The drivers for China’s wind energy technology innovation system

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Abstract

China has witnessed a massive growth in wind technology deployment within a decade (from 1GW to 145 GW). In order to understand the drivering forces, this paper incorportes quantitative indicators to the system functions to unfold the historical changes of China’s wind energy innovation system. The findings are three folds: a) the system functions approach originating in developed countries can be employed to well examine the dynamics of technological innovation in developing countries; b) the functional patterns between developed and developing countries can be quite different – the establishment of legitimacy, guidance of search and resources mobilisation have contributed most to China’s rise in wind power rather than knowledge development and knowledge exchange; c) the proposed indicators have demonstrated valuable for measuring the functioning of innovation systems. This paper makes a methodological contribution to quantitative analyses on technological innovation systems, and implies the need for a deeper understanding of the differences between developed and developing countries in the process of system-building.

Keywords: wind energy; innovation system; system functions; quantitative indicators; China

1 Introduction

China is a latecomer in wind energy, but it has caught up fast. The country’s first grid-connected wind farm was not constructed until 1986, with three wind turbines imported from Denmark (Shi 1997). Now China has become the world’s largest adopter of wind power, comprising 33% of global wind power capacity (BP 2016), far ahead of the USA (17%) and Germany (10%). Wind power has surpassed nuclear and become China’s third largest source of electricity generation after coal and hydro. Among the world’s ten biggest wind turbine manufacturers, half of them are Chinese enterprises (REN21 2016). The maximum sizes of Chinese wind turbines leaped from 600 kW in 1997 to 6 MW by 2010 (Shi 2007, CWEA 2015b). Pilot R&D projects on developing 7 MW + turbines have been launched by several Chinese enterprises (Gosens and Lu 2013).

The rapid development of Chinese wind power has attracted wide interest. The key question is what has driven China’s growth in wind technology innovation. Urban, Nordensvärd, and Zhou (2012) hold that China's wind energy sector relies largely on international technology transfer and cooperation in the first stage, and on local content requirements to reduce competition from foreign firms in the second stage. Currently, the reliance on both factors has decreased and some Chinese firms have become competitive with strong state leadership and financing (Urban, Nordensvärd, and Zhou

2012). Gallagher (2014) argue that low-cost capital is one of the most important factors that enables+ China to acquire, modify, develop, manufacture and export cleaner energy technology.

China does not develop wind energy in isolation but has learnt much from international peers in both technology and policy arenas (Dai et al. 2014). McDowall et al. (2013) argue that China's innovation system for wind energy involves a process of system-building that differentiates it from those of countries where wind technology originates. Lewis (2011) shows that China has acquired advanced wind technology by building access to technical know-how that originated in developed countries through international technology transfer and mergers and acquisition (M&A). Slepniov et al. (2015) demonstrate how the Chinese wind turbine manufacturer Envision Energy has upgraded innovation capability by tapping into the Danish innovation system.

GWEC and IRENA (2012) argue that China’s rapid development of wind power attributes to a strong long-term legislative background, a clear tariff structure, and a strong industrial base. In particular, the Renewable Energy Law (2005) stimulates renewable energy R&D and equipment manufacturing, and results in the creation of an exceptionally large number of wind power projects (GWEC and IRENA 2012). However, many Chinese wind turbines are not certified by international agencies. While the emergence of domestic certification agencies is improving this situation, lower quality and reliability, and lower levels of experience with wind turbines undermine Chinese exports to the European and North American markets (GWEC and IRENA 2012).

The above arguments have emphasised parts of the story. China’s growth in wind energy innovation has involved a number of factors, and thus needs a systemic perspective to understand the inducement or blocking mechanisms. Klagge, Liu, and Silva (2012), McDowall et al. (2013) and Gosens and Lu (2013) have attempted to analyse China’s wind energy sector with an innovation systems approach, but have suffered from the absence of quantitative evidence. This research aims to close these gaps by adopting the system functions approach (Hekkert et al. 2007a) combined with quantitative indicators to identify the drivers for China’s wind technology innovation. This helps uncover how effectively China’s wind energy innovation system functions and can stimulate further discussions on linking indicators to innovation systems.

The paper is structured as follows. Section 2 reviews the concepts of innovation systems and the associated indicators. Section 3 describes the methods and indicators to be used for this research. Section 4 quantitatively characterises the functions of China’s wind energy innovation system with 18 indicators. Section 5 draws the major findings, limitations, and outlook for future research.

2 Literature review

2.1 Innovation systems

The Innovation systems (IS) approach has develped into a large body of literature and evolved into several branches, with the widely-used frameworks being the national innovation system (NIS) (Freeman 1987, Lundvall 1992, Nelson 1993), regional innovation system (RIS) (Cooke 1992), sectoral innovation system (SIS) (Malerba 2002), and technological innovation system (TIS) (Hekkert et al.

2007a, Bergek et al. 2008). These concepts orginate in developed countries but have diffused fast to developing countries (see Watkins et al. (2015), Lundvall, Joseph, et al. (2009)).

The NIS is concerned with macro structure and institutions. The focus of RIS is to understand the phenomenon of innovation clusters. The SIS emphasises sectoral differences in innovation. The TIS is to study the processes that stimulate (or hamper) innovation activities occurring in a particular technological area. The multiple ISs may be regarded as variants of a single generic IS approach (Edquist 2005). When the analysis is focused on geographical dimension, a particular country or region determines the boundaries of the system. In other cases, the main interest lies with a sector or technology. The different variants of IS coexist and complement each other. Whether the most adequate framework in a certain context should be national, regional, sectoral or technological, depends on the questions to be addressed (Edquist 2005).

This research mainly focuses on innovation in a national and technological context, so NIS and TIS will suit better. A major flaw of NIS is that it is extremely difficult to map out the dynamics of the system due to the vast number of actors, networks and institutions involved. If the level of analysis is narrowed down to a specific sector or technology, the key actors and processes that influence the operation of the system can be captured. Also, the increasing internationalisation of corporate R&D and globalised distribution of innovation resources is eroding geographical borders (Gallagher 2014, Gosens, Lu, and Coenen 2015, McKelvey and Bagchi-Sen 2015). National boundaries may not be suitable for anaysing innovation systems. It is necessary to be more explicit about the relationships between globalisation and national systems (Lundvall 2007).

2.2 Technological innovation system

The concept of a technological innovation system (Hekkert et al. (2007b), Bergek et al. (2008)) stems from the term 'technological system' coined by Carlsson and Stankiewicz (1991). A technological system is defined as *"a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology*" (Carlsson and Stankiewicz 1991). An important contribution of TIS is the introduction of system functions - knowledge development, knowledge networks, guidance of search, entrepreneurial activities, market formation, resources mobilisation, and creation of legitimacy (Hekkert et al. 2007a, Bergek et al. 2008).

