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Comparing the innovation strategies of Chinese and European wind turbine firms through a patent lens

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ABSTRACT

Based on a patent-analysis method, this paper compares the firm-level technology pathways of wind turbine firms from China and Europe, and examines the firms' unique innovation strategies that may lead to these pathways being modified to capitalize on any opportunities that arise. This paper finds that Chinese firms have different firm-level pathways compared to their European counterparts, whereby they are influenced by different innovation strategies that involve technological foci, learning, and R&D collaboration, as well as globalization strategies. We find that European firms are stronger in most of these strategic dimensions, while Chinese firms demonstrate a strong learning capacity and customized innovations. We propose that there might be a limited divergence of the sector-level technological trajectories between China and Europe. In addition, we suggest that there is limited opportunity for Chinese firms to leapfrog with regard to the existing technology trajectories and surpass their European counterparts in the near future.

1. Introduction

Wind turbine firms adopt various strategies to develop and exploit innovations as they move along their unique technological pathways. Alongside other macro-level impacts, such as markets or policies, firm strategies are viewed as a significant factor that may lead to modifications of these pathways in response to growth opportunities (Teece et al., 1997; Dosi et al., 2000). Specifically, some recent research has explored whether the leading Chinese wind firms may lead to different technology trajectories through leapfrogging (Lema et al., 2014; Dai et al., 2014), and firm-level innovation strategies have played an important role in this. This paper will explore this question while examining the leading wind manufacturers in China and Europe, and try to compare their firm-level pathways. Based on this, this paper will explore whether the distinctive innovation strategies of Chinese firms will help them to leapfrog in the existing technology trajectory and surpass the current European leaders.

Innovation growth and strategies have been characterized by various concepts or methodologies in order to obtain a picture of how they develop or evolve. In recent years, patents and other intellectual property (IP) data have become employed for understanding technology pathways and strategies, which serve as the basic indicator of innovation performance (Li et al., 2014). Patent analysis methods, including counting patents to evaluate innovation performance along growth (Schmoch and Schubert, 2009; Choi and Park, 2009), identify the key patents or technologies for forecasting future pathways (Damrongchai et al., 2010; Robinson et al., 2013) are commonly used. However, there are limited patent studies that probe into firm-level pathways (Bekkers and Martinelli, 2012) as well as innovation strategies (Luciano et al., 2014), and even fewer that have examined wind firms for international comparisons.

This paper develops a framework and methodology for exploring what patents can tell us about the firm pathways, as well as the innovation strategies that may shape the former. For wind turbine firms, the key dimensions of the firm strategy includes an emphasis

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on key technologies, the capability for learning or spillover, the role of R&D collaboration, and strategies of globalization (Teece, 1986; Chesbrough, 2003; Luciano et al., 2014). This paper examines these strategic dimensions of representative firms through a patent lens, which may provide better validity with the support of authoritative patent data.

In order to explore the above issues, this paper will focus on conducting an in-depth case study of four leading wind turbine firms: Goldwind (China), Mingyang (China), Enercon (Germany), and Vestas (Denmark). Each of these cases is structured in the three building blocks following the above strategic dimensions. Based on these multiple case studies, this paper attempts to address the following questions: How and to what extent do the technological pathways at the firm-level differ between the four lead firms? What are the firm strategies that differentiate these technological pathways? What are the differences between the strategies and firm-level pathways that may lead to the divergence of sectoral-level technology trajectories between China and Europe? In addition, this paper will also discuss the policy implications for wind manufacturing development in Asia and Europe.

2. Literature review and analytical framework

2.1. Wind's sectoral-level trajectories and firm-level pathways

Wind energy is the most successful type of renewable energy available with stable and strong annual growth. The rapid growth of this industry's technological trajectories has attracted considerable attention as emerging economies, like China, are positioning themselves to challenge the incumbents by developing unique trajectories (Lema and Lema, 2012; Schmitz and Lema, 2015). Theoretically, technological trajectories can be analysed from the evolutionary perspective, which demonstrates how the initial choices involving the technologies and institutional settings may influence the trajectories (Dosi, 1982). The historical and contextual embeddedness of such evolutionary processes may result in a variety of very different trajectories (Altenburg and Pegels, 2012; Johnson et al., 2014). The wind power industry operates on the innovation frontiers of a new energy industry, and may evolve in different directions due to a combination of macro or micro-level conditions, such as the initial starting points, government policies, demand conditions, firm strategies as well as their embeddedness in related innovation networks (Lema and Lema, 2012; Lema et al., 2014).

In this industry, the core technology (e.g. the wind turbine) may be used to analyse the technological pathways of the wind turbine manufacturers (Altenburg and Pegels, 2012). Deployment innovations, however, may be less stressed in this trajectory analysis as their key actors are utility organizations, although sometimes the wind turbine firms may become involved in deployment through maintenance and service. Therefore, the complementary technologies and other technological dimensions for reliability and grid connections should be taken into account.

Many existing theories emphasize the significance of the macro-level conditions that shape technology pathways, including the market settings, factor conditions, and government policies (Johnson et al., 2014). Porter (1990), however, emphasized that individual firm strategies and firm networks are critical alongside macro-level "Porter's diamond factors". This study will focus on the firm-level strategies, which may significantly shape the individual firm's pathways when operating under global innovation settings and reflect the specific patterns of national conditions.

Scholars have distinguished three major concerns related to firms' formulation of innovation strategies (Teece et al., 1997): (i) the competitive position from an industry-based view; (ii) technological resources and capabilities from the resource-based view; (iii) the strategic context for innovation from the institution-based view, as well as the connection between the organization and other elements in its external environment. All of these concerns are closely related to the firm-level innovation strategies that may shape the technological pathways.

The lead market approach has been applied in Denmark, Germany, and China to support the growth of eco-innovation niches and socio-technical regime with government backing (Walz and Köhler, 2014). To overcome the established regime of fossil fuel power, there needs to be a link between the niche and regime to create what Walz and Köhler (2014) call a "feedback loop" that sustains the growth and viability of the new industry. This demand-side approach has enabled China and Europe to build up their wind industries and become world leaders (Lema and Lema, 2012).

2.2. The analytical framework from a patent perspective

Patent and literature-based techniques is increasingly used to monitor the competition, assess core and complementary technologies, observe knowledge transfer, and learn from collaborations (Ernst, 2003; Tseng et al., 2011; Walz and Köhler, 2014). Specifically in the wind power industry, patent-research has been conducted to study development at the sectoral level (Dubarić et al., 2011). However, there is limited study probing into the firm-level and examines the technological pathways and firm-level innovation strategies.

