategies, they have a chance to challenge the global leaders on the existing trajectory, or may even duplicate the catch-up successes achieved by Huawei or Lenovo, both Chinese, in the information and communication technology (ICT) industry.

This study also produced further insights into the dynamics of the wind turbine sector. For example, the knowledge network analysis suggests that the wind sector is still young and relatively fragmented. The comparison of knowledge networks showed increasing fragmentation and increasing distance. This differs from other sectors, such as the ICT industry which is characterised by increasing density and decreasing distance (Bekkers and Martinelli 2012). It seems that the leading wind turbine firms (Vestas, Enercon etc.) are much less dominant in this network, unlike Cisco and Huawei in the ICT sector. In addition, compared to the ICT sector there is less open innovation among the wind industry leaders, and wind firms tend to collaborate first and foremost with value chain partners. Leading wind firms (especially the European leaders) emphasise technology portfolios. These findings align with research which shows that high-technology firms have diversified portfolios that may increase their R&D outputs whereas low-technology firms need a more strategic focus (Lichtenthaler 2010).

The above findings may offer important implications for systematic and nuanced policies (Quitzow et al. 2014). European players have successfully developed the dominant designs based on the long-term supply-side policies in renewable energy innovations, along with the regulatory incentives for the policy-driven leading market. However, they are facing challenges as the onshore wind technologies mature. In this case, cost-reduction and technology robustness can threaten the first movers' advantages, creating opportunities for those trying to catch up. European governments need to create new lead markets for the next generation of wind technologies (e.g. offshore) to ensure their leadership positions. Asian governments may need to modify their policy frameworks for better catch-up strategies, such as balancing the developing market and lagging indigenous R&D, encouraging open innovation and collaboration for technology exploration, and reframing the globalisation policies. First, the Asian governments need to recognise that encouraging market booms but neglecting the supply of key technologies may jeopardise Asia's chances in the long term. In addition, participation in global knowledge networks and collaboration needs to be combined with strengthening Asian national innovation systems (Urban et al. 2012).

There are limitations to our research. First, patent analysis methods must take care to reduce the data bias in future research (see Section 4.4). In addition, single patent indicators may cause false results due to data bias, so future research may consider using integrated indicators. In addition, advanced text mining methods for patent categorisation should also be explored in future research (e.g. avoiding double counts for technologies that fall into two or more categories). Methodology-wise, patent data can provide quantitative estimations in general, and may help to find aggregate phenomena that qualitative inquiry cannot detect or may overlook. However, for some specific cases, the use of patent indicators may require assistance. For example, Enercon's innovation competence might be underestimated if we only consider patents (see Section 4.2) whereas interviews with domain experts indicate that Enercon's decline in terms of patents may also be attributed to their specific strategy of being low-profile to protect their business secrets. In addition, patents can only explain explicit knowledge bases, but might have difficulty deciphering other tacit capabilities, especially for those trying to catch up. For example, some Chinese firms have limited patents but can learn very quickly by adopting various measures and can achieve market success by leveraging other competitive edges. Despite the significant value of patent data, we argue that this patent analysis might be complemented by qualitative enquiries for a better overview, as in Lema et al. (2014), Dai et al. (2014) and Narain et al. (2014). This may also indicate a fruitful direction for our future research. We may consider integrating patent methods and qualitative interviews to improve the validity of our research.

