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Giant and Dwarf - China's Two Faces in Wind Energy Innovation

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Abstract

A functional analysis of the TIS for wind energy in China has revealed a great disparity in performance with respect to different functions of innovation. A particular strength of the Chinese TIS is the rapid diffusion of wind power equipment which presupposes the development of domestic production capabilities, the successful adoption of existing technology, the creation of markets and legitimacy as well as the ability to mobilize financial resources. Furthermore, Chinese universities and research institutes have quickly expanded their capabilities in the area of basic research. In contrast, China's performance in the area of applied research is mixed. Although the growth in the number of transnational and domestic wind energy patents indicates that China is now among the most inventive countries in the world, a more detailed analysis suggests that inventions are less focused on the most relevant technology subfields and that Chinese firms are reluctant to engage in innovation. The most prominent drawback of the centralized planning approach in China are governance deficits relating to the integration of wind energy into China's electricity grid as well as to the lack of complementary infrastructure for energy transmission and storage. These deficits result in high curtailment rates, low incentives for quality oriented innovation, and a low overall efficiency of wind energy in China.

Keyword: Technological Innovation System, Functions of Innovation, China, Wind Energy

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1 Introduction

Rising concerns about air pollution in China's cities and international pressure on China to mitigate climate change have prompted the Chinese government to adopt ambitious targets for the deployment of renewable energy. The 13th Five-Year Plan includes objectives for non-fossil renewable energy consumption to reach 15 % by 2020 and 20 % by 2030. Wind energy plays a crucial role in China's ambition to transform its energy system. For this specific technology, the target is to reach cumulative installed capacity of 210 GW by 2020 (GWEC 2017). With 145 GW installed wind energy capacity in 2015, China is now the leading market in the world and has a share of 33.6 % in the world's total capacity for wind energy (GWEC 2016). Given the ambitious political targets for 2020 and 2030, annual growth of wind energy is likely to continue at a rapid pace throughout the next years.

During the early stages of development, the emergence of the Chinese wind energy industry has been very much depended on technology transfer and technological collaboration with Western companies (Lema, Lema 2013; Dai, Xue 2015). Today the Chinese market is dominated by Chinese OEM and the market share of foreign manufacturers has been steadily falling from 75 % in 2004 to somewhat below 3 % in 2015 (Liu, Goldstein 2013; GWEC 2016).

In face of the future challenges for the development of wind energy in China, the question arises whether China's technological innovation system (TIS) for wind energy is mature enough to bring about the necessary degree of innovation for a successful transformation of the energy system. This envisaged transformation puts high financial requirements on the Chinese government, in particular for financing the deployment of wind energy through feed-in tariffs. As Lam et al. (2017) point out, the costs of carbon mitigation in China have been four to six times higher than official estimates, largely due to inefficiencies in the management of the overall energy system. As similar concerns are shared by many governments in the world, cost reductions have been a major objective for innovation in the wind energy sector. As a consequence, the levelized cost of wind energy has fallen by 14 % over the past six years and is forecast to fall a further 18 % over the next decade. In addition, the average load factor of new wind farms has risen from less than 20 % in 2008 to 25 % in 2015, and is forecast to rise to 37 % by 2025. Important drivers of these developments have been increasing turbine sizes and optimization of wind park performance through big data analysis (FS-UNEP 2016).

However, in China these efficiency gains are eaten up by high curtailment rates in the North-Western Provinces, where the development of wind energy in China has mainly taken place. In 2015, 43 % of wind energy generated in the Gansu province had to be curtailed, 38 % in Xinjiang, 30 % in Jilin, and 21 % in Inner Mongolia (GWEC 2017). Now the focus of wind energy development is shifting towards the Central and Southern regions, which have much smaller curtailment rates due to their proximity to load centers. As these regions are often characterized by low wind speeds, i. e. average wind speeds of 5.2 m/s, one important innovation challenge for China is the development of low wind speed turbines. From a technological perspective, the turbine including the drive train and the generator are the components requiring the highest degree of technical knowledge and R&D investment (Wiser et al. 2011).

Based on these demarcations of the TIS in focus, the following analysis closely follows the methodological approach described by Bergek et al. (2008). In section 2, this methodology is briefly described. Section 3 denotes the most important actors, networks and institutions of the TIS. Section 4 assesses to what extent the TIS is performing in terms of key innovation processes. These key processes have also been termed functions of innovation. Finally, section 5 draws conclusions from this analysis.

2 Methodological Approach

The TIS framework has been developed to complement the analysis of national and regional innovation systems (Nelson 1993; Cooke et al. 1997) which is confined to innovation taking place within clearly defined geographic boundaries (Gosens, Lu 2013). In contrast, the TIS framework acknowledges that many innovation processes are international in nature (Bergek et al. 2008) and are often characterized by international linkages between different actors. Hence, the TIS framework is focused on the development, diffusion and use of a particular technology (Bergek et al. 2008).

Different types of actors are involved in innovation processes, e. g. universities, research institutes, firms, industry associations, financing institutions, and government agencies. Weaknesses in the structure of the TIS may lead to systems failure. Klein Woolthuis et al. (2005) have pointed to different types of system failures that can arise from structural weaknesses of innovation systems, i. e. infrastructure failure, institutional failure, interaction failure, and capabilities failure.