Therefore, this paper attempts to develop a framework that uses patent data to analyse the technological pathways of wind firms across China and Europe by comparing the innovation strategies that shape these pathways (Lema and Lema, 2012; Schitz and Lema, 2015). We review the existing patent method literature to determine which strategic dimensions can be measured by patent-based indicators, and how to measure them. Based on the reviews, we developed the analytic framework (Table 1) that focuses on the three major dimensions through a patent lens: technology emphasis, learning/spillover/R&D collaboration, and globalization strategies. We collated the patent analysis methods that can measure or study the proposed strategic dimensions of firms. While some of these methods have been tentatively used in the wind power sector recently, othsing lead market factors to assess the potential for a sustainability transitioners are used within other technology domains, which can be extended to wind turbine firms.

Table 1
The strategic dimensions analytical framework based on patent methods.

Strategic dimensions	Key items of strategic dimensions	Patent methods (indicators)	Existing literature
Technological pathways	Technology development	Patent counts	Lee and Lee (2013)
	Similarity or diversity of technology portfolios	Cosine similarity	Olkowski (2014)
	R&D competence on key technologies, and the competitive positions as innovation leaders or catch-uppers	Patent citation frequency	Braun et al. (2010), Li-Ying et al. (2013)
Technology emphasis (foci)	Platform technologies Complementary technologies (portfolios) Emerging technologies Customized innovations for niche markets	Patent counts, coupled with experts' interpretations	Ernst (2003), Dubarić et al. (2011), Phan and Daim (2013)
Learning, spillover, and R&D collaboration	International technology transfer or knowledge exchange: learning from leaders vs. spillover to latecomers	Patent citation network, coupled with patent licensing activities	Braun et al. (2010), Li-Ying et al. (2013)
	R&D collaboration over patenting	Patent co-authorship	Tseng et al. (2011), Li et al. (2014)
	R&D collaboration over scientific research	Bibliometric co-authorship	
Globalization strategy	Intellectual property strategy for globalization	Patent family	Gosens and Lu (2014)
	Globalization strategy: compete globally with standardized innovative products vs. competing with MNCs in the domestic market;	Patent family & patent counts	

3. Methodology

3.1. Research design and case selection

This paper adopts a multi-case longitudinal approach to study the three dimensions of firm strategy and technology trajectories. Following Yin (2003), four firms are selected as representative cases for in-depth analyses and comparison for pattern matching. Three case selection criteria were highlighted: 1) These firms are the leading wind manufacturers in their home country, and have innovative products that enable them to access the overseas markets for global competition; 2) their technology pathways are based on innovative products, which can be analyzed through patents; and 3) they have sufficient heterogeneity and specific innovation strategies in terms of technology foci, IP internationalization, and R&D collaboration and learning.

Following the case selection criteria, we purposively select Goldwind and Mingyang from China, Vestas from Denmark, and Enercon from Germany for this study. In China, Goldwind and Mingyang are both among the top five wind turbine firms. Furthermore, Mingyang is the only non-state-owned enterprise among the top five Chinese wind turbine firms, which may lead to some idiosyncrasies in the comparisons. Comparing the cases ensures the internal validity of this research. Since we cannot choose all cases, so we deliberately chose idiosyncratic firms when considering national representativeness – for example, we chose Enercon rather than Siemens because Enercon is more specialized in terms of technological pathways. Fig. 1 displays patent submissions and international patents of sample firms over time.

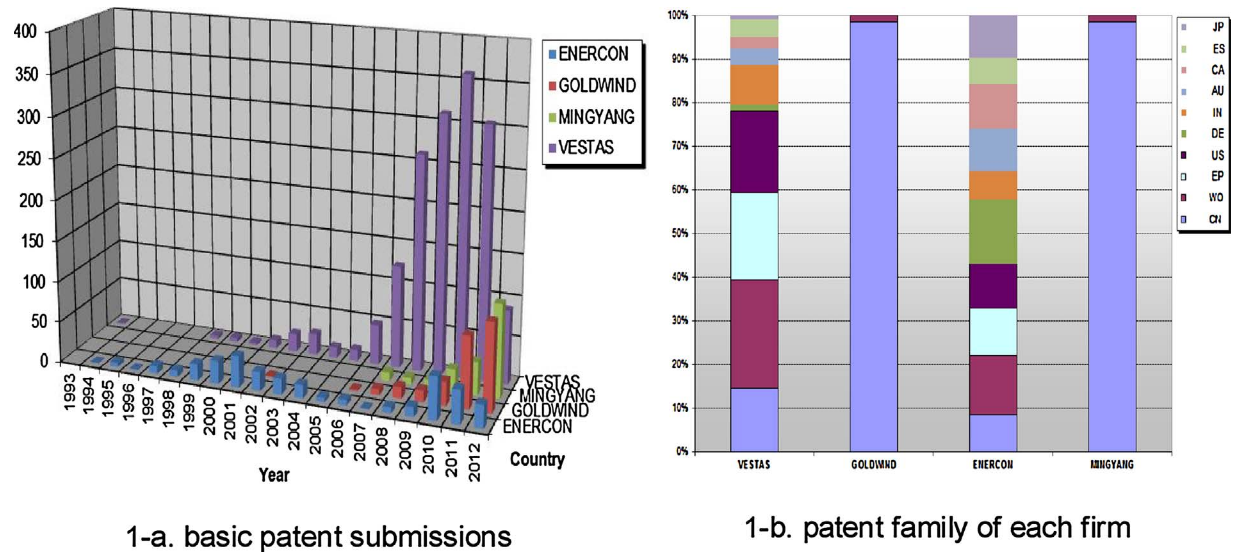

Fig. 1. Patent submissions of the sample firms.

3.2. Patent data and analysis

As aforementioned, this paper will investigate the four cases through a patent lens. The patent data are retrieved from the Derwent Innovation Index (DII) patent database of the ISI website, as well as the Thomson Innovation (TI) search engine. The DII and TI databases involve patents from most countries of the world, and those patents have been rewritten by experts at Derwent to reduce the number of errors and lead to better interpretation. Moreover, patents in DII & TI have applied the Derwent Classification with Manual Code (DCMC). This classification system will be used in this paper to understand the differences between the patenting technologies.

We search the patent data up to August 2014, with the patenting year (the priority year of submissions) during the period from 1993 to 2012. To make valid comparisons, we need to set the same timeframe to analyse the multiple pathways of the cases. We recognize that some of the sample firms were established earlier or later than 1993; prior to 1993, we use literature data and interviews to support the analysis.[1] Because an 18 month time period exists between the priority date of application and publication, the patents in 2013 and 2014 are not included as they are incomplete and may cause data bias.