The system functions approach has been a useful tool for diagnosing systemic problems in technological innovation. Recently, scholars have provoked hot debates on the contextal structures and interaction dynamics of TIS (see (Bergek et al. 2015)). Markard, Hekkert, and Jacobsson (2015) suggest that the identification and incorporation of new functions may mean a step forward in the development of TIS. In the field of wind technology, the historical lessons from the Netherlands (Kamp, Smits, and Andriesse 2004) and the USA (Norberg-Bohm 2000) show that the inconsistency between supply-push and demand-pull policies led to early failures. The alignment between supply-push and demand-pull policies has also been emphasised in Gallagher, Holdren, and Sagar (2006), Grubler et al. (2012), and Grubler and Wilson (2014), and may be worth examination to explore the 'new' function of TIS.

Another issue relates to the globalisation of innovation. The increasing transnational connections between firms and countries require a global perspective that goes beyond national borders. China, India and South Korea have all benefited from international technology transfer in wind energy (Lewis 2011). An investigation on how they have acquired the technology across borders requires a wider (global) perspective to study innovation systems (Lewis 2011). McKelvey and Bagchi-Sen (2015) show that countries can improve technological capability by tapping into foreign innovation systems. The interplay between domestic and foreign innovation systems may provide interesting insights about how the innovation systems are shaped by the emergence, decline or absence of international linkages.

2.3 Indicators for measuring technological innovation system

The dynamics of TIS can hardly be well understood without quantitative indicators. There are many studies on innovation metrics, but not many on linking quantitative indicators to energy innovation systems. Studies differ from each other in terms of measurement frameworks, indicator selections, interpreting methods and data sources (Hu, Skea, and Hannon forthcoming). Kettner et al. (2014) borrow the indicator framework from the Innovation Union Scoreboard (Hollanders and Es-Sadki 2013) and adapte 10 indicators. The indicators are process-oreinted (enablers→inputs→ouputs), but fail to reflect the dynamics of innovation systems.

Klitkou, Scordato, and Iversen (2010) evaluate the innovation performance of low-carbon energy technologies through 12 indicators, such as R&D intensity, publications, patents, energy technology exports and a few less relevant indicators like industrial specialisation, energy mix and resource endowment. Gosens and Lu (2013) suggest a list of indictors to measure the functions of technological innovation sytems but have not tested their efficacy with empirical analyses. Based on TIS functions approach, Borup et al. (2013) propose a wider range of indicators to analyse the Danish energy innovation system. However, some indicators could not be operationalised due to data constraints, and some functions are not covered by output indicators.

Indicators can be developed theoretically, but can be hard to apply in reality due to the issue of data availability (Borup et al. 2013, Grubler et al. 2012, Klitkou, Scordato, and Iversen 2010). In this case, it is necessary to study available indicators and statistics as the first step, and from there work to identify which can be utilized to measure the core aspects of innovation (OECD 2013, Sagar and Holdren 2002). For example, it is difficult to figure out how many product and process innovations have been generated in China's wind turbine industry, but it is possible to analyse the scaling-up of unit capacities of Chinese wind turbines. Developing indirect indicators is a progmatic approach for enriching metrics for energy innovation systems (Hu, Skea, and Hannon forthcoming).

3 Methodology

This research adopts system functions approach (Hekkert et al. 2007b), along with one extra dimension – alignment between supply-push and demand-pull policies, to analyse China's wind energy innovation system. The transnational dimension is to be illustrated by the variety of technology development strategies adopted by Chinese multinational enterprises (MNEs). The interplay between domestic and foreign innovation systems is a complicated issue and will not be discussed here.

To characterise the functions of TIS quantitatively, about 18 indicators are proposed to conduct empirical analyses (see table 1). Unlike prior studies that considered either the European Patent Office (EPO) or the US Patent and Trademark Office (USPTO), this research includes statistics from the EPO, USPTO and China's State Intellectual Property Office (SIPO) to produce a more complete picture. The searching queries for bibliometric and patent analyses are summarised in annex 1.

Descriptive statistics with time-series data are used to elaborate the functioning of China's wind energy innovation system over time. Based on quantitative descriptions of individual indicators for each function, a rating scale (1-3) method is employed to assess the overall performance of the functioning of the innovation system (see annex 3). All data is collected from (internationally) recognised sources, such as the Web of Science, PATSTAT, PIAS, government official documents, company websites, Bloomberg database, IEA/IRENA database and Chinese Wind Energy Association. Some arguments are also supported by interviews that the authors carried out in fieldwork.

Table 1 Indicators for measuring the functions of technological innovation system

Functions	Indicators
Knowledge development	• Number of (the world's top 10%) scientific publications • Number of patent applications to SIPO, EPO and USPTO
Knowledge networks	• Shares of scientific research funded by public and private sectors • Linkages between wind turbine producers and wind farm developers
Guidance of the search	• Policy targets on cumulative capacity • Policy targets on turbine sizes • Policy targets on localisation rate
Entrepreneurial activities	• Number of new entrants • Technology development strategies • Evolution of turbine sizes • Establishment of R&D facilities
Market formation	• Domestic deployment of wind power • Foreign exports on wind turbines
Resources mobilisation	• R&D expenditure on wind technology • Asset finance for wind power plant projects • Subsidy for wind power integration
Creation of legitimacy	• Issuance of laws and regulations
Alignment between supply-push and demand-pull policies	• Presence of supply-push policy • Presence of demand-pull policy

Source: adapted from Hekkert et al. (2007b) and Gosens and Lu (2013)

4 Empirical analyses on China's wind energy innovation system

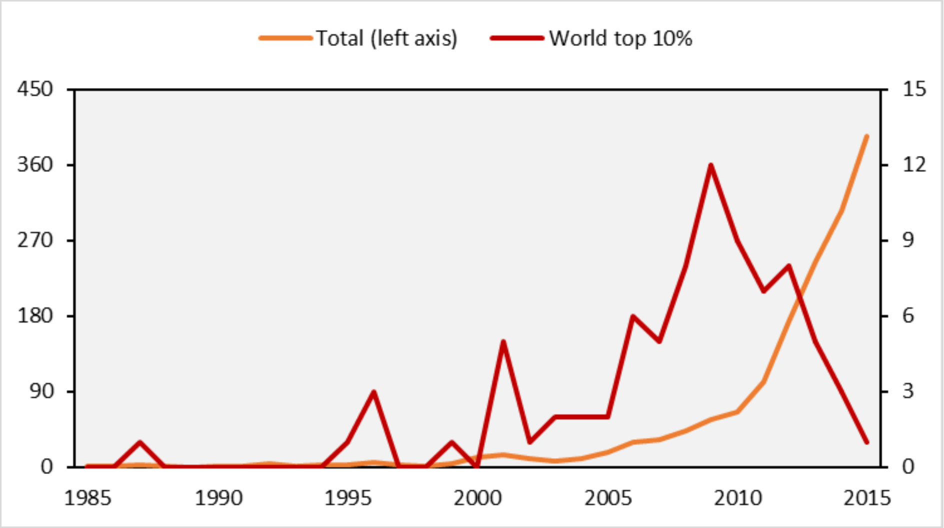
This section applies the proposed indicators to evaluating the functioning of China's wind energy innovation system. It is structured according to the system functions as outlined in table 1, consisting of eight subsections.