Notes

1. Knowledge bases may refer to the resources and capabilities to produce ideas, thoughts, programmes, and products through creations and innovations and turn them into economic value and wealth.
2. Having installed 17.63 GW wind turbines in 2011, China became the global leader in terms of both annual and total installation capacity, reaching 62.36 GW and accounting for 40% of the global installed capacity (Chinese Wind Energy Association 2013). In India, the total installed wind power capacity had reached 11.75 GW by the end of March 2010, up from 1.63 GW in 2001–2, with an average annual growth of 28.6% (Narain et al. 2014).
3. In 2013, the top 15 leading firms (in terms of market share) were: Vestas (13.2%), Goldwind (10.3%), Enercon (10.1%), Siemens (8%), Suzlon (6.3%), General Electric (4.9%), Gamesa (4.6%), Guodian United Power (3.9%), Mingyang (3.7%), Nordex (3.4%), XEMC (3.2%), Envision (3.1%), Dongfang Electric (2.3%), Sinovel (2.3%) and Shanghai Electric (2.2%) (World Wind Energy Association 2013). Some of the top firms are briefly introduced in Section 3.
4. Vestas is the flagship leading firm of the Danish wind energy sector. Since its foundation in 1981, it has worked closely with Risø National Laboratory (Denmark Technical University) on cutting-edge research. Enercon and Siemens (originally Danish) are Germany's most important and best-established wind energy firms. They have been operating for nearly 30 years (BWE 2012). Enercon's most significant platform innovation is the DD turbine, on the basis of which they developed a series of leading-edge products (e.g. the 7.58 MW E-126 turbine in 2007). Enercon's founder, Aloys Wobben, developed the world's first DD turbine in the early 1990s. Suzlon was founded in 1995 and remained the largest wind turbine manufacturer in India until 2013. China's Goldwind (founded in 1998) and Mingyang (founded in 2006) are both among the top three wind turbine firms and are listed on stock exchanges (Goldwind was listed in Hong Kong in 2008 and Mingyang was listed in New York in October 2010). In addition, Mingyang is the only non-state-owned enterprise among the top five Chinese wind turbine firms, which may lead to several idiosyncrasies in the case comparisons.
5. The major wind turbine technology categories include: drive system, generator, control system, grid integration technologies (including wind farm management), tower construction and foundation, blade etc. In this study, we only looked at those key technologies that have undergone dynamic changes in their technology trajectory over the past 20 years. For example, tower technologies have exhibited limited changes since the 1990s (and will have no significant change for offshore paradigms), and thus were excluded. To allow a better comparison, blade technologies were not studied because most of the sample firms had no such portfolios.
6. Density is the sum of all of the values divided by the number of possible links. In this study, density is calculated by the number of patents for a specific firm (node) over the number of citations (links). The average distance is the average of the shortest

distances between nodes that may explain the complexity of the network. In this study, it means the average shortest citation paths between key firms (nodes). Fragmentation is the proportion of firms (nodes) that cannot reach each other, like isolated islands. Reciprocity refers to the mutual links (citations) within the total links in the network. Degree centrality considers the number of links a node has, and because our network is directed, we distinguish between in- and out-degree centrality. In the context of our network of firms, the first indicates the number of forward citations (being cited) and the latter the number of backward citations (citing). The net citation count (forward citations minus backward citations) separates the net producers of knowledge from the net consumers.

7. National patent offices include: the US Patent and Trademark Office (USPTO), the European Patent Office (EPO), China's State Intellectual Property Office (SIPO) etc. International patent offices include the World Intellectual Property Organisation (WIPO), which has international patents under the Patent Cooperation Treaty (PCT). In recent years, there have been worldwide patent databases that include patents from various offices for transnational patent studies, such as the DWPI and the DPCI, the EPO Worldwide Patent Statistical Database (PATSTAT), the Derwent Innovation Index (DII), the National Bureau of Economic Research (NBER), and the US patent citation databases etc.
8. To mine the above data, we used an integrated method developed and validated by our team and patent searching experts (Thomson Reuters and China Academy of Science). This method combines a DCMC code-search and keyword-search as follows:

- platform technologies: DCMC (X15-B01B generator and X15-B01A drive)
- complementary technologies: DCMC (X15-B05 control) and keyword 'grid'
- emerging technologies: DCMC (X15-B05 offshore)
- customised innovations: keywords (e.g. high altitude etc.)