3.2.1. Technology foci: patent count

Based on interviews with industry experts, some of the technology dimensions in our analytical framework can be further specified for wind turbine firms. In this study, we only look at those core technologies that have undergone dynamic changes in their technology trajectory. First, we define the ***generator and drive system*** technologies as the platform technologies, including: ordinary direct drive (DD), permanent magnet direct drive (PMDD), dual-fed induction technology (DFIT), and single-fed induction technology (SFIT). In addition, the ***grid connection and control system*** can be viewed as the key complementary technologies that improve the reliability and quality of wind turbines. Third, the most important emerging technology is recognized as being ***off-shore wind turbine*** technology.[2] Last, the customized innovation of wind turbine firms include ***high-altitude***, ***low wind speed***, ***extreme temperature***, ***sand-proof***, etc.[3]

On occasion, we add some experts interpretations to supplement the inefficiency of the existing patent data. Additionally, this study involves patents from China, where the current patent system was not established until the late 1990s, so it is necessary to add secondary data and expert input to supplement the lack of patent data. The Chinese patent system started to accept patent applications in 1985, but the compulsory requirement for references in the patent application documentation started in 1997 (Li-Ying et al., 2013). China's State of Intellectual Property Office (SIPO) only started to include the records of technology licensing agreements in 2000. So with regard to technology transfer, we found that the major licensing or joint-development transactions for Goldwind and Mingyang were missing and had to employ secondary data (e.g. company yearbooks) instead. We argue that this integrated method improves the analysis the industry as the quantitative databases and experts' interpretations complement and contrast with each other to produce triangulated outcomes.

3.2.2. Learning, spillover and R&D collaboration: patent citation map

Patent citation map displays enterprise' technological position through patent citations. Most previous studies from the macro-level displays firms' R&D cooperation relationship in order to find which firm benefit from knowledge spillover or learners of knowledge. Starting from the micro-level, we examine important patents to identify the forward or backward citations of a firm within the industry. If a patent has a robust number of forward citations, this patent's firm maybe the technological leader in this area, which as the knowledge spillover makes the technology transfer to the leapfrogging emerging economies.

3.2.3. Globalization strategy: Aduna map and knowledge network

International innovation layout as a national strategy is the inevitable choice for leading firms to deal with the global competition and expand the development space, which is also an important indicator of a national technology innovation. The global reach of a firm's innovative activities can also play an important role in its technology development strategy. As firms enhance their presence around the world by expanding manufacturing bases or R&D facilities, they are also increasingly able to tap into the global knowledge base.

In this paper, we use the TDA to map the cooperative relationship of the leading firms. We search and collate the links to the patent assignees to demonstrate the relationship and the quantities of the different patent assignees clearly, which is represented by the Aduna map. After all of raw data were imported and cleaned, then 2435 data records are abstracted from the firms. The outcomes are illustrated as a matrix. Then the TDA software converts this matrix into a visual format and the Aduna map can be obtained, in which nodes represent the patent assignees, links between nodes illustrating the cooperative relationships.

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[1] We select 1993 as the starting point year, because this was the earliest year of the recorded patent submissions (in the DII & TI databases) of the selected cases: (i) Vestas filed the patent (WO1995006975A1) on control methods in 1993; (ii) Enercon filed the patent (DE4436197A1) on an electrical generation turbine design in 1994.

[2] Offshore wind turbine technology is very different to onshore, in terms of design, control, grid connection, etc.

[3] For this specific patent searching, we use an integrated method that combines a DCMC code-search and keyword-search, followed by the validation by our team and patent searching experts (e.g. Thomson Reuters, China Academy of Science, etc.), depicted as follows: (i) platform technologies: DCMC (X15-B01 B generator and X15-B01A drive); (ii) complementary technologies: DCMC (X15-B05 control) and keyword "grid"; (iii) emerging technologies: DCMC (X15-B05 offshore); (iv) customized innovations: keywords, e.g. high altitude, etc.

Year \Patents	2006	2007	2008	2009	2010	2011	2012
Total	1	3	13	14	27	84	92
PMDD	0	1	1	4	15	36	39
PMDD (invention)	0	0	0	1	9	23	19
Grid/control	0	0	3	1	6	29	13
Grid/control (invention)	0	0	1	1	5	22	10
Offshore	0	0	0	0	0	2	3
Customized	0	0	0	1	3	0	0

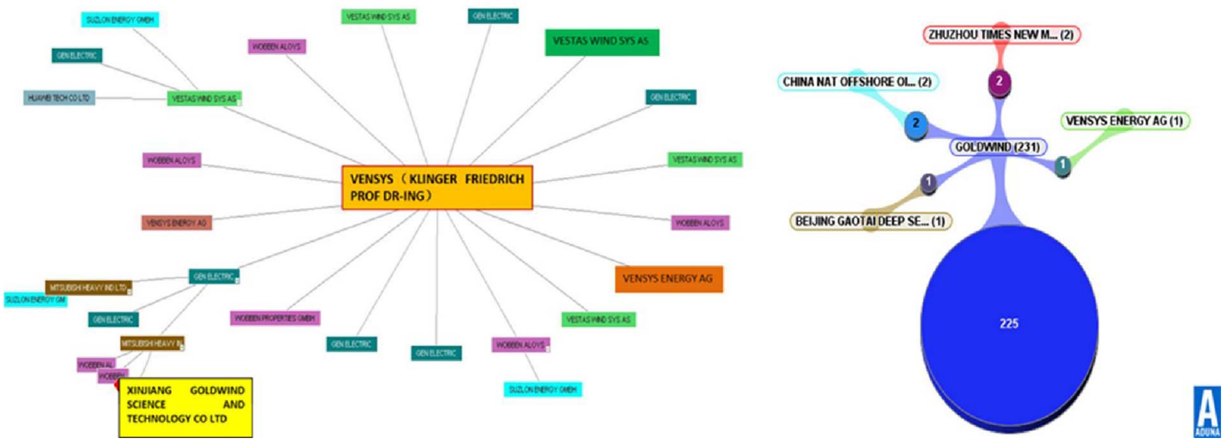

Fig. 2. A summary of Goldwind Patents[4]: Citation map of patent CN200710111649A (generator) (left) & R&D collaboration over patenting (right).

4. Multiple case studies

4.1. *Goldwind*

Goldwind was founded in 1998 and is headquartered in Xinjiang, China. In 2012, Goldwind was the largest manufacturer of wind turbines in China and the second largest globally (BTM Consult 2013). It became the major shareholder of Vensys in 2008 after their collaboration on PMDD-based wind turbines since 2003. In this case, PMDD is viewed as Goldwind's unique platform technology, which the firm uses to be compete with other wind manufacturers in developing countries.