4.1 Knowledge development

China has performed excellently in knowledge building measured by the total number of scientific publications. Before 2005, Chinese scientists had rarely published in wind energy. There was only 1 publication in 1985, but this increased to 18 by 2005 and rocketed to over 390 by 2015. However, China performs less well in terms of the world's highly-cited (top 10%) publications. Between 2005 and 2009, about 10%-20% of Chinese publications in wind energy can be labelled as high quality. This may imply that there exists an inflation of Chinese publications. Publication records in China are related to an academic's promotion, award and tenure. Doctorate students are also required to publish in recognised journals before they can graduate.

To advance wind technology, the Ministry of Science and Technology (MOST) and National Energy Administration (NEA) have approved about 17 state labs or national engineering centres engaged in wind energy (annex 2). According to the data, state labs or national major S&T programmes (e.g. 863, 973) have produced 15% of the country's wind publications with the remaining 85% contributed by others. This raises a question as how effectively the Chinese state labs or major S&T programmes have performed in discovering, codifying and promoting wind technology. They may be more focused on technical inventions than publishing papers, but this needs to be verified by in-depth patent analyses.

Figure 1 Chinese scientific publications in wind energy, counts

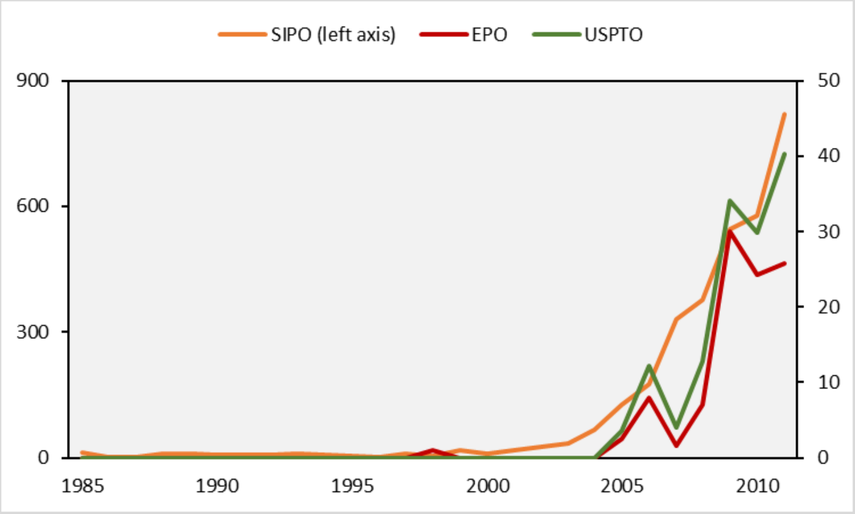


Source: calculated from SCIE, ISI Web of Science

China's rapid growth of scientific publications in wind technology has been accompanied by the increase of patents (see figure 2). In 2004, only 68 patent applications by Chinese inventors to the SIPO were recognised relating to wind motors, but this increased to 128 one year after and up to 820 by 2011. It may be assumed that Chinese patents have lower quality as it is easier to obtain a patent grant in China. But, in 2009, China amended its patent law to require absolute global novelty instead of 'relative novelty' (SIPO 2009). This means that the quality gap between Chinese and foreign (e.g. EPO, USPTO) authorised patents is closing.

Chinese patent applications to the EPO and USPTO have been rising sharply since 2005. When compared to domestic patent applications, the ratio of foreign ones is still low, accounting for about 0.5% to 7%. The size of the Chinese wind power market is equivalent to the entire European market. It is understandable that Chinese manufacturers may firstly exploit domestic markets before venturing abroad to compete with leading firms. But, the obvious deficit in intellectual assets will inevitably constrain Chinese enterprises' exploration in mature markets where IPRs have become a strategic asset for firms to compete. Chinese manufacturers need to intensify patenting activities in foreign markets if they decide not to rely too heavily on the domestic market.

Figure 2 Chinese wind patent applications to the SIPO, EPO and USPTO, counts



Source: calculated from the PIAS and PATSTAT

4.2 Knowledge networks

Interactions between public and private organisations in China's wind energy sector are not frequent. About 4%-5% of China's scientific research in wind energy is funded by industry (see table 2). This is consistent with the conclusion of Klagge, Liu, and Campos Silva (2012) that there exists few collaborations between industry and university. Firms involved in wind technology have been reluctant to fund public institutes to conduct scientific research. State Grid has played a larger role than other private enterprises in funding scientific research, but underperformed in terms of high-quality research. This may answer why state-owned enterprises (SOEs) have relied heavily on foreign technology and have been more willing to establish links with foreign partners than domestic universities and research institutes (Klagge, Liu, and Campos Silva 2012).

It may be true that university academics are more interested in publishing papers than establishing links between their research findings and industrial use (Klagge, Liu, and Campos Silva 2012). firms outside wind power industry (e.g. Delta Environmental & Educational Foundation) have played almost as an equal role as the incumbents (see table 2). This may be because Chinese universities have traditionally been weak in wind technology, so they are not ‘trusted’ by private firms. A CEO of a top Chinese wind turbine manufacturer responded that “*patents produced by [Chinese] universities are of low value, […] they can undertake parts of the technology research but cannot complete the entire technology for which the firms are the focal points*”.

Table 2 Chinese publications funded by public and private organisations (1970-2015), %

Categories	Funding sources	Total	World top 10%
Public vs. private	public sector	96.0	94.9
	Private sector	1.5	4.4
	State Grid^	2.5	0.6
Public	National High Technology Research and Development Programme ("863" project)	7.6	7.4
	National Basic Research Programme ("973" project)	3.8	4.0
	National Science and Technology Support Programme (NSTSP)	0.7	1.3
	National Major Science and Technology Projects (NMSTP)	0.2	0.0
	state labs	2.6	2.0
	others*	85.0	85.2
Private	within industry	19.1	12.5
	outside industry	18.1	75.0
	State Grid	62.8	12.5

Note: ^State Grid is included in the private sector; others refer to the funds excluding those channels.

Source: calculated from SCIE, ISI Web of Science

The state labs and national engineering centres are missioned to experiment advanced wind technologies, but the facilities are based at private firms and not available for other firms within the industry to use. “*We lack a strong public research laboratory like Risø …The state labs are assumed to be public and play a neutral role, but it seems that they have become the firms’ private assets*”, a senior expert responded in an interview. The established state labs are so dispersed and cannot be effectively organised to develop nor test cutting-edge wind technology.

The formalised connections between wind farm developers and wind turbine producers lessen the pressure to innovate. Four of China’s top ten wind farm developers have wholly or sizeably owned some of wind turbine producers’ stocks (see table 3). Three manufacturers have formed ‘strategic alliances’ with wind farm developers, with only three turbine suppliers having secured contracts through bidding. The formalised connection will reduce competition on high-quality and high-power-output turbines, and undermines the motivation to innovate (Gosens and Lu 2014).