The functional approach towards technological innovation systems stresses the importance of different innovation processes, termed functions of innovation, that determine the overall performance of the innovation system (Hekkert et al. 2007). Bergek et al. (2008) distinguish the following functions: knowledge development and diffusion, influence on the directions of search, entrepreneurial experimentation, market formation, legitimation, resource mobilization, and development of positive externalities. The main objective of this analysis is to identify relevant policy issues and to set goals for the future development of the TIS. A particular focus is on the identification of weaknesses or system failures that threaten the performance of the TIS.

The TIS framework has been applied to the wind energy in China before by other authors, e. g. Gosen, Lu (2013), Walz, Delgado (2012). Whereas the work of Gosen and Lu (2013) is focused on the relative performance of China, which they characterize as a "lagging TIS", to the technological frontrunner countries; Walz and Delgado (2012) compare China and India. Due to the rapid development of the wind energy TIS in China and its importance for the global fight against climate change, it seems appropriate to revisit this issue. Furthermore, the TIS for wind energy in China has outgrown its formative phase now and some earlier trends in its evolution might have become more significant and visible today.

Thus, in the following, data from various patent and publication analysis, as well as from publicly available reports and documents about institutional, market, industrial and technological developments related to wind energy in China will be used to assess the performance of the TIS. The purpose of this study is to contribute to the future development of the wind energy TIS in China, based on a better understanding of its functional dynamics and specific strengths and weaknesses.

3 Identifying the structural components of the TIS

The objective of this chapter is to identify the most relevant actors, networks and institutions of the Chinese TIS for wind energy. As highlighted by the extant research on technological innovation systems, e. g. Hekkert at al. (2007), companies are crucially important for successful innovation because they can dispose of the necessary financial, managerial and technological resources to coordinate activities of different actors in the innovation system.

Reflecting the rise of China's domestic wind turbine industry, the leading wind turbine manufacturers in the Chinese market are all domestic companies. In the year 2016, Goldwind was the market leader with a share of 27.1 % of newly installed capacity, followed by Envision, MingYang, and Guodian United Power. The most important foreign manufacturers in China in 2015 were Gamesa with 434 MW (1.4% market share), followed by Vestas with 283.8 MW (0.9%) and GE with 113.7 MW (0.4%) (GWEC 2016).

Table 1: Leading Wind Turbine Manufacturers in China in 2016

Manufacturer	Installed Capacity (MW)	Market share in %
Goldwind	6.343	27,10%
Envision	2.003	8,60%
Mingyang	1.959	8,40%
Guodian United Power	1.908	8,20%
CSIC	1.827	7,80%
Shanghai Electric	1.727	7,40%
XEMC	1.236	5,30%
Dongfang Electric	1.227	5,20%
Windey	724	3,10%
Huachuang	715	3,10%

Source: GWEC 2017

For the 29 wind energy OEMs active in China in 2011, Liu and Goldstein (2013) carved out that of those 18 OEMs that represented 97 % of the market, 11 were State-owned enterprises (SOE) and 7 OEMs were private companies, thereof four domestic and three foreign companies.

For offshore wind power, which is still in its infancy in China and had only 0.4 GW cumulative installed capacity in 2013, the most active companies were Sinovel, Goldwind, and Siemens (CREIA/CWEA/GWEC 2015). However, the development of offshore wind has attracted considerable investment in recent years and is expected to become increasingly important in the coming years (FS-UNEP Collaborating Centre 2016).

Some of the wind turbine OEMs produce their own blades, e. g. Mingyang, Dongfang Electric, Guodian United Power, and Vestas, whereas other OEMs source blades from specialized local suppliers, such as Sinoma Science & Technology or Zhongfu Lianzhong (CREIA/CWEA/GWEC 2015). Established Chinese manufacturers of gearboxes include NGC, CQ-Gearbox, Dalian Heavy

Industry, Hangzhou Advanced Gearbox. In addition, the two German manufacturers ZF Friedrichshafen[1] and Winergy maintain gearbox production facilities in China (CREIA/CWEA/GWEC 2015).

The most important wind farm developers are all state administered companies, except for Tianrun which is a subsidiary of Goldwind. In terms of cumulative installed capacity in 2013 the most important developers were Guodian (19.2 % of installed capacity), Huaneng (11.7 %), Datang (11.6 %), Huadian (6.4 %), and China Power Investment (5.8 %). Tianrun had a share of 2.9 % (CREIA/CWEA/GWEC 2015) .

Furthermore, Chinese state owned banks, such as the China Development Bank, are an important source of finance for the capital-intensive wind energy industry.

With regard to universities and research laboratories active in the field of applied research for wind energy, an analysis of patent applications at the State Intellectual Property Office (SIPO) of China revealed the results displayed in Table 2.