Before 2006, Goldwind filed limited patent submissions (Fig. 2), which signals their weak initial R&D competence. Most of their technologies were acquired through licensing (Lewis, 2013). After 2003, Goldwind started on its innovation path with increasing patent submissions. A total of 231 patents have been filed up to 2012. However, Goldwind's patents are not highly cited and so are not top quality patents from the industrial perspective.

4.1.1. *Technology foci*

Goldwind appears to have successfully developed their platform technology strategy. They filed their first PMDD-related patent in 2007 and proceeded to file a series of patents on PMDD technologies for larger size turbines. They own 28 of the 231 patents on this technology. PMDD patents are the core patents of Goldwind and are highly cited. However, Goldwind was weak in terms of its technology portfolio strategies, as it made limited efforts with complementary technologies and emerging innovations before 2010. Research on off-shore and grid connection technologies began in 2011 even though China's large-scale wind farms urgently needed these to solve their high "abandoned wind" and instability issues. Goldwind also developed limited customized technologies such as high-altitude and low-speed wind turbines.

[4] In China, there are three categories of patents: invention patents, utility models, and designs. Specifically for platform and key complementary technologies, we are advised by experts to use invention patents as the indicator of core innovations of Chinese wind turbine firms, and these invention patents only account for 1/3-1/2 of the total patents of Chinese firms. For Goldwind, out of their 231 patents, 93 are invention patents. In addition, Goldwind does not enjoy exclusive rights to the patents of Vensys, so we cannot count on Vensys' patents (30 patents by 2012) in this case.

4.1.2. Learning, spillover and R&D collaboration

Since Goldwind's patents are less frequently cited, we argue that Goldwind has limited knowledge spillover capabilities, and is mainly a learner. Goldwind built its learning capacity through collaboration with Vensys, based on their acquisition of Vensys' technologies, to develop its own patents for PMDD turbines. Goldwind's learning about generator technologies can be traced to the citations of Vensys' patents (shown as "Klinger") since 2007 (Fig. 2).[5] However, apart from Vensys, Goldwind have limited R&D alliances (Fig. 2), which weakened its *technology exploration capability in the long-run.*

4.1.3. Globalization strategy

Goldwind faces challenges when promoting its innovations on the global markets despite its ambitious marketing strategy. From Fig. 1, we maintain that Goldwind still has limited innovation capabilities for global competition, as they only have developed only one international patent as of 2012. 99% of Goldwind's patents are filed only in China, so it has weak international IP competitiveness. Goldwind may rely on other resources for globalization such as financial loans.

4.2. Mingyang

Mingyang was founded in 2006, in Guangdong, China, as a spin-off of Mingyang Electrics Pte Ltd which produces electrical control equipment. Mingyang was listed on the New York stock exchange in October, 2010, and was ranked among the top 5 in China and among the top 20 worldwide (BTM Consult, 2013). Mingyang has chosen dual-fed induction (DFIT) as their platform technology.

From Fig. 3, Mingyang started to catch up in innovation, from 2007, through patent filings, as of 2012, they have 200 patents in total. However, Mingyang's patents have very limited citations, with only 29 of their 200 patents being cited. The top ten most frequently-cited patents have only been cited twice, on average, and these are related to the anti-lightening and anti-humidity technologies for wind turbines. We argue that Mingyang has yet to develop high-value patents and therefore lack core technologies.

4.2.1. Technology foci

From Fig. 3, Mingyang has developed competences based on their platform technology. There are 109 patents on the dual-fed induction system out of their 200 patents in total. In addition, Mingyang has designed a series of customized wind turbines to cater to China's markets, such as turbines for high-altitude, extreme temperatures, sand-proof, and high-speed wind conditions. However, Mingyang is relatively weak in terms of technology portfolio strategies when considering their limited efforts to develop complementary technologies, such as grid connection and control systems, and off-shore technologies until 2012. Mingyang engaged in joint technology development with the German wind firm, Aerodyn, which may be one reason why it lags behind in developing and patenting its own technology.

4.2.2. Learning, spillover, and R&D collaboration

Mingyang's IPO documents indicate they worked with Aerodyn through licensing and joint-R&D on a series of products (see Fig. 3 as an example of generator technologies). However, based on our search results, Mingyang has very few R&D alliances with regard to either patenting or research, so we argue that they have a limited capacity for new technology exploration.

4.2.3. Globalization strategy

Like Goldwind, Mingyang has limited innovation competitiveness while accessing global markets, because it has limited international patents. Mingyang only had 3 international patents submissions out of 200 in total up till 2012 (Fig. 1). Mingyang has no international acquisition operations, which may explain why 99% of their sales are in China.

4.3. Enercon

Enercon is Germany's most important and best-established wind energy firm with a market share of over 60% in Germany and 13% worldwide (BTM Consult 2013). Enercon's most significant platform innovation is its direct drive turbine, which Enercon used to develop a series of leading-edge products.[6] Enercon's Aloys Wobben developed the world's first direct drive turbine in the early 1990s.

Fig. 4 indicates Enercon has distinguished itself in filing patents before 2002. Before 2002, they accounted for about 40% of the world's patents in the wind manufacturing sector. However, since 2003, their patent filings has declined and surpassed by other players, despite a brief recovery in 2010.[7] Enercon's patents have been intensively cited. Their ten most frequently-cited patents

[5] The licensing transactions cannot be found in China's SIPO database, but we found the record in Goldwind's annual report (2009). Meanwhile, out of Vensys' 30 patents, only 3 have been cited or co-authored by Goldwind. According to interviews with domain experts, there might be two reasons for this: (i) Goldwind has weak intellectual property management that might reflect China's weak IPR regulations; or (ii) Goldwind still relies on Vensys' core-patents for PMDD turbines. Either reason may deter Goldwind's ambitions of becoming a global innovation leader.

[6] The E-126 has a rotor diameter of 127 m (m), and a hub height of 135 m. It is gearless, has a direct drive, single-blade adjustment and its cut-out wind speed is 28–34 m/s. It has therefore been built to withstand even stormy conditions.