Table 3 China’s top ten wind farm developers and their relationships with turbine producers, 2014

Wind farm developer	Market share of developer (%)	Turbine supplier	Developer-producer relationship	Share from the producer (%)
Huadian	14.6	Goldwind	strategic alliance	15.9 (1st)
Guodian	13.1	United Power	Subsidiary*	60.0 (1st)
CGN	11.0	Goldwind	strategic alliance	27.6 (2nd)
Huaneng	10.6	Mingyang	joint venture^	20.6 (1st)
SPIC	8.7	XEMC	bidding & contract	22.5 (1st)
China Resources	4.7	XEMC	bidding & contract	54.2 (1st)
Datang	3.6	CWE	70% of share#	21.7 (1st)
PowerChina	2.2	Windey	bidding & contract	38.4 (1st)
Three Gorges	2.1	Windey	strategic alliance	20.6 (2nd)
State Grid	1.8	Xuji	subsidiary	11.8 (4th)

Note: * the producer is a subsidiary of the developer; ^ the developer and producer create a joint venture; # percentage of the producer's stock owned by the developer; the number in bracket represents the producer's ranking (by capacity supplied) among the developer's all wind turbine suppliers.
Source: calculated from CWEA (2015a)

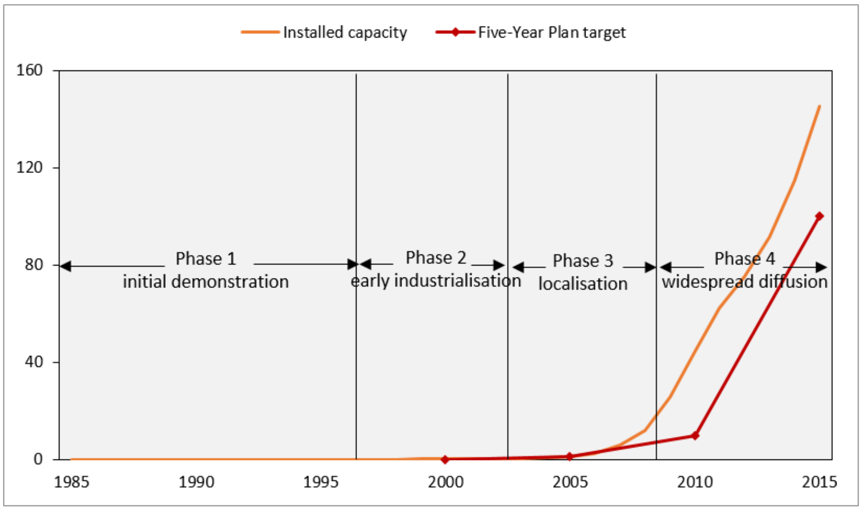
4.3 Guidance of search

China's energy policy has long been oriented towards fossil fuels. The central government began to consider diversifying energy sources in 1996. The 9th Five-Year Plan for New and Renewable Energy Development (1996-2000) sets a target of developing 200 MW of wind power by the end of the 20th century. The 10th Five-Year Plan for New and Renewable Energy Development (2001-2005) aims to reach 1.2 GW wind power. The five-year plan targets have greatly motivated stakeholders to invest in wind technology. The policy targets set over the 11th and 12th five-year plan periods were far surpassed by the actual installed capacities (see figure 3).

It is too costly to rely on imports as China's demand for wind power is huge. A 2 MW wind turbine costs approximately €0.9 million/MW to €1.2 million/MW (incl. gird connection) (EWEA 2009). A localisation requirement (40%-80%) has been imposed by the government to stimulate the firms to master manufacturing capability of wind turbines (see figure 4). This policy has been remarkably successful in internalising foreign wind technologies. China had heavily depended on foreign suppliers or joint ventures. Less than 40% of annual additions were supplied by Chinese manufacturers. This situation began to change since 2007, and now 99.5% of China's newly installed capacity is contributed by Chinese firms.

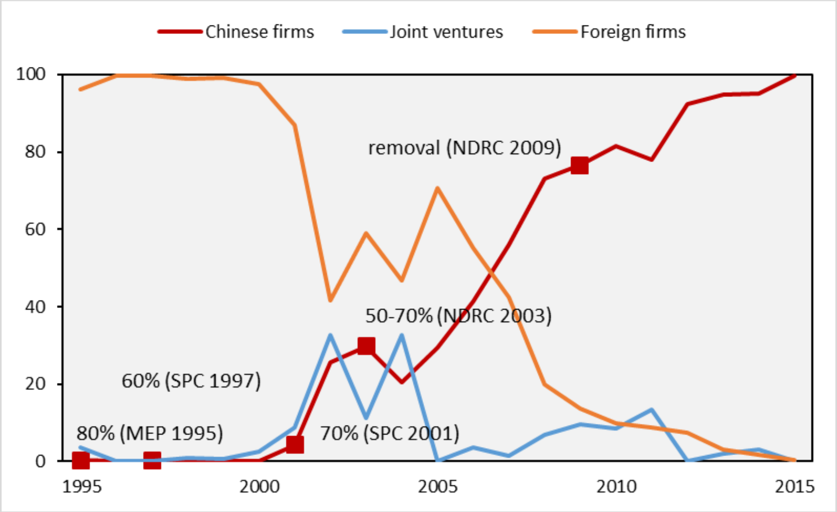
The government has also proposed specific targets on the desired unit capacity of wind turbines to be produced by Chinese enterprises. The 8th Five-Year Plan for Science and Technology (1991-1995) set a target of developing 150 kW – 300 kW turbines, and the 12th Five-Year Plan for Wind Power Science and Technology (2011-2015) aims to develop 7 MW+ wind turbines. Currently, several Chinese manufacturers are able to produce 5-6 MW wind turbines (see diagram 1). This policy has greatly encouraged firms' exploration for advanced wind technology. Without the guidance of search, China's knowledge building in wind energy may not have happened so fast.

Figure 3 Five-Year Plan target and cumulative installed capacity of wind power, GW



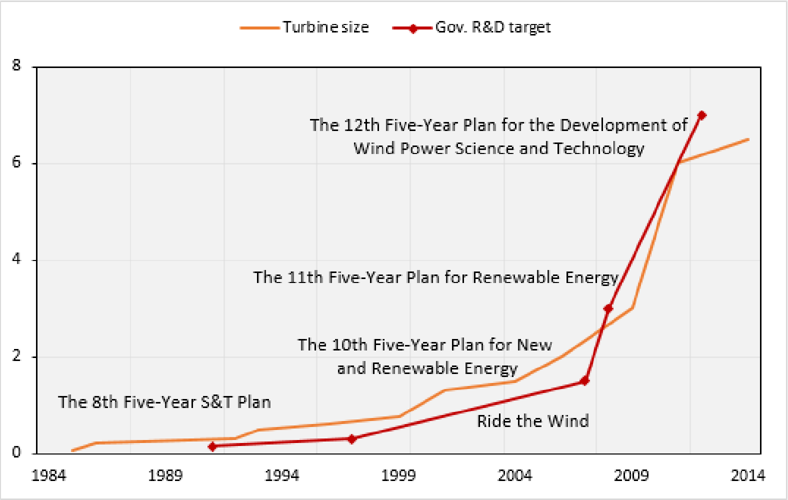
Source: elaborated from Shi (2007), CWEA (2015b), CWEA (2016) and the authors' own database

Figure 4 Localisation policy and market share of newly installed capacity by Chinese firms, %



Source: calculated from Shi (2007), CWEA (2015b) and the author's own database

Figure 5 Gov. R&D target and maximum unit capacity of installed wind turbines, MW



Source: elaborated from IEA/IRENA (2016) and the authors' own database

4.4 Entrepreneurial activities

There were few Chinese firms engaged in wind turbine technology before the early 2000s. As of 2015, about 32 turbine manufacturers, 21 gearbox providers, 18 blade makers, 17 control system developers, and 6 testing and certification organisations are active in the Chinese market (Chinawindnews 2016). The emergence of new entrants and phase-out of prior incumbents has made the industry rather dynamic. But, fierce competition has forced the manufacturers to compete on cost. Low cost often results in lower quality, which can be destructive to the industry when the technology is not mature enough as a whole.

