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The Innovation Path of the Chinese Wind Power Industry

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Joint project with:

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Tsinghua University
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Abstract

The Chinese wind energy sector has undergone rapid development over the past 30 years, yet its path has differed from that of its European counterparts. There is much discussion in the literature on what the path of innovation is for the Chinese wind energy sector and where this path will lead. This research contributes to the literature by attempting to answer three questions: What is the technological path of innovation in China’s wind sector? How did this path of innovation emerge? What are the determinants of this path?

To fully understand the Chinese wind energy innovation path, this research first summarises the history of the development of wind energy technology from the perspectives of both core technology innovation and deployment technology. The core technology innovation involved a change in strategy from preferring lower prices to preferring higher quality, from small-turbine to large-turbine technology and from imported technology to indigenous technology, while wind energy deployment experienced a path change from a centralised deployment pattern with a partial production chain to a de-centralised pattern with a whole-production-chain strategy.

Against these background features, this paper presents three individual cases of a wind turbine producer, a wind farm and a wind blade producer to illustrate how foreign collaboration and technology, choice of deployment strategy, and government policy have influenced the sector to continually improve its technology.

The findings indicate that foreign technology and collaboration have had a significant role in helping wind energy technology to develop in China, and were also key elements in stimulating indigenous innovation when high prices held the domestic wind market back from massive expansion. While public policy has played a key role in many aspects of the development of the innovation path, the long-term, enduring goal of developing the required technology was the essential driver. The development of the wind sector occurred alongside the economic development and social improvement of the nation. Thus, while it may be too soon to predict the future path of innovation for Chinese wind energy technology, an emphasis on research and development and increasing international competition is a trend that is likely to continue.

Preface

Mitigating climate change by reducing carbon emissions is one of the biggest and most complex issues the world has ever faced. Technological innovation plays a major role in taking on this challenge. Old and new industrial powers alike are increasingly reforming their policy frameworks to encourage low-carbon investment and innovation.

Evolutionary economics has demonstrated how initial choices of technologies and institutional arrangements preclude certain options at later stages; hence, innovations evolve in an incremental and cumulative way, resulting in context-specific technological pathways. Such path dependency implies that technologies and institutions do not progressively converge toward a unique best practice, as neoclassical equilibrium models might suggest. The historical and social embeddedness of such evolutionary processes instead results in a variety of very different technologies and institutions across countries.

The starting assumption of our research was that low-carbon technologies depend to a high degree on politically negotiated policies, mainly due to the failure of markets to reflect environmental costs. The way national governments and industries deal with the low-carbon challenge varies greatly depending on levels of environmental ambition, technological preferences (such as different attitudes towards nuclear energy, shale gas, carbon capture & storage), the ways markets are structured, and the importance attached to expected co-benefits (such as green jobs or energy security). Consequently, low-carbon technologies are more likely to evolve along diverging pathways than other technologies whose development is more market-driven.

To test this assumption we conducted the international research project "Technological trajectories for low-carbon innovation in China, Europe and India". The project explored to what extent, how and why technological pathways differ across countries. Case studies were conducted in two technological fields, electromobility and wind-power technologies, in China, India and leading European countries. Whether a diversity of pathways emerges or a small number of designs becomes globally dominant has important implications. From an environmental perspective, diversity may help to mobilise a wide range of talents and resources and deliver more context-specific solutions. Convergence, on the other hand, might help to exploit economies of scale and thereby bring about bigger and faster reductions in the cost of new technologies. From an economic perspective, diversity may provide niches for many firms, whereas a globally dominant design is likely to favour concentration in a small number of global firms – which may or may not be the established ones. Comparing European incumbents with Asian newcomers is particularly interesting, because China and India might well become the gamechangers – responsible for most of the increase of CO_2 emissions but also leading investors in green technology. In addition, the project explored lessons for international technology cooperation, emphasising ways to navigate the trade-offs between global objectives to mitigate climate change effects and national interests to enhance competitiveness and create green jobs locally.

The project was carried out between 2011 and 2014 as a joint endeavour of four institutions: the German Development Institute / Deutsches Institut für Entwicklungspolitik (DIE), the Institute of Development Studies (IDS) Brighton, the Indian Institute of Technology (IIT) Delhi and the School of Public Policy at Tsinghua University, with additional collaborators from the Universities of Aalborg, London and Frankfurt. The project was truly collaborative, to the extent that international teams jointly conducted interviews in China, India and Europe which helped to build common understanding.