[7] Enercon is viewed as a low-profile company. Patent intelligence has difficulties in researching about Enercon, because most of their patents are filed under the inventor's name. Some claim that this is a strategy for avoiding technology intelligence. Furthermore, Enercon is not listed on any stock exchange. Some also argue that Enercon has slowed down their patent filing activities, because their managers believe in business secrets rather than patents. Enercon also has a high degree of vertical

Year \Patents	2006	2007	2008	2009	2010	2011	2012
Total	0	10	9	9	20	39	113
DFIT	0	2	5	8	15	18	61
DFIT (invention)	0	1	2	1	7	11	28
Grid/control	0	0	2	0	1	5	15
Grid/Control (invention)	0	0	1	0	0	3	8
Offshore	0	0	0	0	0	0	19
Customized	0	0	4	0	7	0	0

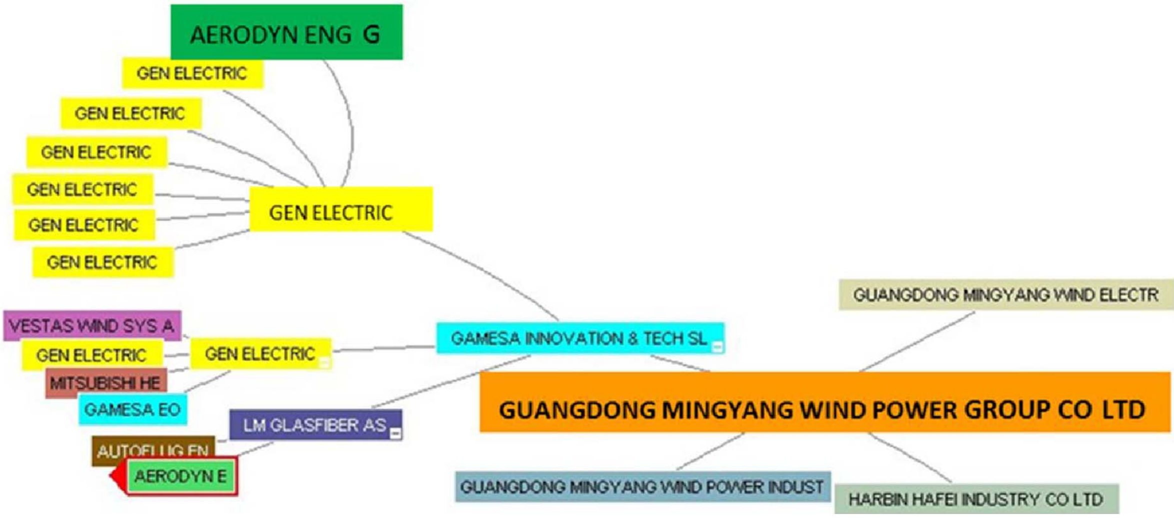

Fig. 3. A summary of Mingyang's patents: Citation map of Mingyang's patent CN201010275431A (Generator).

(38–63 times each) are used in various areas, including wind turbine generators, rotor blades, wind power systems, and installation methods. This reflects Enercon's core position within its technological domain, high quality of innovation, and influence in the industry.

4.3.1. Technology foci

From Fig. 4, Enercon has a strong competence in terms of platform technology. There are 117 highly-cited patents that are related to direct-drive turbine innovations, which was originally invented by this firm. Enercon also has robust technology portfolio strategies. Its core patents cover not only generator technologies, but also other complementary domains, such as control, installation, blade, and grid connection. Enercon is also one of the leaders in emerging technologies, with patent submissions for off-shore turbines dating back to 2001, making it the earliest entrant. However, Enercon has paid little attention to developing customized technologies for niche markets until recently.

4.3.2. Learning, spillover, and R&D collaboration

From Fig. 4, Enercon's patents have high citation rates, which indicates it's an innovation leader (see Fig. 1, Enercon's generator technologies have been widely-adopted). However, Enercon has engaged in limited scientific research collaboration, which may indicate that they have paid little attention to new technology exploration at least from a patent perspective. This may partially explain why their patent filing has slumped. By contrast, Enercon plays a very significant role in knowledge spillover and transfer to latecomers.

(*footnote continued*)
integration, producing almost all of their 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 engages in limited R&D collaboration. They are extremely careful about selecting collaborators and aim to keep any insights arising from their technology in-house.

Year \Patents	1993-2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Total	75	40	27	21	15	7	7	1	7	12	52	43	51
Direct-drive	10	8	8	10	3	2	1	2	7	4	13	24	25
Grid/control	2	2	0	2	0	1	0	0	1	2	5	14	12
offshore	1	0	2	2	2	0	0	0	0	0	0	0	0
High altitude	0	0	0	0	0	0	0	0	0	0	0	0	0

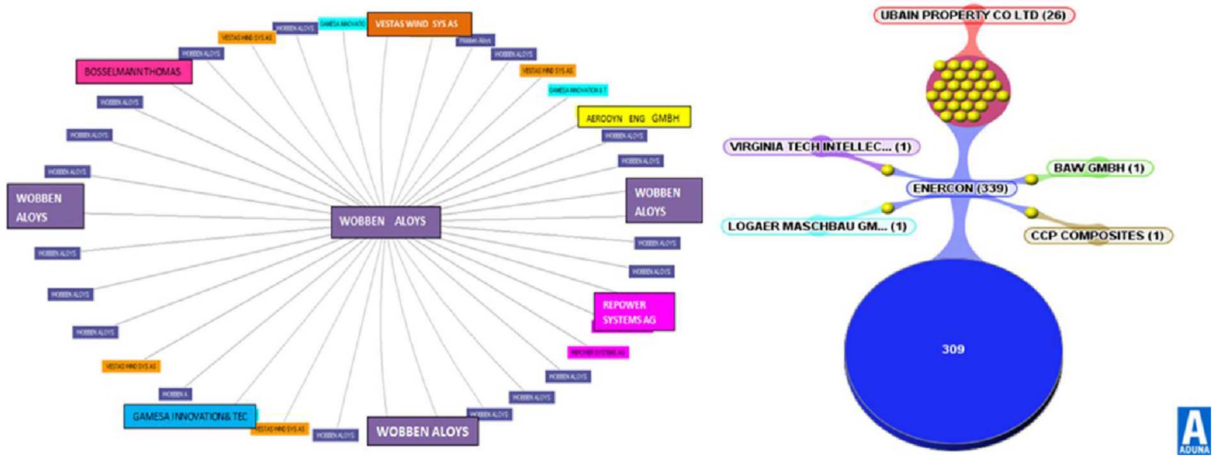

Fig. 4. A summary of Enercon's patents: Citation map of Enercon's patent DE19731918A1 (Generator) (left) & R&D collaboration over patenting (right).

4.3.3. Globalization strategy

Enercon is active in filing patents globally. It has more than 4000 international filings in more than 20 countries based on 339 foundational patents. Enercon has more cumulative patents than Vestas. Therefore, Enercon is highly competitive globally in terms of innovation with an 8% global market share (BTM Consult, 2013). However, in certain emerging markets with limited IP protection, Enercon may have limited market access when competing against cheaper products in Asia.[8]

4.4. Vestas

Vestas is the flagship firm of the Danish wind energy sector that accounts for 14% of the global market (BTM Consult 2013). Since its founding in 1981, it has worked closely with Risø National Laboratory (Denmark Technical Unviersity) on cutting-edge research, and has developed the world's largest testing facility for state-of-the-art reliability and engineering tests. Vestas developed the dominant design of wind turbines with gears in the wind power industry, so this dual-fed induction platform design may be termed the "Danish Concept" (Lema et al., 2014), based on which Vestas developed a series of successful products.