To enhance technological capability, Chinese manufacturers have adopted a variety of technology development strategies, including technology licensing, joint R&D, mergers and acquisitions (M&A), and establishing R&D centres in knowledge clusters. Before 2005, China had no choice but had to license technology from foreign companies (Zhou et al. 2012). having developed the ability to produce wind turbines through production licensing, they began to build design capability through joint R&D. Compared to independent R&D, technology collaboration with foreign companies allows them to acquire technology quicker and probably less risker.

Windey was able to produce 250 kW turbines in the late 1990s with their own IPR, but the firm licensed 750 kW technology from REpower to acquire more sophisticated know-how. The company then conducted joint R&D on 800 kW turbines before they became able to design 1.5 MW turbines. After they mastered the 1.5 MW technology, they carried out joint R&D on 2.5 MW technology. Now Windey can design 5 MW turbines with advanced techniques (see diagram 1). Chinese firms have trained technicians, improved technological capability and have created more patents via joint R&D (Zhou et al. 2012). The technological entrepreneurship of Chinese wind turbine manufacturers can be featured by the process of "introduction → absorption → digestion → re-innovation"- a type of China's indigenous innovation strategies (see State Council (2006)).

Diagram 1 Technology development pathways of the top ten Chinese wind turbine manufacturers

Source: elaborated from company websites, Gosens and Lu (2013), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012) and Zhang et al. (2009)

Note: a) overseas R&D units are coloured in red; b) only maximum turbine sizes for each year are displayed.

Chinese manufacturers have embarked on international development by M&A or establishing overseas R&D centres. In 2008, Goldwind purchased 70% of Vensys' shares to develop 3 MW turbines. In 2009, XEMC purchased Darwind for €10 million to acquire 3-5 MW technologies (Yan 2009). Mingyang established a R&D centre in Demark to cooperate with Risø-DTU (Mingyang 2010) and launched an offshore R&D centre in North Carolina University in the USA (Quilter 2012). Envision Energy acquired its first research subsidiary in Denmark in 2010, which allows the company to access skilled R&D personnel and excellent test facilities (Slepniov et al. 2015). Chinese MNEs' entrepreneurial activities are driven by the huge market demand created by the political agenda and subsequently by the pursue of advanced technologies originating from developed countries.

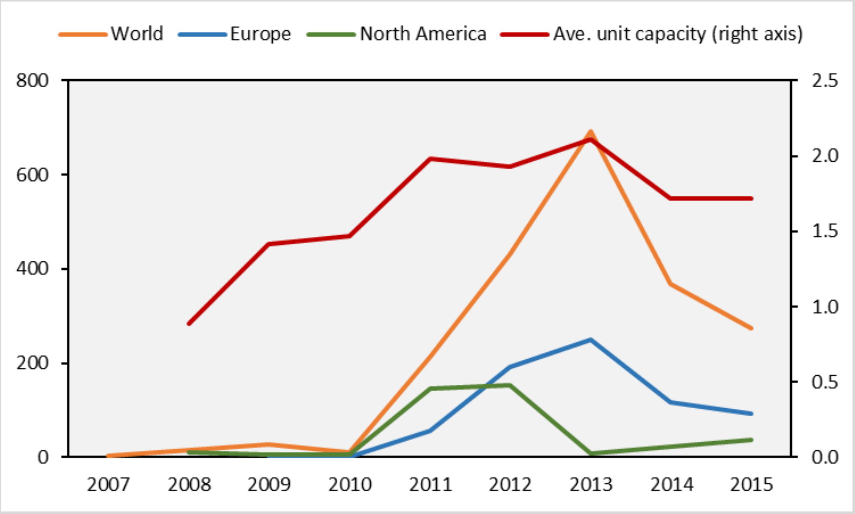
At present, the majority (80%) of Chinese top 10 wind turbine manufacturers can produce 5 MW+ turbines through indigenous or overseas R&D units. Despite these, China lacks the core technologies in intellegent manufacturing, quality control, and relies on foreign technologies for blade design, bearing systems, inverter and control systems (MOST 2012). The removal of the localisation requirement may imply that Chinese manufacturers have become able to produce the majority of wind plant components; otherwise, it is too costly to rely on imports given China's huge demand for wind turbines. Some components, especially high-quality steel bearings and control systems, still need to be imported, albeit high values (Gosens and Lu 2013).

4.5 Market formation

China has created a large market for wind power (145 GW). It has been estimated that about 2600 GW onshore (70m height) and 500 GW offshore (water depth 5-25m, 100m height) is technically exploitable (IEA/ERI 2011). It is forcast that wind power alone could meet the country's entire projected increase in electricity demand up to 2030 (Liu et al. 2013). The draft of the 13th Five-Year Plan for Wind Power (2016-2020) sets a target of developing a cumulative capacity of 200 GW by 2020. This requires an annual addition of 10 GW, half that of previous years as the government grows more concerned about grid connection. China has greater capacity than the USA (75 GW), but has generated slightly less power due to curtailment of wind power, differences in turbine quality and delayed connection to the grid (Lu et al. 2016).

Different from solar PV (Liu and Goldstein 2013), Chinese wind turbines have been primarily manufactured for domestic installations. Chinese firms embarked upon exporting wind turbines in 2007, but the capacity supplied has been only 2 GW by 2015 (CWEA 2015b). Foreign market expansion requires higher standards of turbine quality. The gap/deficit in international certification and shorter operational history of wind turbines acts as the major barrier to enter the foreign market (GWEC and IRENA 2012). Chinese operational records are not accepted by foreign developers even if the turbine models are manufactured based on licenses from globally recognised designs (Gosens and Lu 2014).

Figure 6 Wind turbines exported by Chinese manufacturers, MW



Source: BJX (2014), CWEA (2015b) and CWEA (2016)

The requirement to have a long and solid operational history is disadvantageous for Chinese players and will sqeeze out them from the European and US markets (Gosens and Lu 2013). This may represent the major reason why China has performed rather poorly in wind technology exports. Alternatively, Chinese manufacturers can export to developing countries where lower-quality turbines may be accepted. But, the localisation policy being emphasised by these countries as well as the high maintenance cost occuring in transport may challenge Chinese firms' cost advantage (Gosens and Lu 2014, Wang, Qin, and Lewis 2012). Less developed countries often have financial difficulties in developing wind power. In order to operate wind farms in these countries, the Chinese side has to accept financial risks in providing loans (Tan et al. 2013).