We read some patents to test false positives as the simple validation, together with the domain experts. This method performs well in categorising most patents, except those patents that fall into two or more categories (such as a generator's control technology), in which case we count the patents in both categories. More advanced data mining methods may be needed for patent categorisation in future research, such as subject–action–object semantic methods.

9. In China, there are three patent categories: invention patents, utility models and designs. For platform and key complementary technologies, we were advised by patent experts to use invention patents as the indicator of core innovations of Chinese wind turbine firms, including Goldwind and Mingyang. We can see that these invention patents only accounted for one-third to a half of the total patents of Chinese firms. For Goldwind, 93 of their total of 231 patents were invention patents. This may partially indicate the 'patent tsunami' issue in China, as the real value of many patents is somewhat dubious.
10. The increase in the average distance may mean that the knowledge network becomes more complex, and that more key players become involved in knowledge production and consumption, respectively. This may indicate that more Asian firms are coming in as knowledge consumers, or that more European design firms are producing more knowledge to transfer to Asia's leading firms.
11. XEMC was an abnormal outlier here, and thus will require more investigation in future studies.
12. Some experts have opposed this argument, claiming that Suzlon acquired Repower but had limited integration. For example, Repower's staff mentioned that Suzlon does not have access to Repower's patents, although these may officially belong to Suzlon (in 2010–4). Suzlon sold Repower in 2015, and the latter is now known as Senvion. Others have argued that in most cases the Repower side produced the most valuable patents, from which Indian teams mainly developed niche customised innovations.
13. Enercon also had a high degree of vertical integration, producing almost all of its components in-house, including insuring their own turbines to minimise the insights gained by external insurance companies and technicians (Lema et al. 2014). This may also explain why Enercon engaged in limited R&D collaboration. It was extremely careful about selecting collaborators and aimed to keep any insights arising from its technology in-house. However, Enercon is viewed as a low-profile company, and patent intelligence has difficulty researching it as most of its patents are filed under the inventor's name (e.g. Aloys Wobben, Rohden Rolf etc.). Some have claimed that this is a strategy for avoiding technology intelligence. In addition, Enercon was not listed on any stock exchange. Some have also argued that Enercon has slowed down its patent filing activities because its managers believe in business secrets rather than patents.
14. There are many causes of institutional bias: for example, some patent systems have tight control on the scope of applications that encourage many narrow patents (e.g. Japan) while others have less rigorous examinations that attract a great number of filings (e.g. China). In addition, different offices have different categories of patents (e.g. utility model and design in China, software and continuations at USPTO) that may cause bias.

Acknowledgements

This research was supported by the joint project 'Technological Trajectories for Climate Change Mitigation in China, Europe and India' funded by the Svenska Riksbankens Jubileumsfond. This research was also supported by the National Natural Science Foundation of China (Grant 71203117), the Humanities and Social Science Project by the Ministry of Education of China (12YJC630324, 14YJC630071), the Public Administration of Beijing City Running and Modern Service Innovation in Big Data Era (011000546615006), and the EC-HVEN European Framework 7 Project (No. 295130). Specifically, we thank two anonymous reviewers for their constructive comments that helped to improve this paper. Thanks to Hubert Schmitz, Tilman Altenburg, Ambuj Sagar and Xue Lan for helpful suggestions. In addition, we thank Thomson Reuters' experts for their advice on patent analysis. Also, many thanks to our research assistants Ms Pan Meijuan, Ms Wang Xiuqin and Mr Jin Dan for their valuable work on the data mining.

References

Bekkers, R., Duysters, G. and Verspagen, B. (2002) 'Intellectual property rights, strategic technology agreements and market structure: The case of GSM'. *Research Policy*, 31: 1141–61.

—— and Martinelli, A. (2012) 'Knowledge positions in high-tech markets: Trajectories, standards, strategies and true innovators'. *Technological Forecasting and Social Change*, 79: 1192–216.