From Fig. 5, Vestas has been a historic leader in terms of patent submissions since the 1990s. Vestas' patents are widely-cited as its 10 most-frequently cited patents (40–106 times each) involve broad domains ranging from wind turbine generators, rotor blades, wind power systems, and installation methods. Clearly, Vestas possesses core technologies in several key domains and its innovations are high quality and valued by the industry.

4.4.1. Technology foci

From Fig. 5, Vestas has a strong platform technology. There are 823 patents related to the dual-fed induction turbine innovations. Vestas is also strong in terms of technology portfolio strategies. Its core patents cover more than generator technologies related to other complementary technologies. This is echoed by its benchmark product V112-3.0 MW turbine, which is well-rounded, including the blade design, nacelle design and cooling systems, with thousands of components being tested to ensure the highest reliability (Lema et al., 2014). Vestas was one of the early entrants in emerging technologies, such as off-shore turbines, since 2003.[9] However, Vestas hasn't invested in developing customized products for niche markets and only provides "add-ons" for flexibility and localization.

[8] For example, Enercon India (now called WindWorld India) had legal battles around IPR infringements and then split off from the Indian side (Urban et al., 2012).

[9] Siemens and Vestas accounted for 57% and 27% of the global off-shore market share of total accumulated installed offshore capacity respectively.

Year \Patents	1993-2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Total	14	10	28	28	22	22	63	118	193	231	252	217	83
DFIT	2	5	8	8	3	3	6	61	126	170	192	170	69
Grid/control	0	0	0	2	6	1	12	33	50	89	115	81	33
offshore	0	0	0	0	0	0	0	4	4	5	17	16	13
High altitude	0	0	0	0	0	0	0	0	0	0	0	0	0

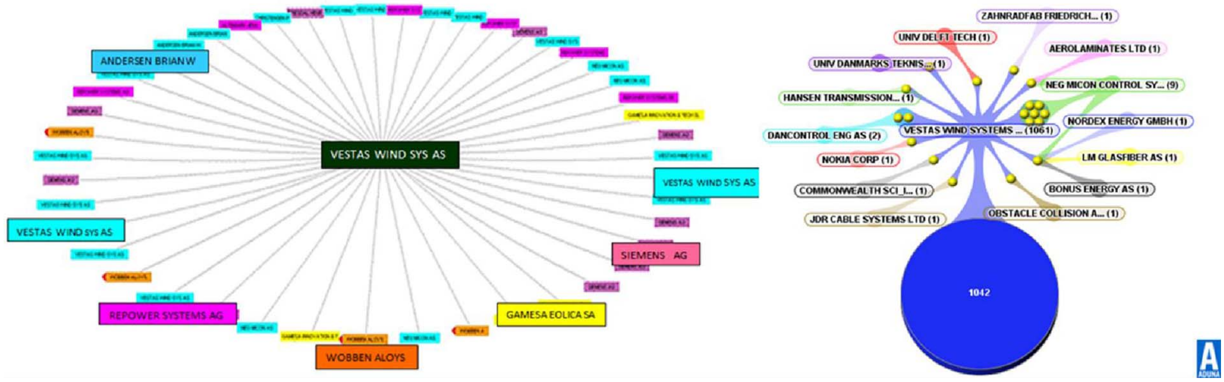

Fig. 5. A summary of Vestas' patents: citation map of patent WO1999DK595A (control) (left) & R&D collaboration over patenting (right).

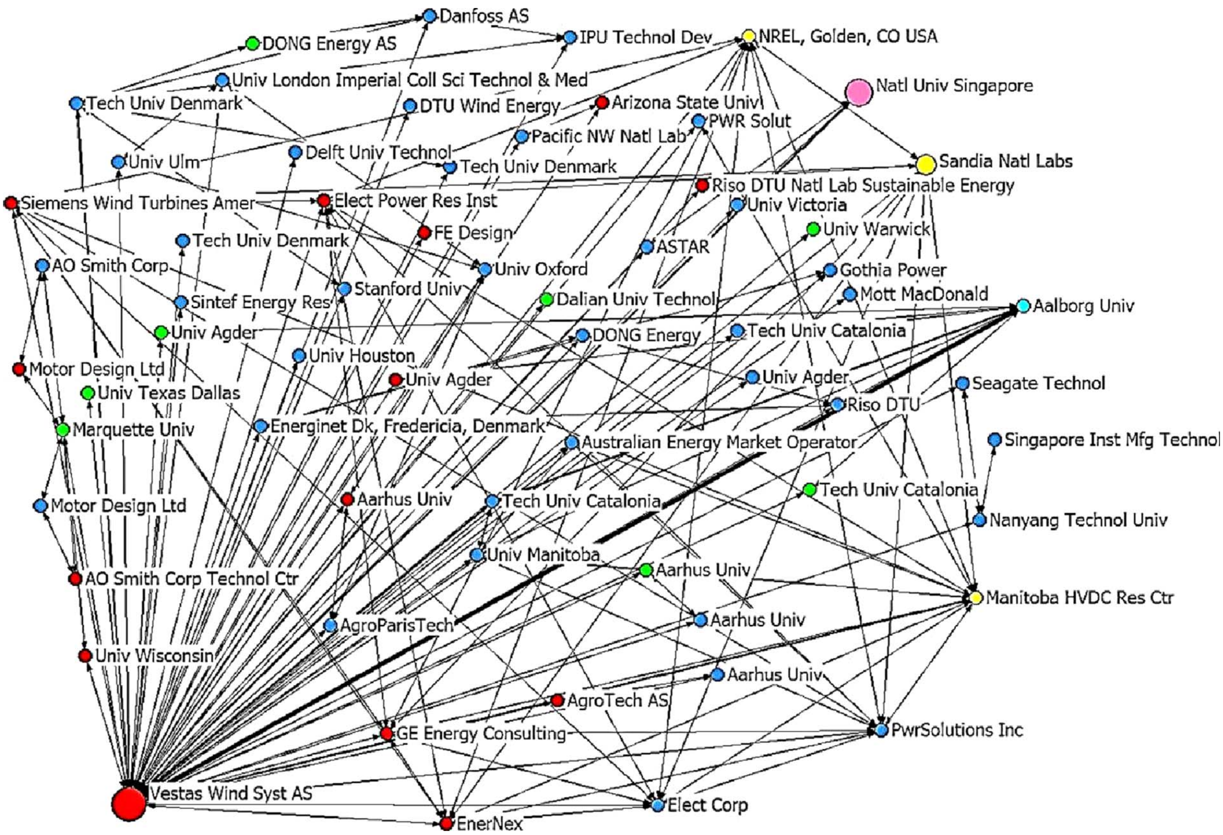

Fig. 6. Vestas: R&D collaboration over scientific publications (SCI papers).