4.6 Resources mobilisation

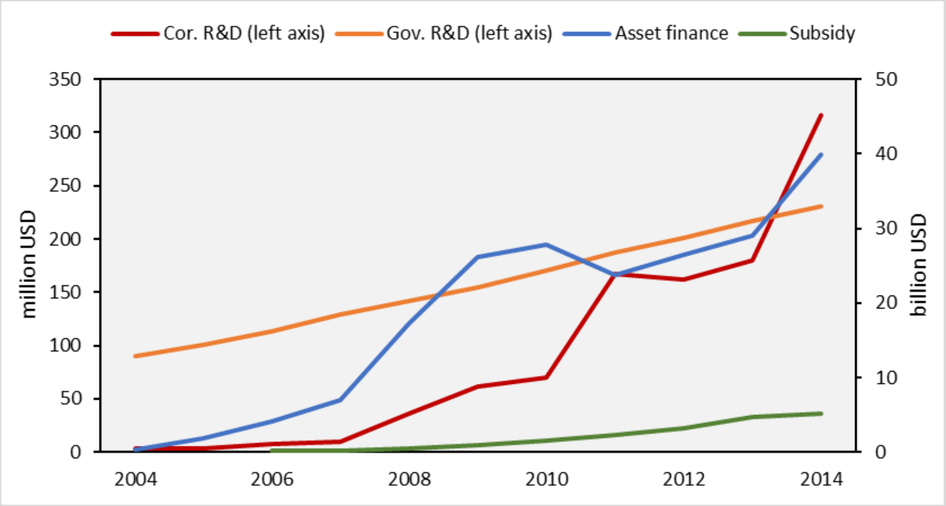
Technological innovation needs capital. To quantify China's financial investment in wind energy, three types of resources have been identified (see figure 7) – R&D expenditure for wind technology development, asset finance for wind power plant projects, and subsidy for wind power integration.

Between 2004 and 2014, about $2.8 billion was invested to improve wind technology through R&D (BNEF 2016). The government had been the major investor in wind R&D, but was overtaken by private enterprises in 2013. The 12th Five-Year Plan for the Development of Wind Power Science and Technology (2012-2015) sets ambitious goals to advance wind technology, including developing 7 MW+ tubines, and turbines suitable for low-wind speed, high altitude and low temperature conditions (MOST 2012). The relevant R&D projects have been funded by both the "863" project and the NSTSP.

With regard to asset finance, about $204 billion was invested in wind power generation projects between 2004 and 2014 (BNEF 2016). In 2010, the Chinese government announced the construction of seven wind power bases, each with a minimum capacity of 10 GW by 2020. As of 2015, the 10 GW target had been achieved by five bases and cumulatively 96 GW was already installed in all seven regions (NEA 2016). In addition to financing domestic installations, the government supports the firms to ‘Going out’ (internationalisation of businesses). For example, China Development Bank (CDB) extended a credit line of $6 billion to Goldwind in 2010 for its overseas activities, and a second agreement was signed in 2012 to credit another $5.3 billion (Xinhua News Agency 2012). Mingyang and Sinovel obtained $5 billion and $6.5 billion respectively from the CDB for exploiting foreign markets (Yicai Global 2011, China Energy 2010).

Wind subsidy has grown fastest over the past decade. Between 2006 and 2014, about $18.3 billion was spent for subsidising wind power (Zhao, Guo, and Fu 2014)[1]. The introduction of the feed-in-tariff in 2009 represents a milestone for China’s wind power industry. price setting is categorised according to four classes based on wind resources: 0.51 CNY/kWh, 0.54 CNY/kWh, 0.58 CNY/kWh and 0.61 CNY/kWh. Offshore wind enjoys a higher rate - 0.978 CNY/kWh for the Donghai Bridge Wind Power Project. Utilities and grid operators bearing the cost of feed-in-tariff will be compensated by the distribution of a/the Renewable Energy Premium (NPC 2005, 2009).

Figure 7 Chinese financial resources allocated to wind energy sector



Source: calculated from BENF (2015) and Zhao, Guo, and Fu (2014)

4.7 Creation of legitimacy

The scale of wind power in China had been small before wind technology was legitimised by the Renewable Energy Law in 2005. The law lays out rules on capacity targets, standardisation, education and training, RD&D, industrialisation and pricing. The purpose of developing renewable energy is to increase energy supply, improve energy mix, ensure energy security and protect environment.

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[1] The yearly data was modified (2006-2011) or extrapolated (2012-2014) with a linear regresson model ($y= -0.0054x + 0.2459$, $R^2=0.959$) derived from the datasets of Zhao, Guo, and Fu (2014).

According to the law (NPC 2005), renewable energy will be prioritised in the energy agenda through government targets (total volume). This will facilitate the establishment of a renewable energy market which both SOEs and private enterprises are eligible to enter. Special funds will be provided to support the research, development, demonstration and commercialisation of renewable energy technologies (RETs). Renewable energy projects will be included into the nation's high-technology development plans (e.g. 863, NSTSP), and can apply for discount government loans and tax incentive schemes. Higher education system and vocational schools will offer courses on renewable energy, and standardisation authorities are required to set standards on RETs. Power generation from renewable energy sources can be sold at guaranteed prices to grid operators who can recover the associated costs through their own selling prices.

The law was amended in 2009 to emphasise mandatory purchase (by grid operators?), grid connection and subsidies (NPC 2009). Firstly, the new regulation requires that a target of the proportion of renewable energy power in total electricity generation be made by energy administrative departments. Secondly, the law binds grid operators to buy the whole renewable energy power and improve transmission systems to facilitate the integration of electricity from renewable sources. Thirdly, a special fund for renewable energy will act as a mechanism allocating government funding to balance the extra cost of integrating renewable energy power. Fourthly, in case of non-compliance with the imposed mandatory purchase policy, grid operators are required to compensate renewable electricity producers by an amount equal to twice the economic losses they have suffered.