Braun, F. G., Schmidt-Ehmcke, J. and Zloczysti, P. (2010) 'Innovative activity in wind and solar technology: Empirical evidence on knowledge spillovers using patent data', Discussion Paper 993. Berlin: German Institute for Economic Research.

BTM Consult (2013) 'International Wind Energy Development: World Market Update 2012' Ringkøbing, Denmark: BTM Consult.

BWE (Bundesverband Wind Energie) (2012) 'Wind industry in Germany 2012', Berlin.

Chinese Wind Energy Association (2013) 'Statistics on Chinese wind turbine installation capacity in 2012, (in Chinese). *Wind Energy (Feng Neng)*, 3: 44–55.

Chesbrough, H. W. (2003) *Open Innovation: The New Imperative for Creating and Profiting from Technology*. Boston, MA: Harvard Business Publishing.

Choi, C. and Park, Y. (2009) 'Monitoring the organic structure of technology based on the patent development paths'. *Technological Forecasting and Social Change*, 76: 754–68.

Dai, Y. X., Zhou, Y., Ding, M., Xia, D. and Xue, L. (2014) 'The innovation paths of the Chinese wind power industry', GDI Working Paper. Bonn, Germany: German Development Institute.

Damrongchai, N., Satangput, P., Tegart, G. and Sripaipan, C. (2010) 'Future technology analysis for biosecurity and emerging infectious diseases in Asia-Pacific'. *Science and Public Policy*, 37: 41–50.

De Rassenfosse, G., Dernis, H., Guellec, D., Picci, L. and de la Potterie, B. V. P. (2013) 'The worldwide count of priority patents: A new indicator of inventive activity'. *Research Policy*, 42: 720–37.

Dosi, G. (1982) 'Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change'. *Research Policy*, 11: 147–62.

Dubarić, E., Giannoccaro, D., Bengtsson, R. and Ackermann, T. (2011) 'Patent data as indicators of wind power technology development'. *World Patent Information*, 33: 144–9.

Ernst, H. (2003) 'Patent information for strategic technology management'. *World Patent Information*, 25: 233–42.

Frietsch, R. and Schmoch, U. (2010) 'Transnational patents and international markets'. *Scientometrics*, 82: 185–200.

Gosens, J. and Lu, Y. (2014) 'Prospects for global market expansion of China's wind turbine manufacturing industry'. *Energy Policy*, 67: 301–18.

International Energy Agency (2009) 'Wind energy technology roadmap' <http://www.iea.org/publications/freepublications/publication/Wind_Roadmap.pdf> accessed 14 Sep. 2014.

Jeong, Y. and Yoon, B. (2015) 'Development of patent roadmap based on technology roadmap by analyzing patterns of patent development'. *Technovation*, 39–40: 37–52.

Ju, Y. and Sohn, S. Y. (2015) 'Patent-based QFD framework development for identification of emerging technologies and related business models: A case of robot technology in Korea'. *Technological Forecasting and Social Change*, 94: 44–64.

Karvonen, M. and Kässi, T. (2013) 'Patent citations as a tool for analysing the early stages of convergence'. *Technological Forecasting and Social Change*, 80: 1094–107.

Lee, K. and Lee, S. (2013) 'Patterns of technological innovation and evolution in the energy sector: A patent-based approach'. *Energy Policy*, 59: 415–32.

Lema, R., Nordensvärd, J., Urban, F. and Lutkenhorst, W. (2014) 'Technological trajectories for climate change mitigation in Europe, China and India. Wind energy in Europe'. GDI Working Paper. Bonn, Germany: German Development Institute.

Lewis, J. I. (2013) *Green Innovation in China: China's Wind Power Industry and the Global Transition to a Low-Carbon Economy*. New York: Columbia University Press.

Li, X., Zhou, Y., Xue, L. and Huang, L. (2015) 'Integrating bibliometrics and roadmapping methods: A case of dye-sensitized solar cell technology-based industry in China'. *Technological Forecasting and Social Change*. 97: 205–222.