Table 2: Wind Power Patent Applications of Chinese Universities and Research Institutes at SIPO in 2010-2013

Universities	Patent Applications	in % of Total
UNIV NORTH CHINA ELEC POWER	29	0,7%
UNIV XI AN JIAOTONG	26	0,6%
UNIV SHANGHAI JIAOTONG	24	0,5%
UNIV TIANJIN	23	0,5%
INST ENG THERMOPHYSICS CAS	22	0,5%
UNIV HARBIN ENG	22	0,5%
UNIV ZHEJIANG	19	0,4%
UNIV NANJING AERONAUTICS	17	0,4%
UNIV CHONGQING	14	0,3%
UNIV SOUTHEAST	13	0,3%

Source: SIPO, author's calculations

As evident from Table 2, capabilities for applied research in wind energy seem to be widely spread among several universities and research institutes and show a low degree of concentration. However, in geographic terms there seems

[1] In 2015, ZF Friedrichshafen acquired the gearbox unit of Bosch Rexroth.

to be a slight degree of concentration on the Beijing-Tianjin region, as the North China Electric Power University, the University of Tianjin and the Institute of Engineering Thermophysics (Chinese Academy of Sciences) are all located in this area.

As with regard to actor networks, the strong performance of the University of Tianjin might be indicative for the R&D activity in the Tianjin wind energy technology cluster. This cluster encompasses important foreign firms such as Vestas, Gamesa, Suzlon, LM Glasfiber, Winergy, and Hexcel, as well as domestic firms such as Tianjin Dongqi Wind Turbine Technology. Another cluster for wind energy is located in Baoding (Hebei Province), which is about 150 km southeast from Beijing, and has become host to major renewable energy companies, including wind power equipment manufacturers such as HuaYi Wind Power and Tianwei. Another regional cluster is in Shenyang (Liaoning Province), where, among others, General Electric's subsidiary GE & HE Wind Power and the Chinese company A-Power are located (UNCTAD 2009).

Another very important institution in China's TIS for wind energy is the State Grid Corporation of China (SGCC) which owns and operates China's electricity network. The SGCC is also an important player in the field of wind power innovation with 44 SIPO patent applications in the period running from 2010 to 2013, which is equivalent to 1 % of total applications. The SGCC's research unit is the China Electric Power Research Institute (CEPRI) which also runs a Wind Power Test and Inspection Center located in the Hebei province. Apart from testing and standard setting activities in the field of wind power, the CEPRI is involved in innovation in the fields of Ultra-High Voltage (UHV) power transmission and transformation and smart grid technology which is highly complementary for the deployment of wind power in China.

Important industry associations are the Chinese Renewable Energy Industry Association (CREIA) and the Chinese Wind Energy Association (CWEA) which frequently publish reports about the development of wind energy in China, develop policy recommendations, and contribute to efforts of the Global Wind Energy Council (GWEC).

The highest administrative authority of energy policy making in China is the National Energy Commission (NEC) which is currently headed by Li Keqiang, the Premier of the People's Republic of China. The NEC was formally established in 2010 and consists of 21 members from various government ministries, government agencies, military and other government representatives. The National

Development and Reform Commission (NDRC) is an important institution of the central government and has a broad set of responsibilities, including policy, planning and pricing decisions in the energy sector (Downs 2008). The National Energy Administration (NEA) is an agency within the NDRC, replacing NDRC's former Energy Bureau, and responsible for the operative affairs of the NEC. The NEA consists of nine different departments, including the offices for New and Renewable Energy, and Development and Planning. As a supervising authority of the energy industry the State Electricity Regulatory Commission (SERC) is another important player in the Chinese energy governance (Downs 2008; Lewis 2013). However, China's energy policy is influenced by other ministries as well. For instance, the Ministry of Finance (MOF) is responsible for subsidies, whereas the Ministry of Industry and Information Technology implements industrial restructuring measures (Lewis 2013). Energy policies in China are usually centrally planned by the above-mentioned agencies, but policy makers at the provincial level can influence how these policies are implemented (Urban et al. 2012).

The regularly updated Five Year Plan (FYP) which is issued by the NEA is an important policy document and includes targets for different energy sources. The current 13th FYP formulates targets for the period from 2016 to 2020 and includes the objective for non-fossil energy sources to reach a share of 15 % of energy consumption (GWEC 2017).

The Renewable Energy Law that came into force in 2006 represents a milestone policy instrument for the development of wind energy in China. This law introduced nationwide renewable energy targets, a feed-in tariff system for wind energy, an obligatory purchase and connection policy, and a fund for renewable energy development, which pushed the development of renewable energies significantly. In addition, the Medium and Long Term Development Plan for Renewable Energy that came into force in 2007, targeted the development and use of renewable energies by implementing preferential financial and tax policies, including funds subsidizing renewable energies as well as the reduction or elimination of taxes for certain projects. In 2008, the Ministry of Finance issued a funding policy for the commercialization of all locally produced wind power generation equipment. All turbines over 1 MW capacity were rewarded with a subsidy of 600 RMB/kW, provided that they had been connected to the grid and put into operation (Lewis 2013). In the same year, the Corporate Tax Law implemented the provision that wind farm projects are exempted from corporate tax for the first three years, and exempted from 50 % of the corporate tax for the next three years (Liu, Goldstein 2013).

4 Mapping the functional pattern of the TIS

4.1 Knowledge development and diffusion

This function captures the development of the knowledge base in basic and applied wind energy research. The performance of the Chinese TIS is compared to the situation in other countries. Scientific publications are used as an indicator for innovation activity in the area of basic research and patent applications as indicator for applied research.