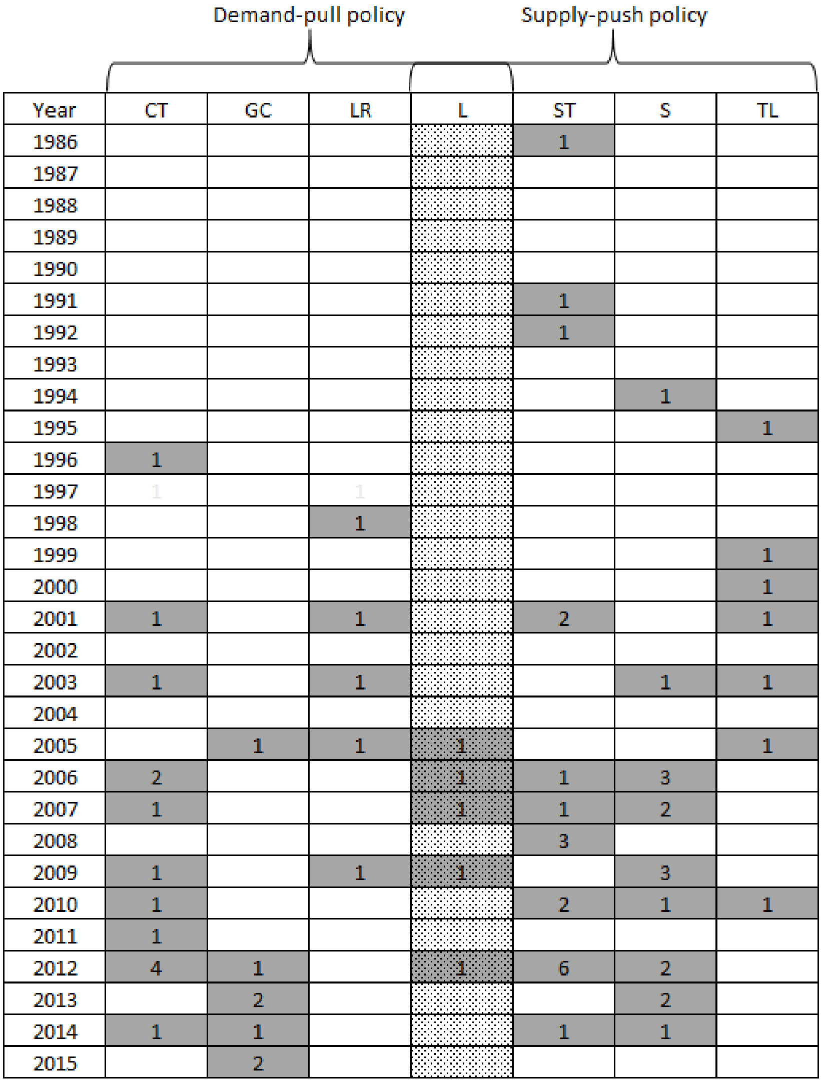
The legitimacy of wind power may perhaps represent the biggest driver for China's rapid growth in wind power. All data has indicated that China's wind power industry did not take off until the issuance of the Renewable Energy Law (2005). It emphasises the need and sets guidelines for technology development, market regulations and financial support of renewable energy. This is vital for China to create a niche market when the electricity market is dominated by coal-power plants.

4.8 Alignment between supply-push and demand-pull policies

China's wind power industry has experienced four stages: initial demonstration (1985-1996), early industrialisation (1997-2002), scale-up and localisation (2003-2008), and widespread diffusion (2009-present) (see figure 3). In 1986, China built the country's first grid-connected wind farm with three Vestas 55 kW turbines. In 1997, the programme 'Ride the Wind' was implemented to develop 400 MW by 2000, investing 23.6 million RMB to nurture two 'national teams' (domestic manufacturing and S&T bases). In 2003, the 'Wind Power Concession Programme' was initiated to attract domestic and foreign firms to bid for large-scale projects (100-200MW) meanwhile imposing a localisation rate of 40%-70%. In 2009, the 'localisation policy' was removed, and the annual addition of wind power began to grow at a speed of 20 GW.

The 30-year history of Chinese wind power industry has witnessed a variety of policies. China's success in the last decade marks a match between supply-push and demand-pull policies (see diagram 2). Between 1985 and 1995, there were a few supply-push policies emphasising R&D or financial resources but no demand-pull policies. abundant coal reserves enabled China to generate power at low cost. As a consequence, pilot wind power projects had almost no influence on national energy consumption (Dai and Xue 2015). Wind power served only as a supplementary energy source for rural or remote areas where electricity could not otherwise be accessed (Li et al. 2008).

Diagram 2 Coordination between supply-push and demand-pull policies



	Demand-pull policy				Supply-push policy		
Year	CT	GC	LR	L	ST	S	TL
1986					1		
1987							
1988							
1989							
1990							
1991					1		
1992					1		
1993							
1994						1	
1995							1
1996	1						
1997	1		1				
1998			1				
1999							1
2000							1
2001	1		1		2		1
2002							
2003	1		1			1	1
2004							
2005		1	1	1			1
2006	2			1	1	3	
2007	1			1	1	2	
2008					3		
2009	1		1	1		3	
2010	1				2	1	1
2011	1						
2012	4	1		1	6	2	
2013		2				2	
2014	1	1			1	1	
2015		2					

CT - capacity targets	ST - S&T policy
GC - grid connection	S - subsidies (incl. feed-in-tariff)
LR - localisation	TL - tax incentives & loans
L - legislation	

Note: The values indicate the frequency of the same type of policies presented.

Source: elaborated from IEA/IRENA (2016) and the authors' own database

Since 1996, the government has implemented demand-pull policies, such as the 9th Five-Year Plan for New and Renewable Energy Development (1996-2000) and 'Ride the Wind' (1997). The demand for wind power was small (less than 1GW) and many policies were concerned with localising core components of wind turbines. The goodwill for developing wind power can hardly be achieved without a promising market and prior accumulation of wind technology. During this period, intensive efforts were made to localise wind turbine technology through licensing and joint ventures (see diagram 1).

The Renewable Energy Law (2005) enabled China's huge potential for deploying wind turbines to be realised. The subsequent 11th Five-Year Plan for Renewable Energy (2006-2010) sets an ambitious goal of developing 10 GW of wind power by 2010, and of 100 GW by 2015 as claimed in the 12th Five-Year Plan for Wind Power Development (2011-2015). Given the promising market for wind power, S&T and subsidy-related policies have been increasingly implemented. Most importantly, government policy for wind power has taken the form of five-year plans, such as the 12th Five-Year Plan for Wind Power (2012-2015) and the 12th Five-Year Special Plan for Wind Power Science and Technology (2012-2015).

To be more specific, the demand for large turbines and the supply of capital resources to the firms have affected the evolution of China's innovation pathways in wind turbine industry. Before the early 200s, few Chinese firms were engaged in wind technology. After the Renewable Energy Law (2005) was issued, the number of Chinese wind turbine manufacturers reached nearly 100 (Chinawindnews 2016). The '*Market Entry Standards for Wind Equipment Manufacturing Industry (2010)'* requires that new entrants must have R&D capacity and be able to produce 2.5 MW+ turbines with at least five years' experience in mechanical and electrical industry. This policy locked out potential entrants with limited R&D capacity, and meanwhile pushed the incumbents to target at larger turbines. firms upgraded their technologies by collaborating with foreign companies, M&A or setting up overseas R&D centres in knowledge-intensive areas.

5 Conclusions

5.1 Findings

The explanatory power of the system functions approach has been empirically demonstrated by China's experience in wind technology innovation. This analytical tool originated in developed countries, but can be adapted to examine the process of technological innovation in developing countries. However, the functional patterns may be different between developed and developing countries. It was assumed that knowledge development, entrepreneurial activities and market formation are respectively the most critical system function in pre-development, development and take-off, and acceleration phases (see Hekkert et al. (2011)). But, China's wind industry has been characterised by creation of legitimacy, guidance of search and resource mobilisation (see annex 3).

It demonstrates that quantitative indicators can be incorporated into functions analysis to identify the drivers for or barriers to the innovation system. This is of prime importance to characterise quantitatively the dynamics of technological innovation system. The IS approach has been criticised for being a policy framework rather than a theory due to the lack of normative empirical research (Sharif 2006, Edquist 2005). The systems function approach has to some extent made the concept less ambiguous. The proposed indicators may be adapted to work towards a more operationalised theory of innovation systems. But, the time lags between R&D, commercialisation and export as well as the cumulative R&D effect must be verified before and considered in empirical analyses (see Popp (2016)).