Eight reports have been published in, or are currently being finalised for, the DIE Discussion Paper series:

(1) *Altenburg, Tilman* (2014): From combustion engines to electric vehicles: a study of technological path creation and disruption

(2) *Bhasin, Shikha* (2014): Enhancing international technology cooperation for climate change mitigation: lessons from an electromobility case study

(3) *Chaudhary, Ankur* (2014): Electromobility in India: attempts at leadership by businesses in a scant policy space

(4) *Lema, Rasmus / Johan Nordensvärd / Frauke Urban / Wilfried Lütkenhorst* (2014): Innovation paths in wind power: insights from Denmark and Germany

(5) *Schamp, Eike W.* (2014): The formation of a new technological trajectory of electric propulsion in the French automobile industry

(6) *Ling, Chen / Doris Fischer / Shen Qunhong / Yang Wenhui* (forthcoming): Electric vehicles in China: bridging political and market logics

(7) *Dai, Yixin / Yuan Zhou / Di Xia / Mengyu Ding / Lan Xue* (2014): The innovation path of the Chinese wind power industry

(8) *Narain, Ankita / Ankur Chaudhary / Chetan Krishna* (forthcoming): The wind power industry in India.

On the basis of these case studies, the team is currently working on a series of cross-country comparative analyses to be published in academic journals.

The research team is very grateful for generous funding and the very supportive attitude of the Swedish Riksbankens Jubileumsfond under a joint call with the Volkswagen Foundation and Compagnia de San Paolo.

Bonn, October 2014 Tilman Altenburg

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Abbreviations

BMUB	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, Germany)
BMWi	Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy, Germany)
CAE	Chinese Academy of Engineering
CO_2	Carbon dioxide
CPI	China Power Investment Corporation
CTC	Climate Technology Network, Netherlands
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatt hour
HT	Hui Teng
IEA	International Energy Agency
KV	Kilovolt
kW	Kilowatt
kWh	Kilowatt hour
kW/km^2	Kilowatt per square kilometre
LVRT	Low voltage ride through
M&A	Mergers and acquisitions
MoFTE	Ministry of Foreign Trade and Economic Cooperation, China
MoST	Ministry of Science and Technology, China
MW	Megawatt
NDRC	National Development and Reform Commission, China
NOx	Nitrogen oxide
NPC	National People’s Congress, China
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
PMDD	Permanent magnet direct drive
R&D	Research and development
REL	Renewable Energy Law, China
SDIC	State Development and Investment Corporation, China
SERC	State Electricity Regulatory Commission, China
SO_2	Sulphur dioxide
TWH	Terawatt-hours
UHV	Ultra-high voltage
US	United States
USD	United States dollars
VAT	Value-added tax
W	Watts
W/Cap	Installed capacity per capita in watts

1 Introduction

Climate change is becoming one of the most important issues in human development. Countries, states and cities are searching for ways in which to reduce greenhouse gas (GHG) emissions by changing modes of human development. The widely discussed philosophy of 'low-carbon development' is accepted as the future developmental mode for reducing carbon dioxide emissions while preserving economic growth. There is a consensus that technological innovation and development may help humans to fulfil the goal of low-carbon development. The Kyoto Protocol, for example, states that to fulfil their responsibilities in reducing GHG emissions, Annex I countries should undertake *"research on, and promotion, development and increased use of, new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies".* As the first agreement made in response to climate change, the Kyoto Protocol considered developing countries (those not in Annex I) mainly as receivers of technology.

In practice, various countries are encouraging multiple technology developments. The European Union has taken a leading position in response to climate change, in terms of both equipment production and technology deployment. Technologies such as renewable energy, electronic mobility, power storage, fuel cells and energy efficiency technology have been strongly promoted in the recent national strategy plans of countries such as Denmark, Germany, France and the United Kingdom (BMWi / BMUB 2010).

World economic development and the distribution of GHG emissions have changed since 1997. Emerging powers have high rates of economic development and increasing amounts of GHG emissions. Although they were not included in the Kyoto Protocol China, India, Russia and Brazil have become important players in the global climate strategy.

Having maintained its economic development at the high rate of 8-10% for almost a decade, China has not only experienced rapid economic and social development, but has also incurred heavy environmental costs. China has become the world's largest emitter, overtaking the United States (IEA 2007). In 2013, the number of smog days with heavy air pollution exceeded 51% in Beijing.[1] Faced with international pressure to reduce GHG emissions and improve its poor domestic environment, China has put much effort into drawing up a climate change strategy and gearing its economic development to a low-carbon mode. For example, China now has a large share of the wind turbine market. Its increasing market share and the high growth rate of this industry positions China as a potential competitor for developed countries in the area of wind energy.

During the process of developing its wind energy industry, China followed a different path of technological innovation that attracted much attention from academics. Having relatively small R&D (research and development) capacities, Chinese firms forged ahead by importing production lines, gaining technological licenses through acquisition, and purchasing intellectual property. China's strong manufacturing base, low labour costs and extensive investment in the industry resulted in Chinese wind energy technology taking a different path from that of its EU counterparts.