Data on scientific publications[2] in the field of wind energy was extracted from the Web of Science, a scientific citation indexing service. Table 4 shows the number of scientific publications for nine countries and the world in total. It becomes evident that the number of scientific publications on wind energy has considerably increased throughout the observed 12- year period. When comparing the period 2010-2013 with the period 2002-2005, the number of publications increased by the factor 6.9. In 2013, for example, 2,134 new publications on wind energy were published worldwide, whereas in the year 2000 there were only 121 publications. Although China is frequently considered as a latecomer in the field of wind energy technology, the figures reported here suggest that capabilities for basic research have been expanded very rapidly and China is now leading in terms of output from basic research activities.

An additional analysis of international co-publications revealed that Chinese researchers quite frequently collaborated with academics from other countries. During the period running from 2010 to 2013, 13 % of publications of authors from Chinese universities and research institutes were international co-publications. The most important collaborators in terms of number of papers came from the United States (73 co-publications with China), United Kingdom (32), Australia (19), Canada (19), Denmark (10), and Germany (7).

[2] To avoid double counting, conference proceedings have been excluded from the search. This is because publications in conference proceedings are frequently followed by publications of the same results in academic journals.

Table 3: Number of Scientific Publications on Wind Energy

	2002-2005	2006-2009	2010-2013	Total
Denmark	49	136	252	437
Germany	78	221	300	599
Japan	69	227	206	502
Netherlands	20	59	87	166
Spain	42	135	251	428
United Kingdom	65	190	330	585
United States	174	473	1154	1801
Brazil	15	51	74	140
China	54	624	1460	2138
World	948	3439	6511	10898

Source: Web of Science, author's calculations

Data on patent applications in the field of wind energy was extracted from the European Patent Office's (EPO) Worldwide Patent Statistical Database (PATSTAT). Patent applications were identified according to the priority year, i. e. the year of their worldwide first filing, and based on the concept of 'transnational patents' suggested by Frietsch and Schmoch (2010). In detail, all filings at the World Intellectual Property Organisation (WIPO) under the Patent Cooperation Treaty (PCT) and all direct filings at the EPO without precursor PCT filing are counted. This excludes double counting of transferred PCT filings to the EPO. Thus, all patent families with at least either a PCT filing or an EPO filing are taken into account. Patent applications were assigned to different countries based on the inventor's country of residence.[3]

Table 4 shows that the number of patent applications has likewise increased considerably, although at a slower rate than scientific publications. Germany and Denmark are ahead of the USA in terms of total patent applications in the observed period. China's performance in terms of patenting activity seems to fall short of its publishing performance, although it has to be noted that, since the period 2006-2009, China has managed to catch-up with the United Kingdom and Spain, two countries that have started much earlier to invest substantially in wind energy R&D.

3 This methodology applies to all further analysis of patenting activity in this paper unless explicitly mentioned.

Table 4: Number of Transnational Wind Energy Patent Applications

Transnational Patent Applications	1994-1997	1998-2001	2002-2005	2006-2009	2010-2013	Total
Denmark	15	60	115	520	888	1598
Germany	42	236	347	733	1084	2442
Japan	12	43	112	214	478	859
Netherlands	8	25	28	111	117	289
Spain	4	19	57	180	349	609
United Kingdom	5	19	54	164	287	529
United States	24	53	153	573	685	1488
Brazil	0	0	4	13	20	37
China	1	6	17	186	340	550
Total	111	461	887	2694	4248	8401

Source: PATSTAT, author's calculations

As foreign markets are still of minor importance to the Chinese wind energy sector, filing transnational patent applications might not be a relevant strategy for Chinese firms and conclusions based on the analysis of transnational patents might be biased. Thus, in order to gain additional insights on the Chinese innovation system for wind energy, domestic patent applications at the State Intellectual Property Office (SIPO) were examined. For the period running from 2010 to 2013, a total of 4403 patent applications were identified. The German company Siemens was the most active applicant, representing 6.3 % of total patent applications. The patenting applications of the leading Chinese turbine manufacturers are displayed in Table 5.

Table 5: Wind Power Patent Applications of the Leading Chinese Wind Turbine Manufacturers at SIPO in 2010-2013

Manufacturer	Patent Applications	in % of total
Guodian United	104	2,4%
Goldwind	74	1,7%
Mingyang	61	1,4%
Sany	52	1,2%
DongFang Electric	25	0,6%
XEMC	14	0,3%
Shanghai Electric	11	0,2%
CSIC	8	0,2%
Windey	6	0,1%
Envision	4	0,1%

Source: SIPO, author's calculations

Even though the leading Chinese firms, such as Guodian, Goldwind and Mingyang, were quite active, their share in total domestic patent applications seems to be rather low when compared to the situation in Germany, where, for instance, during the period running from 2010 to 2013, Siemens had a share of 42 % in all transnational wind power patent applications, Enercon 7.4 %, Nordex 5.4 %, and Bosch 3.6 %.

The overall impression is, that innovation activity in the area of applied research has strongly increased in terms of the number of patent applications – although still lagging considerably behind the world's leading countries in this field –, but lacks in focus on the most important technology subfields and on leading domestic companies.

4.2 Influence on the directions of search

This function addresses how the search for new technological solutions is influenced by certain mechanisms and to what degree new companies and other organizations are enticed to engage in the TIS. Among others, important mechanisms that influence the direction of search are visions and expectations of actors, their perception regarding the relevance of different sources of knowledge, future technological opportunities, as well as political priorities and regulations (Bergek et al. 2008).