4.4.2. Learning, spillover, and R&D collaboration

Vestas is very active in R&D collaboration regarding both patenting and scientific publications (Figs. 5 and 6), which may partially explain why they have become the global leader in new technology explorations in recent years. In addition, Vestas plays a

Table 2
Company similarity matrix (0–1): 1993–2012 (left) and 2008–2012 (right).

	MINGYANG	ENERCON	GOLDWIND		MINGYANG	ENERCON	GOLDWIND
VESTAS	0.597	0.654	0.62	VESTAS	0.619	0.864	0.582
GOLDWIND	0.867	0.554		GOLDWIND	0.855	0.689	
ENERCON	0.527			ENERCON	0.75		

significant role in knowledge spillover and transfer to developing countries (see Fig. 5 as an example of Vestas' spillover control technologies).[10] For example, Vestas' patent WO1999DK595A has been cited by more than 20 players in the wind sector, including Enercon, etc.

4.4.3. Globalization strategy

Similar to Enercon, Vestas is active in filing patents globally. From Fig. 1, Vestas has 5093 international filings in more than 20 countries based on 1061 foundational patents. Therefore, Vestas is very competitive in terms of innovation globally. Echoing this, Vestas is actually no longer a 'Danish Firm' but rather a global firm that only sells a small fraction of its wind turbines to Denmark. The firm's growth comes from the US, China and other external markets (BTM Consult, 2013).

5. Cross-case analysis and discussion

5.1. Divergent technology trajectories between China and Europe? A comparison of pathways of the leading firms

This section compares the firm-level pathways from a patent perspective with regard to the following aspects: total patent submissions and citations, platform technologies as core competences, and complementary technologies as portfolios. In addition, we also use the patent similarity test (cosine similarity) to compare the technology portfolios between these lead firms, in order quantitatively to explore the similarity of companies in accordance with their growth.

Overall, European firms are leading in terms of global wind turbine innovations with higher patent submissions and higher patent citations. Chinese firms have been catching up very quickly with the amount of patent submissions, especially in recent years. However, Chinese firms are still lagging behind in terms of patent quantity when considering patents for core innovations and citations. Some claim that this over-emphasis on patent quantity may be termed a "patent tsunami", which leads to over-estimates of the innovation competence of Chinese firms. In this case, we agree that Chinese firms are still lagging behind the European leaders in terms of innovation, while presenting competitiveness by creating high quality, efficient-cost, performance products.

First, pertaining to platform technologies, we argue that there is no divergence between the dominant designs in Asia and Europe. These firms are adopting dual-fed induction (DFIT) or gearless direct drive (DD) technology based on their own strategies, when these two dominant designs will co-exist for some time into the future (Lema et al., 2014); for example, Enercon and Goldwind are following the DD pathway, while Vestas and Mingyang are adopting DFIT systems. In this case, we believe that the Chinese firms are also followers in these two dominant designs and learning from their European counterparts.

In addition, Chinese firms may have more issues when considering innovations for reliability and quality (key complementary technologies), such as grid connection and control technologies. From the case studies, we argue that Chinese firms paid very little attention to these significant technological domains until very recently. Again, the origins of these patents can be traced back to the European leaders. This may also partially explain why many "*abandoned wind*" issues and turbine accidents have occurred in relation to Chinese wind farms in recent years.

Further-more, by using the patent similarity matrix 0–1, where 0 means totally different, and 1 means identical), we compare the similarity in the technology portfolios between firms (see Table 2). In this aspect, the European companies have a higher degree of similarity with each other, while the Chinese firms are more alike. This partially supports our earlier argument that the European firms have better technology portfolios, while the Chinese firms are still catching up. The 2008–2012 data also show that this situation is improving but no revolutionary change has occurred so far.

From the above analysis, we claim that the European wind turbine firms are quite different from the Chinese firms in terms of their innovation competence and technology portfolios, and their firm-level technological pathways differ, as global leaders (European) and followers (China), respectively. Through the patent lens, the European firms are still leading in terms of wind turbine innovation, while the Chinese firms may demonstrate their competitiveness in cost-reduction but not yet in platform design and portfolio technologies. In the future, at the sectoral level, however, we argue that there will be a limited divergence of sectoral-level trajectories between China and Europe. The European firms will probably still create the dominant designs for wind turbines, and the China firms will follow the trajectories and actively participate in the incremental innovations of the existing platforms.

[10] European practice is often core to the formulation of standards in other parts of the world, and Vestas has worked closely with other R&D arms. Vestas, however, has an in-house production model, compared to its open model for R&D collaboration.

Table 3
A comparison of the firms' innovation strategies.

Strategic dimensions	Key factors (items)	Goldwind	Mingyang	Enercon	Vestas
Technology emphasis (foci)	Platform technologies	Medium	Medium	Strong	Strong
	Complementariness	Weak	Weak	Strong	Strong
	Emerging technologies	Weak	Weak	Medium	Strong
	Customized innovations	Medium	Strong	Weak	Weak
Learning, spillover, R&D collaboration	Learning vs. spillover	Strong learning	Strong learning	Strong spillover	Strong spillover
	R&D collaboration in patenting	Weak	Weak	Medium	Strong
	R&D collaboration in scientific research	Weak	Weak	Weak	Strong
Globalization strategy	Intellectual property for globalization	Weak	Weak	Strong	Strong
	Global competitive strategy	Cost/performance	Cost/performance	Leading in IP	Leading in IP

5.2. *Any chance of leapfrogging by the Chinese firms? A comparison of the firms' innovation strategies*

Based on the case studies, we develop a table (Table 3) to compare the innovation strategies of Chinese and European firms in following the strategic dimensions: technology emphases, learning, spillover, and R&D collaboration, and globalizations strategies. We use a three-point scale to evaluate the specific items: strong, medium, and weak, when considering both the quantity and quality of the patent indicators.[11] In addition, we also consult with domain experts to ensure that there is no fundamental misinterpretation of the patent data.

5.2.1. *From a technology perspective*

Chinese firms are adopting diverse technology strategies to catch up on a fast-track. Chinese firms emphasize the indigenous platform technologies, for both PMDD and DFIT based on firm-level preferences. However, Chinese firms paid little attention to the emerging offshore technologies as well as the technology portfolios in terms of their quality and reliability. Compared to Chinese firms, European firms have acted as innovation leaders in the dominant designs of the existing platforms, and are also leading the emerging offshore technologies with new technology paradigms.