Lichtenthaler, U. (2010) 'Intellectual property and open innovation: An empirical analysis'. *International Journal of Technology Management*, 52: 372–91.

Lin, B. W., Chen, C. J. and Wu, H. L. (2006) 'Patent portfolio diversity, technology strategy, and firm value'. *IEEE Transactions on Engineering Management*, 53: 17–26.

Li-Ying, J., Wang, Y., Salomo, S. and Vanhaverbeke, W. (2013) 'Have Chinese firms learned from their prior technology in-licensing? An analysis based on patent citations'. *Scientometrics*, 95: 183–95.

Luciano, K., Youtie, J. and Shapira, P. (2014) 'Signs of things to come? What patent submissions by small and medium-sized enterprises say about corporate strategies in emerging technologies'. *Technological Forecasting and Social Change*, 85: 17–25.

Narain, A., Chaudhary, A., Krishna, C. and Sagar, A. (2014) 'Wind energy technology trajectories in India'. Unpublished mimeo. Delhi: Indian Institute of Technology.

Nepelski, D. and De Prato, G. (2015) 'International technology sourcing between a developing country and the rest of the world. A case study of China'. *Technovation*, 35: 12–21.

Nesta, L. and Saviotti, P. P. (2005) 'Coherence of the knowledge base and the firm's innovative performance: Evidence from the US pharmaceutical industry'. *Journal of Industrial Economics*, 53: 123–42.

Pavitt, K., Patel, P. and Granstrand, O. (1997) 'Multi-technology corporations: Why they have distributed rather than distinctive core competencies'. *California Management Review*, 39: 8–25.

Phan, K. and Daim, T. (2013) 'Forecasting the maturity of alternate wind turbine technologies through patent analysis' in *Research and Technology Management in the Electricity Industry: Methods, Tools and Case Studies*, T. Daim, T. Oliver and J. Kim (eds), pp. 189–211. London: Springer.

Quitzow, R., Walz, R., Köhler, J. and Rennings, K. (2014) 'The concept of "lead markets" revisited: Contribution to environmental innovation theory'. *Environmental Innovation and Societal Transitions*, 10: 4–19.

Schmitz, H. and Altenburg, T. (2015) 'Innovation paths in Europe and Asia: Divergence or convergence?. *Science and Public Policy*, (2015, this issue).

—— and Lema, R. (2015) 'The global green economy: Competition or cooperation between Europe and China?' in *The Triple Challenge: Europe in a New Age*, J. Fagerberg, S. Laestadius and B. Martin (eds), pp. 118–41. Oxford, UK: OUP.

Teece, D. J. (1986) 'Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy'. *Research Policy*, 15: 285–305.

Tseng, F. M., Hsieh, C. H., Peng, Y. N. and Chu, Y. W. (2011) 'Using patent data to analyze trends and the technological strategies of the amorphous silicon thin-film solar cell industry'. *Technological Forecasting and Social Change*, 78: 332–45.

Urban, F., Nordensvärd, J. and Zhou, Y. (2012) 'Key actors and their motives for wind energy innovation in China'. *Innovation and Development*, 2: 111–30.

World Wind Energy Association (2013) 'World wind energy report 2013' <http://wwindea.org/home/images/stories/publications/half_year_report_2013_wwea.pdf> accessed 3 Mar. 2014.

Yin, R. K. (2003) *Case Study Research: Design and Methods*, pp. 5, 11. Thousand Oaks, CA: Sage.

Zhou, Y. and Minshall, T. (2014) 'Building global products and competing in innovation: The role of Chinese university spin-outs and required innovation capabilities'. *International Journal of Technology Management*, 64: 180–209.

——, Zhang, H. and Ding, M. (2015) 'How public demonstration projects affect the emergence of new industries: An empirical study of electric vehicles in China'. *Innovation: Management, Policy and Practice*, 17: 1–23.