As the identification of important actors and institutions in section 3 has revealed, the Chinese TIS for wind energy is dominated by state-owned wind turbine manufacturers and state-owned wind park developers, universities, public utilities and government agencies. With regard to important institutions, the development of the TIS is guided by the FYP and policy instruments such as the Renewable Energy Law. Hence, it can be assumed that the direction of search will also be heavily influenced by priorities formulated by the Chinese government.

Regarding the search for technology, Lall (1992) has pointed out that, from the perspective of the technology recipient, import of foreign technology and indigenous technology investment are two options which can complement each other and to a large extent substitute each other. As China is a latecomer country in the field of wind power technology, the aspect of technological learning from more advanced countries and political initiatives, such as Local Content Criteria (LCC) and subsidies, to stimulate such learning has been a very prominent issue during the early stages of development (Lema, Lema 2012). As the Chinese wind energy TIS developed, the focus shifted towards indigenous innovation (Dai et al. 2014).

The NDRC's wind power concession program that was effective between 2003 and 2009 included the first application of the LCC of the 9^{th} FYP from 1996. The original requirements demanded 40 % locally manufactured components of the purchased wind power equipment for newly developed projects. The concession projects from 2003 increased that share further to 70 %. Consequently foreign wind turbine suppliers established own manufacturing facilities in China, since there were only few Chinese manufacturers in the market at that time. The NDRC further institutionalized the LCC in 2005 and denied every wind power project with less than 70 % domestically produced equipment (IEA/IRENA 2014; Lewis 2013). In 2009, Notice No. 2991 of the NDRC fully revoked the existing local content requirement on all wind turbines installed in China.

Some of these restrictions provided strong incentives for foreign companies to locate their production in China and forced them to engage in formal joint ventures or at least joint technology development projects with domestic companies. But other channels for technology transfer and learning, such as licensing, have also been widely used (Lema, Lema 2013). One important characteristic of the Chinese policy approach towards industrial development in the wind sector seems to be the strong emphasis put on technological learning and the responsiveness towards the unfolding technological capabilities of domestic producers. For example, the size of wind turbines eligible for import tariffs was increased as soon as the domestic industry had mastered the respective production technologies. Furthermore, domestic companies received import tariff and VAT rebates on wind power equipment only if they engaged in R&D activities (Liu, Goldstein 2013).

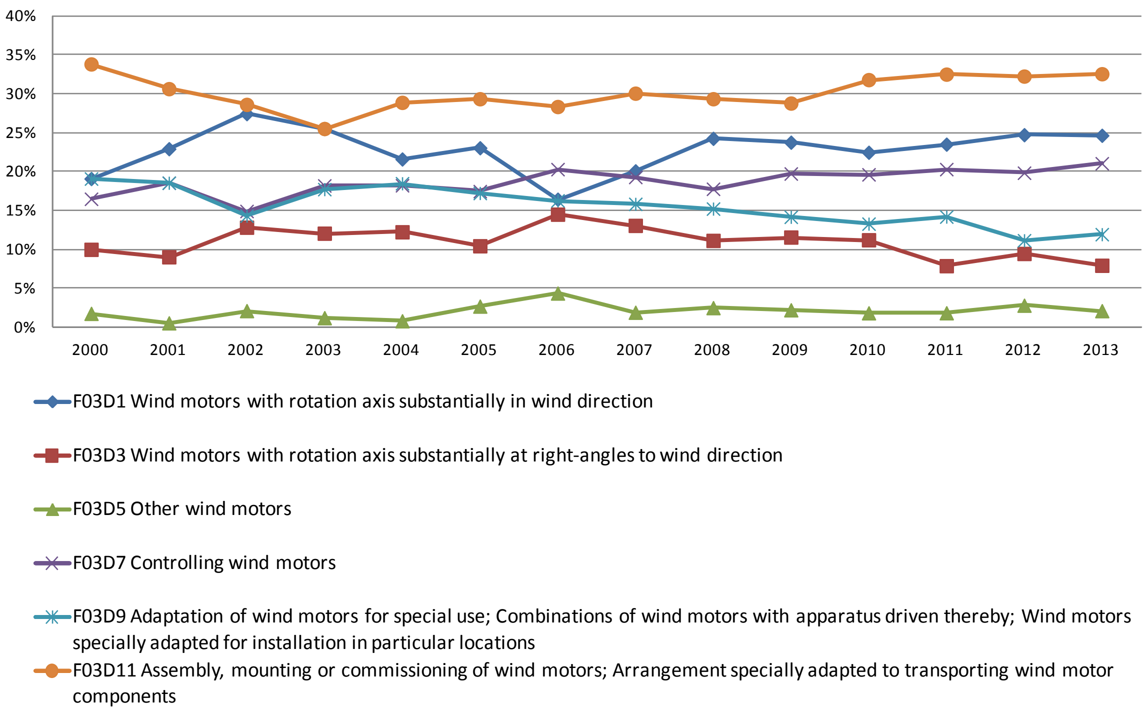
Political objectives for domestic research and development were spelled out in the Twelfth National Energy Technology Five Year Plan issued in 2011. Specifically for wind power the target was set to obtain critical production technologies for 6-10 MW wind turbines. In addition, import duties and value added taxes on key technological wind power equipment and materials were removed for qualified companies in 2012 (Liu, Goldstein 2013). In this context, the technology roadmap published by the NDRC's Energy Research Institute (IEA/ERI 2011) is also an important document.