From the other perspective, the invention patents of Goldwind and Mingyang on generator & drive technologies outnumbered those of Enercon (though not those of Vestas) in 2011 and 2012 respectively. This is a sign that the Chinese wind firms are starting to challenge the existing leaders in the existing technological trajectory, as Chinese firms have done in other sectors, such as Huawei in the Telecoms sector, Lenovo in the personal computer sector, etc. However, the "***patent tsunami***" issue of Chinese firms should be noted. Goldwind and Mingyang produce a lot of patents, but more than half of these are NOT high-value invention patents, and these patents have very limited citations so that the real value of the innovations are dubious. In addition, the limited number of patents related to emerging technologies also jeopardizes the future of Chinese firms.

5.2.2. *From a learning and collaboration view*

Chinese firms are learning very quickly by adopting diverse strategies. Goldwind and Mingyang established collaboration with European wind turbine design firms, and acquired core technologies through licensing and joint-projects. Based on these acquired technologies, Chinese firms develop indigenous patents that provide the platform for further incremental upgrades. The German side produces the most valuable patents then transfers this knowledge to the Asian teams for customized innovation. However, all Chinese firms have made limited open innovation efforts in terms of joint patenting and joint scientific publications. They also have limited in-house competence with regard to exploring new and emerging technologies. This will cause the Chinese firms to suffer when new technology paradigms become dominant in the near future, and they may then repeat the learning and catching-up scenario. In this case, Goldwind should strengthen their link with Vensys to create new opportunities.

5.2.3. *From a globalization perspective*

Chinese firms experience difficulties when developing global products and competing in terms of innovation. Based on the case studies, Chinese firms mainly file patents in the domestic markets (99%), and therefore have limited innovation competitiveness when aiming to achieve a global reach. This echoes the argument that Chinese firms need to compete on cost-performance, and leverage other non-intellectual resources. By contrast, European firms are very active in submitting international patents in diverse markets. As mentioned earlier, Enercon particularly emphasizes international patents due to their globalization strategies. They make more patent submissions than the other firms, if all patents in different countries are counted, which indicates that Enercon has devoted more efforts to market exploitation than technology exploration as indicated by the foundational patents recently.

The above analysis of the firm-level innovation strategies suggest that Chinese firms have a limited chance of leapfrogging to new technology paradigms in wind turbine technologies in the near future. In fact, they even have difficulty meeting the global innovation competition, on the existing trajectories. However, Chinese firms are attempting to duplicate the "catch-upper's success" on the existing technology trajectory through their recent intensive patent submissions. Again, we argue that these efforts help Chinese firms

[11] These scales are relative (not absolute) measures for comparing these five cases; however, we argue that these scales can also be applied to other cases, because the sample cases are national or even global lead firms and can set the upper limit for the measurements.

to achieve leapfrogging for their own innovation capabilities, which enables them to become competitive followers in this global industry.

6. Conclusions and policy implications

This paper finds that technology pathways varies among wind turbine firms, especially when pathways follow different innovation strategies that involve technology foci, learning and R&D collaboration, and globalization strategies. Specifically, European firms are stronger in most strategic dimensions, although they also differ in terms of firm-level strategies and pathways. Chinese firms have a strong learning capacity and customized innovations. However, we propose that there is no significant divergence between the sectoral-level technological trajectories of Chinese and European firms. From an innovation perspective, the European firms are still leading the existing platform technology trajectories and emerging offshore technologies. Thus, we believe that there are limited opportunities for Chinese firms to leapfrog in the existing technology trajectories to surpass their European counterparts in the near future. Comparatively speaking, we recognize that the Chinese firms have "caught-up" in terms of developing of their innovation competences by adopting various innovation strategies and learning from their European counterparts.

Based on these findings, governments, especially in China, should modify their policy frameworks by balancing the demand-side policies for domestic consumption and pursuing indigenous R&D, encouraging collaborations for technological exploration, and reframing global policies. First, the Chinese government should coordinate the technology-push and demand-side policies more effectively. As a follower, if the Chinese government urges marketization and production, but neglects the development of core technologies. Chinese firms are inclined to acquire mature foreign technologies as a short-term solution while ignoring indigenous research. This may undermine China's opportunity to leapfrog in the technology trajectories echo Nemet's (2009) claim that over-emphasizing the demand-pull policies in inappropriate circumstances will discourage the emergence of disruptive innovations. In contrast, the European governments need to continue their strong support for wind energy. Long-term policy frameworks, such as the wind turbine guarantee in Denmark and the renewable energy law in Germany, should be maintained to be competitive (Walz and Köhler, 2014). Furthermore, European governments need to emphasize the new paradigms of wind turbine technologies to maintain their leadership positions.

The abovementioned concerns are confirmed by our analysis on research collaboration. The Chinese firms undertook limited collaboration with basic research partners for technological exploration. They engaged in limited partnership within the industrial communities for patenting. To catch-up, this strategy may be effective when the existing dominant designs can be acquired through technology transfer, based on which the followers can produce high quality cost-performance or customized products. However, this model offers limited opportunities for technology leapfrogging. China should no longer be a "national learning system" through reverse-engineering activities. However, some institutional barriers to open innovations still exist, such as the weak industry-university linkages and limited regulation support for open innovation. Therefore, the Chinese government needs to devote greater resources toward removing these barriers and strengthen the national innovation system.

The patent applications of Chinese firms have been growing exponentially in recent years. However, the quality of these patents remains uncertain and the international claims are very limited. The Chinese government may need to reframe the globalization policy framework to promote emerging industries like the wind sector by emphasizing WTO regulations and encourage local technologies to use a global orientation from the beginning.

The theoretical contributions of this paper are threefold. First, it reveals that the existing wind turbine firms have adopted diverse innovation strategies in China and Europe, which may lead to different firm-level pathways. This contributes to the existing technology trajectory literature on strategy. Furthermore, this paper specifically examines the key strategic dimensions of wind turbine firms, which suggests that the future sectoral-level technology trajectories may be similar for China and Europe. Third, this paper develops a new framework by using patent analysis to evaluate innovation strategies and technological pathways of wind turbine firms by extending the method to firm-level strategies in emerging industries. We believe that this will contrast with other analytical perspectives. This paper has several limitations. First, the sample size could be increased to improve the robustness of this study. The study contributes in-depth case evidence as a basis for further large sample studies. Second, this explanatory framework is not exhaustive. Further study on the institutional, industry and comparative perspectives would be useful. This paper could provide the basis for further work on converting the analysis into guidance for practitioners who wish to address capability and strategic gaps in the RE market.

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