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1 Data source: calculated from Beijing air-quality monitoring station data, http://www.bjmemc.com.cn/g372.aspx.

First, China experienced rapid development in the manufacture of wind energy equipment. In 2011, 29 major wind turbine manufacturers were producing parts, equipment and wind turbine systems in China. Having installed 17.63 GW of wind turbine capacity in 2011, China became the global leader in terms of both annual installed capacity and total installed capacity, with the total capacity reaching 62.36 GW and accounting for 40% of global installed capacity.

Second, the speed of wind energy deployment was also rapid despite severe grid connection problems (Wang 2010). In 2012, grid-connected wind energy provided 100,800 GWh (millions of kilowatt hours), equivalent to 2% of China's total electricity production. However, the national annual average for hours of use decreased from 1920 hours in 2011 to 1890 hours in 2012. East Inner Mongolia and Jilin experienced the most severe wind energy curtailment, which exceeded 50% during the cold season. West Inner Mongolia, Jiuquan in Gansu, and Zhang Jiakou also had averages of 20% wind energy curtailment (Zhang 2014).

Third, China set a goal of increasing its indigenous R&D capacity regarding large wind turbines. Starting with the Renewable Energy Law of 2006, China has consistently emphasised the importance of indigenous innovation. In the wind energy sector, national science and technology programmes, such as Numbers 863 and 973, have designed wind projects. However, the question of whether the R&D capacity of Chinese wind energy firms is sustainable remains (Wang / Qin / Lewis 2012). Will innovation continue after the recent spate of acquisitions?

Now that the Chinese wind energy sector has gone through the stages of 'low-cost manufacturing', 'spate of acquisitions' and 'intended indigenous R&D', it is time to re-examine the sector from the perspective of the many unique aspects of wind energy in China but within the context of the broader lessons learned from other societies. The big question to be answered is: Does the development of Chinese wind energy technology represent a different path of innovation, and is this path of innovation sustainable?

1.1 Key research questions

Our overall research question can be sub-divided into the following independent, yet interrelated, research questions:

1) What is the path of technological innovation in China in response to climate change?
2) How did this path of innovation emerge?
3) What are the determinants of this path of innovation?

To summarise the development of the wind energy sector over the past 30 years, a detailed description of the sector's development, with specific focus on the unique contextual changes, is first required. The Chinese wind energy sector did not develop in isolation. It learned about possible directions for technology and policy from leading firms and countries in the sector and had several opportunities to move ahead during technological development. Understanding how these international contexts shaped the Chinese wind energy sector is essential to explaining the key determinants of the path of innovation. Additionally, the Chinese wind energy sector has also been influenced by the national industrialisation process. Key changes in policy and the national development paradigm have affected all sectors, with the wind energy sector being no exception. Analysis of these effects would help us to understand how Chinese wind energy technology has developed along a concurrent path of innovation, and would guide policymakers in making the adjustments required to continue to stimulate the development of the sector.

1.2 Research methodology

To illustrate the overall country–sector–technology aspects, this research used case studies to explain the specific innovation path taken by China.

We first explored different cases to identify the innovation path and its changes. This paper defines 'innovation case' as 'any event that has made an impact or has the potential to make an impact on the climate change mitigation potential of the technology.'[2] To discover key cases, the research team began by interviewing the key stakeholders involved in the development of wind energy technology in China, including government officials, technological experts and enterprises (manufacturers and wind farms), to identify initial innovation cases that might have influenced the innovation path of the industry. Further interviews were then conducted using the 'snowball' strategy to extend the potential pool of technological innovation cases.

From all of the cases identified, three key cases were selected for further exploration according to two selection criteria. First, only innovations that had reached the stage of commercial success were considered. Second, due to the enormous number of innovation cases in the wind energy sector, only major innovations that could potentially shape a national technological path were selected. Thus, the research did not focus on single, incremental technological improvements conducted by different players in the industry.

To take the continuity of any innovation case into consideration, attempts were made to set up a relatively clear boundary for each case by identifying the type of innovation and the players, and thus permitting the path of technological innovation of each case to be illustrated.

The key factors influencing each innovation case were also addressed, with a particular focus on policy factors, a firm's competition strategy, and international collaboration. Questions were asked as to whether and how innovation capabilities arose, and what direction the innovation path took. Interview questions were adjusted for each case so that the views, interests and actions of the various different stakeholders could be recorded for further analysis.