As soon as domestic firms had demonstrated their capability to satisfy the demands of the fast growing Chinese market, the government's attention shifted away from joint ventures to support measures that directly targeted domestic industry, such as import tariff reduction and VAT rebates for imported wind turbine components. These subsidies could only be claimed by firms that could demonstrate R&D activity and capability for technological learning. Furthermore, in 2008, a subsidy was introduced that benefited smaller domestic companies in the wind energy sector (Liu, Goldstein 2013).

With regard to innovation capabilities in the area of applied research, Zhou et al. (2016) arrive at the conclusion that the leading Chinese wind turbine manufacturers are still lagging behind their European competitors in terms of innovation capacity. As the study of Zhou et al. (2016) focuses on the leading European and Asian wind turbine companies, among them Goldwind and Mingyang from China, rather than countries, we more closely examined transnational and domestic patent applications of Chinese applicants in the field of wind energy. The objective of this analysis is to identify key actors in the field of applied research and to explore whether there are specific patterns in the direction of search for new technological solutions which are distinct from those in the technological frontrunner countries. Lee (2013), for example, has argued that economic catch-up countries cannot simply emulate the technological path of frontrunner countries if they want to be successful. Furthermore, there is some evidence in the literature suggesting that Asian wind turbine firms are specialized in developing customized turbines that are high altitude compatible, sand proof, etc. (Dai et al. 2014) and on smaller turbines for off-grid use (Liu, Goldstein 2013).

In order to analyze whether Chinese inventors focus their innovation activity on a particular technology subclass, we conducted a disaggregated analysis of world-wide transnational patent applications in the FO3D class, the Cooperative Patent Classification (IPC) for wind motors. Figure 1 displays the annual share of each subclass in total F03D applications.

Figure 1: Shares of IPC-Subclasses in Global FO3D patent applications between 2000 and 2013 in Percent.

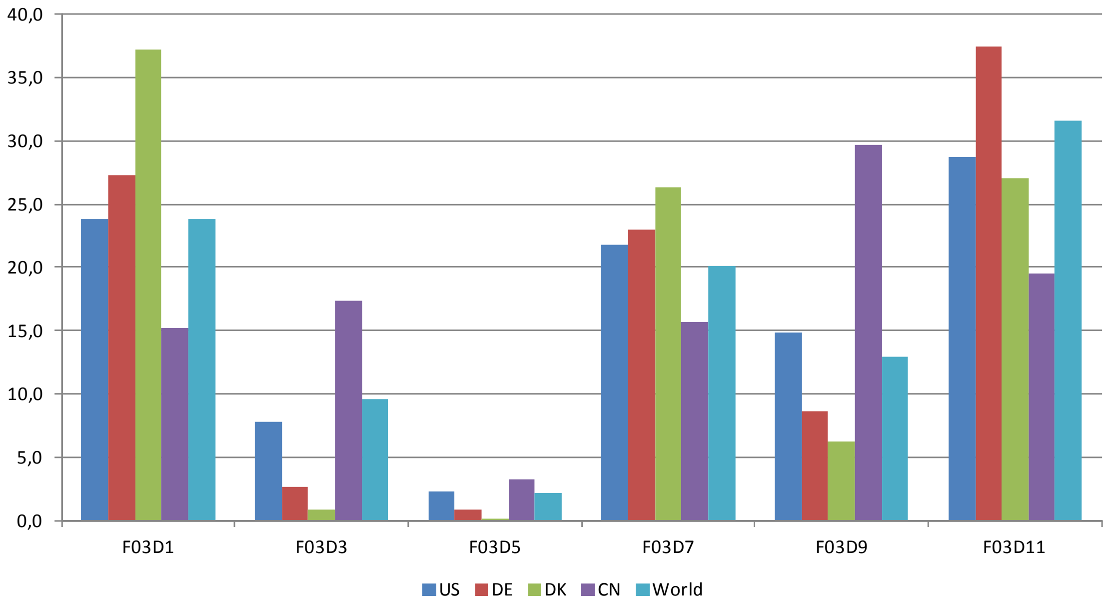


Source: PATSTAT, author's calculations

Without going into the technological details, what can be concluded from this analysis is that the internationally most important subclasses are F03D11, F03D1 and F03D7, whereas the other subclasses are either of minor relevance (F03D5) or decreasing importance (F03D3 and F03D9).

In a next step, the share of Chinese patent applications in each subclass was compared to the share of the technologically leading countries, i.e. Denmark, USA and Germany (Figure 2).

Figure 2: Average Share of Country's F03D Patent Applications for each subclass in the period from 2009 to 2013, in % of Total F03D Patent Applications



Source: PATSTAT, author's calculations

One interesting finding is that Chinese patent applications seem to be concentrated on different technology subclasses than those of the leading countries. China is particularly strong in the FO3D9 category which at first glance seems to support the observation of Dai et al. (2014) that Asian wind turbine firms are specialized on adaptations to specific regional conditions. Another technology subclass in which China is leading is F03D3, which encompasses inventions for wind motors that rotate at a right angle to the wind direction. However, as evident from Figure 1, based on the number of worldwide patent applications, this subclass seems to be of minor and decreasing importance. With regard to the most important technology subclasses (F03D1, F03D7, and F03D11) China is clearly lagging behind the world leaders.