China's innovation system for wind technology has been driven or hampered by multiple factors, namely the presence or lack of certain functions. It shows that the creation of legitimacy, guidance of search, and resources mobilisation represent the most important elements in China's rise in wind power. Chinese MNEs' entrepreneurial activities in exploring advanced technology, the huge domestic market demand for wind power, and the alignment between supply-push and demand-pull policies are also critical system functions. But, China's wind energy innovation system is held back by knowledge development and knowledge networks, especially the latter.

High-quality R&D (e.g. top 10% publications, foreign patents) should be paid closer attention to; otherwise, the interactions between public and private sectors will be hindered as a result of 'trust' dilemma – firms are unwilling to conduct joint R&D with universities as they assume that patents produced by universities are of little value. The weaknesses in knowledge development and knowledge exchange may lead to a type of technology-acquisition oriented entrepreneurship, which usually takes high cost and risks. As a possible solution, stronger supply-push (e.g. reorganisation of state labs and institutes) and demand-pull policies (e.g. bolder enforcement of standardisation, certification and grid connection) are required. They may help activate the current innovation resources to nurture in-house innovation capability, and decrease dependence on foreign technology to expand overseas market.

5.2 Limitations

The paper has attempted to cover all the system innovation functions developed in the literature along with one extra dimension (i.e. alignment between supply-push and demand-pull policies) to produce a general picture, but specific details about how each function operates have not been examined. As is revealed by the indicators, the same function can be strong in some aspects but weak in others (e.g. total versus top 10% publications). The discrepancies cannot be explained without detailed analyses. If the focus is narrowed down, the ultimate drivers behind each function can be identified. For example, the most productive R&D groups can be investigated in a micro perspective to figure out what has driven their successes and what lessons can be learnt from their experience. changes at the system level can be seen as the outcome of changes at the micro level, whereas the system shapes the learning, innovation and competence-building at the micro level (Lundvall, Vang, et al. 2009). An inter-linked loop - macro framework → micro examination → macro extraction may enhance IS approach.

The indicators derived from the existing research are less than perfect. Theoretically, some functions can be measured by more (direct) indicators, but it becomes unfeasible owing to data constraints. For example, the interactions between public and private sectors can be better revealed by asking to what extent they collaborate in R&D activities. Collaborative R&D is one form of interaction. others include technology transfer through buyouts of IPR, outsourcing R&D, joint ventures, technology roadmaps jointly produced by public and private sectors, academic or non-academic conferences and consultancy. It is hard to quantify these interactions under the current conditions. Data collection, compilation and publication is vital for improving the quantitative analysis of energy innovation systems.

5.3 Outlook for future research

Future research may be carried out in these directions: a) the differences in system-building between technological leaders (developed) and follower (developing) countries; b) the impact of the interplay between domestic and foreign innovation systems on technological growth and innovation capability; c) micro-level analyses on functions may offer insights about the micro foundation of innovation systems; d) debates on linking indicators to innovation systems may refine the proposed metrics and improve empirical analyses of innovation systems; e) more research concerning the alignment between supply-push and demand-pull polices is needed; and f) discussions on database construction offer the potential of a one-stop platform for energy innovation statistics.

Annexes

Annex 1 Searching queries for bibliometric and patent analyses

Types	Searching codes
Bibliometrics	TI=(wind energy OR wind power OR blade* OR rotor* OR gearbox* OR generator* OR nacelle* OR tower* OR inverter* OR converter* OR transformer*) AND TS=(wind) Countries/territories=China Language: English Years: 1970-2015 Document type: article, proceedings paper, book chapter, review Database: SCIE, ISI Web of Science
Patent analysis	For PATSTAT (jointly established by the EPO and USPTO), CPC codes were referred to: • blades or rotors (Y02E 10/721) • components or gearbox (Y02E 10/722) • control of turbines (Y02E 10/723) • generator or configuration (Y02E 10/725) • nacelles (Y02E 10/726) • offshore towers (Y02E 10/727) • onshore towers (Y02E 10/728) • power conversion electric or electronic aspects (Y02E 10/76) For PIAS (developed by the SIPO), IPC code was referred to: • wind motors (F03D)

Annex 2 Research institutes in wind energy approved by the MOST and NEA

Year	Research institute	Host organisations	Approved by
2004	State Research Centre for Wind Power Engineering	Goldwind	MOST
2009	State Research Centre for Offshore Wind Power Engineering	CSIC Haizhuang	MOST
2009	National Research Centre for Wind Power Blades	Chinese Academy of Sciences	NEA
2009	National Research Centre for Large-Scale Clean and Efficient Power Generation Equipment	Dongfang Electric	NEA
2009	National Research Centre for Marine Energy Engineering Equipment	CSIC Ship Design Centrer	NEA
2010	State Laboratory of Wind Power Equipment and Control	Guodian United Power	MOST
2010	State Laboratory of Wind Power System	Windey	MOST
2010	State Laboratory of Offshore Wind Technology and Testing	XEMC	MOST
2010	National Energy Large-Scale Wind Power Grid-Connecting System R&D Centre	State Grid	NEA
2010	National Research Centre for Offshore Wind Power Equipment	Sinovel	NEA
2010	National Research Centre for Wind Power Generators	XEMC	NEA
2010	National Research Centre for Wind Power Operation Technology	Guodian Longyuan	NEA
2010	National Research Centre for New Energy Access Equipment	Naval Uni. of Eng., Daqo Group	NEA
2010	National Research Centre for Power Control and Protection	NanRui Electric	NEA
2011	State Research Centre for Wind Power Transmission and Control Engineering Technology	Sinovel	MOST
2011	National Research Centre for Wind & Solar Power Testing and Certification	General Certification Centre	NEA
2013	National Test Centre for Wind Power Technology	State Grid EPRI	NEA

Source: Li et al. (2013) and NEA webpages

Annex 3 Assessment on the functioning of China’s wind technology innovation system

Functions	Sectional score	Overall score
Knowledge development	• Total publications (+2) • Top 10 % publications (-1) • Domestic patents (+2) • Foreign patents (-1)	+1
Knowledge networks	• Public-private knowledge exchange (-3) • Producer-developer connections (-1)	-2

Guidance of the search	• Policy targets on cumulative capacity (+3) • Policy targets on turbine sizes (+3) • Policy targets on localisation rate (+3)	+3
Entrepreneurial activities	• New entrants (+2) • Technology development strategies (+3) • Establishment of R&D facilities (+1)	+2
Market formation	• Domestic deployment of wind power (+3) • Foreign exports on wind turbines (+1)	+2
Resources mobilisation	• R&D expenditure (+3) • Asset finance (+3) • Subsidy (+3)	+3
Creation of legitimacy	• Issuance of laws and regulations (+3)	+3
Alignment between supply-push and demand-pull policies	• Presence of supply-push policy (+2) • Presence of demand-pull policy (+2)	+2

Note: Overall scores are the averages of sectional scores.

	High	Moderate	Low
Positive	+3	+2	+1
Negative	-3	-2	-1

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