4.3 Entrepreneurial experimentation

As the wind energy market in China has already grown out of its formative phase, the current degree of entrepreneurial experimentation is evaluated on the basis of changes in market shares of leading turbine manufacturers during the period 2012 to 2016. As evident from Table 6, the group of market leaders (Goldwind, Mingyang, Guodian) has remained relatively stable. A notable exception is Sinovel which ranked number three in 2012, but saw its market shares quickly eroding afterwards. Likewise, the Western turbine manufactures Gamesa and Vestas were still among the Top 10 in 2012, but were crowded out by their Chinese competitors afterwards. In contrast, Envision is now ranked second after Goldwind, although the company is a relatively new entrant that started its wind turbine business in 2009 only.

Table 6: Annual Ranking of Leading Wind Turbine Manufacturers in China based on installed capacity

Company	2012	2013	2014	2015	2016
Goldwind	1	1	1	1	1
Envision	7	4	4	3	2
Mingyang Wind Power	4	3	3	4	3
Guodian United Power	2	2	2	2	4
CSIC	-	8	8	5	5
Shanghai Electric	6	6	6	6	6
XEMC	5	5	5	7	7
Dongfang Electric	9	9	7	8	8
Windey	-	10	9	9	9
Huachuang	-	-	-	-	10
Sany	-	-	-	10	-
Sinovel	3	7	10	-	-
Gamesa	8	-	-	-	-
Vestas	10	-	-	-	-

Source: GWEC Global Wind Reports 2013 - 2017

Similarly, CSIC (China Shipbuilding Industry Corporation) was not among the group of leading turbine manufacturers in 2012, but is already ranked number five in 2016. The mid-level group encompasses Shanghai Electric, XEMC (Xiangtan Electric Manufacturing Group Co.) and Dongfang Electric. Together with CSIC this group of companies can be characterized as large multidivisional industrial conglomerates that presumably entered the growing market for wind turbines based on their competencies in the field of machine building and electrical equipment manufacturing. The market shares of this group have remained relatively stable during the observed period. Another group of smaller players encompasses Windey, Huachuang, and Sany.

By and large, the wind turbine market in China is characterized by rapid changes in the structure of supply that influence the evolution of the TIS. The incumbent Western companies Gamesa and Vestas as well as Sinovel have dramatically lost market shares. New market entries have mainly taken place during 2006 and 2009 and were undertaken by large multidivisional industrial conglomerates as well as by companies which specialized on wind energy, such as Envision.

4.4 Market formation

Market formation for wind energy in China is mainly driven by the political ambition to increase the share of renewable energies in total energy consumption. This ambition is underpinned by market creating policies which have induced a rapid expansion of wind energy in terms of installed capacity. In 2015, China had a share of 48.5 % of the world’s newly added capacity and a share of 33.6 % in the world’s total installed capacity (GWEC 2016). The rapid development of this market is evident from Table 7.

Table 7: Cumulative Installed Wind Energy Capacity in China.

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
MW	404	470	568	765	1,250	2,599	5,910	12,020	25,805	44,733	62,364	75,324	91,413	114,609	145,362

Source: GWEC (2016)

These figures seem to indicate that the market for wind energy in China has already reached a certain degree of maturity, albeit being far from saturated. Based on these figures, the wind energy market in China appears to have outgrown the state of a nursing or bridging market. Nevertheless, the share of electricity demand covered by wind energy in China is still only about 3.3 % which is well behind the EU’s average share of 11.4 % (GWEC 2016). Thus, it seems to be necessary to assess the market for wind energy generation capacity, i. e. the market for wind power equipment, and the market for wind electricity separately.

Whereas China’s market for wind energy equipment has reached maturity; the corresponding electricity market has been criticized based on high curtailments rates, governance deficits and a low degree of efficiency (CREIA/CWEA/GWEC 2015; Lam et al. 2017). In fact, in 2014 China’s installed wind energy capacity was 75 % larger than that of the USA, but electricity generation was 14 % less (Lam et al. 2017). Thus, the market for electricity generated from wind has still to overcome a great deal of institutional, financial and technological challenges before it can reach maturity. The most pressing technological challenge today is to facilitate the integration of wind energy into China’s grid which depends crucially on technological progress in electricity storage technology, long distance electricity transmission, and smart grid technology. As a consequence, innovation in these complementary technologies is highly influential for the future of wind energy in China.

4.5 Legitimation

Since the early stages of development, wind energy has enjoyed political support in China. Following hydroelectric power, wind power is now the second most important renewable energy technology in China. According to Liu and Goldstein (2013), the initial objective of the Chinese government was to create a competitive domestic wind energy industry that would be able to contribute to export-oriented growth. As the issue of climate change became more and more urgent on the international agenda, the Chinese government formulated ambitious targets for the development of wind energy and other types of renewable energy. According to the GWEC (2016), the air pollution in Beijing and other large Chinese cities has become another, even more pressing social issue in China that threatens the legitimacy of the TIS for fossil energy which is still prevailing. Many earlier proponents of the fossil energy regime in the government seem now ready to accept the concept of an energy transmission, including a higher share of renewable energies (GWEC 2016).

4.6 Resource mobilization

In 2015, Chinese investment in renewable energy technologies has grown by 17 % from 2014. In total, China invested 102.9 billion US$ which was equivalent to 36 % of the world's total investment. On a global level, solar energy was able to attract 161 billion US$ and wind energy 110 billion US$ in the same year. Of the investment in China, 47.6 billion US$ were spent on wind energy, 44.3 billion US$ on solar energy, and 2.7 billion US$ on small hydropower (FS-UNEP Collaborating Centre 2016). Thus, wind energy attracted a higher proportion of total renewable energy investment in China then at the global level.

These figures include spending on R&D, which in 2015 has risen by 4 % and reached 2.8 billion $ for all renewable energy technologies in China. For the first time, this amount was almost equivalent to the EU's spending on renewable energy R&D. At the global level and for all renewable energy technologies, R&D spending amounted to 9.1 billion, thereof 50 % on government R&D and 50 % on corporate R&D. The ratio of R&D investment (government and corporate) to total investment in the world was 0.032; whereas in China it was 0.027. For wind energy specifically, 1.2 billion US$ were spent on corporate R&D and 0.6 billion US$ on government R&D at the global level. For all renewable energy technologies, the split between corporate and government R&D in China was 1.0 to 1.8 billion US$; whereas in the EU it was 1.7 to 1.2 billion US$. Government R&D in China increased by 7 %, whereas corporate R&D remained stable (FS-UNEP Collaborating Centre 2016). Compared to the global situation, investment in China is strongly bent towards public R&D.

These figures suggest that the wind energy TIS in China is profiting from China's overall investment in renewable energy technologies. The bulk of the investment (97.3 %) is spent on projects for electricity generation. However, driven by the rise of government R&D, spending on R&D is growing rapidly as well and China has almost reached the same level of R&D investment as the EU. Compared to the situation EU the private sector in China is more reluctant to invest in R&D.

4.7 Development of positive externalities

Due to the systemic nature of innovation processes, the generation of positive externalities is fundamental to the formation and growth of the TIS (Bergek et al. 2008). One important driver for the generation of positive externalities is the entry of new firms to the TIS because newcomers can provide additional resources for the solution of technological problems and enhance the overall legitimacy of the TIS. In this regard, the market entry of Mingyang (2007), Guodian United Power (2007), and Envision (2009) and in particular that of large, influential industrial conglomerates, such as CSIS, Shanghai Electric, XEMC, and Dongfang Electric in the year 2009, were landmark events that facilitated the rapid development of the Chinese wind energy TIS throughout the following years.

5 Conclusions

The high level of political support for wind energy in China has been crucial to mobilize the necessary financial resources and to attract market entries. As evident from the analysis of the structural components of the wind energy TIS in China, the evolution of the TIS is characterized by the interplay of turbine manufacturers, suppliers, universities, wind park developers, the State Grid Corporation, banks, public R&D facilities, various administrative bodies, and other types of actors. As most of these actors are controlled or at least strongly influenced by the Chinese government, insecurity about the future development of the market was greatly reduced, which facilitated the rapid mobilization of financial resources and enabled the funding of new wind parks, production facilities and R&D projects.

Hence, the rapid diffusion of wind power equipment which presupposes the development of domestic production capabilities can be considered as a particular strength of China's TIS. Further strengths are the successful adoption of existing technology, the creation of markets and legitimacy as well as the ability to mobilize financial resources. Furthermore, Chinese universities and research institutes have quickly expanded their capabilities in the area of basic research. With regard to applied research, the results are mixed. Although the growth in the number of transnational and domestic wind energy patents indicates that China is now among the most inventive countries in the world, a more detailed analysis suggests that inventions in China are less focused on the most relevant technology subfields and that the leading domestic producers of wind power equipment are still reluctant to take a very active and coordinating role in the TIS. Hence, the recent growth in inventions might actually not contribute to closing the still persisting technological gap to competitors in Europe and the US.

The most evident drawbacks of the centralized planning approach in China are governance deficits relating to the integration of wind energy into China's electricity grid as well as the lack of complementary infrastructure for energy transmission and storage. These deficits result in high curtailment rates and a low efficiency of wind energy compared to other countries. Furthermore, the high curtailment rates reduce incentives for turbine manufacturers to engage in more quality oriented innovation. As the share of wind energy in total energy consumption will continue to grow throughout the next years, the solution of these problems will require even closer attention than in the past. Otherwise, the financial strain put on the government might cause setbacks for wind energy in China.

The functional TIS analysis demonstrates yet another interesting theoretical issue – that is to what extent the centralized planning approach affects the different functions of innovation. The analysis suggests that, once the Chinese government had committed to ambitious objectives for the development of wind energy, the TIS was quickly able to provide the following functions: 'entrepreneurial experimentation', 'market formation', 'legitimation', 'resource mobilization', and 'development of positive externalities'. In contrast, TIS performance with regard to 'knowledge development' and 'influence on the direction of search' is less satisfactory, which might be explained by a lack of incentives for companies to engage in the search for new technological solutions and the government's interference in these matters. These deficits point to the 'Archilles heel' of the centralized planning approach and fundamental problems which cannot be overcome without continued efforts to reform China's economy.

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