The remainder of this paper is organised as follows: Section 2 provides a broad review of the industrial development of wind energy worldwide and the rapid growth in the Chinese wind energy industry. The trends of the innovation paths for core technology and deployment are described in Section 3. Section 4 describes three cases that illustrate the key factors influencing the changes in the Chinese wind innovation path. A discussion and conclusions are presented in Section 5.

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2 This definition is taken from the collaborative research project 'Technological Trajectories for Climate Change Mitigation in China, Europe and India'.

2 Wind power development in China

2.1 Contextual background of the development of wind energy technology worldwide

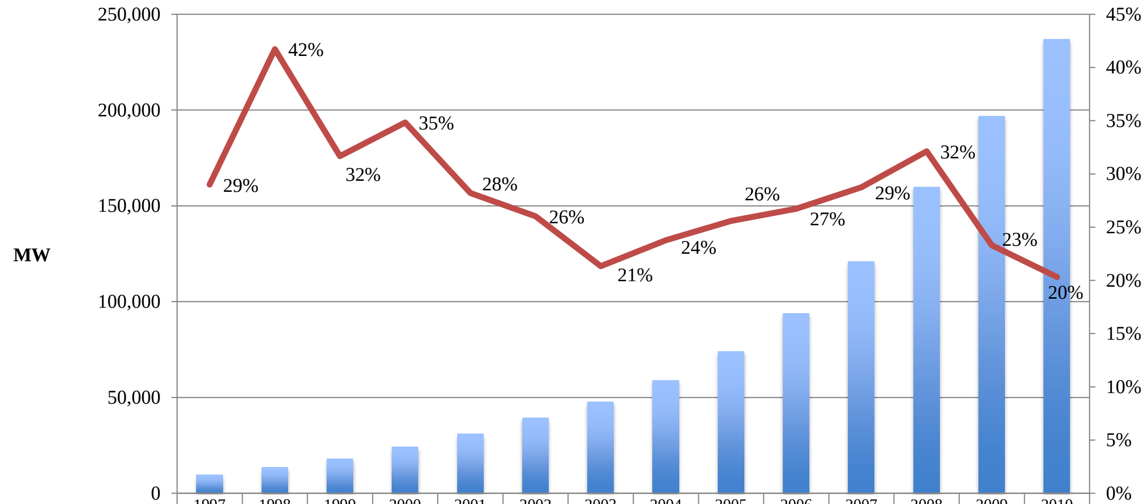
Wind energy is an important renewable resource that has seen dramatic development globally since the late 1970s. Two factors drove this development: the energy crisis of the early 1970s that fostered wind power as a global industry based on technological evolution, and the later concern over global climate change, in particular the implementation of the Kyoto Protocol, that opened up world markets for renewable energy. As the pressure to reduce GHG emissions continued to increase, wind energy contributed an increasingly greater share of the world's energy consumption. In 2008, wind energy provided nearly 20% of the electricity consumed in Denmark, more than 11% of that in Portugal and Spain, 9% of that in Ireland, nearly 7% of that in Germany, more than 4% of all European Union (EU) electricity, and nearly 2% of that in the United States (IEA 2009). The total installed wind power capacity increased from 7,480 MW in 1997 to 237 GW in 2011, an increase of 31 times the 1997 amount. Altogether, wind power provided 500 TWH (terawatt-hours) per annum, equivalent to 3% of global electricity consumption (IEA 2009).

Table 1: Top-ranking countries for wind energy deployment (2011)

Installed capacity per capita (W/Cap)		Installed capacity per land area (kW/km^2)		Installed capacity per GDP (kW/million USD)	
Denmark	710.1	Denmark	91.1	Cape Verde	20.6
Spain	463.5	Germany	81.4	Denmark	19.5
Ireland	434.9	Netherlands	56	Portugal	16.5
Portugal	379.5	Portugal	44.3	Spain	15.8
Germany	356.9	Spain	42.9	Ireland	11.8
Sweden	307.9	Belgium	35.3	Germany	9.8
Canada	154.7	Ireland	28.9	Dominica	9.4
Greece	151.2	United Kingdom	24.7	Sweden	7.9
United States	149.8	Italy	22.4	Estonia	7.5
New Zealand	145.2	Luxembourg	17	China	6.3
Estonia	143.4	Taiwan	15.7	Cyprus	5.8
Netherlands	138.2	Cyprus	14.5	Bulgaria	5.5
Austria	131.9	Austria	12.9	New Zealand	5.2
Cyprus	119.6	Greece	12.3	Greece	5.1
Norway	110.8	France	10.3	Honduras	4.6
		Dominica	9.6	Vanuatu	4.2

Source: Calculations based on data provided by WWEA (World Wind Energy Association) (2012)

Figure 1: Cumulative world total installed wind power capacity, 1997–2011 (MW)

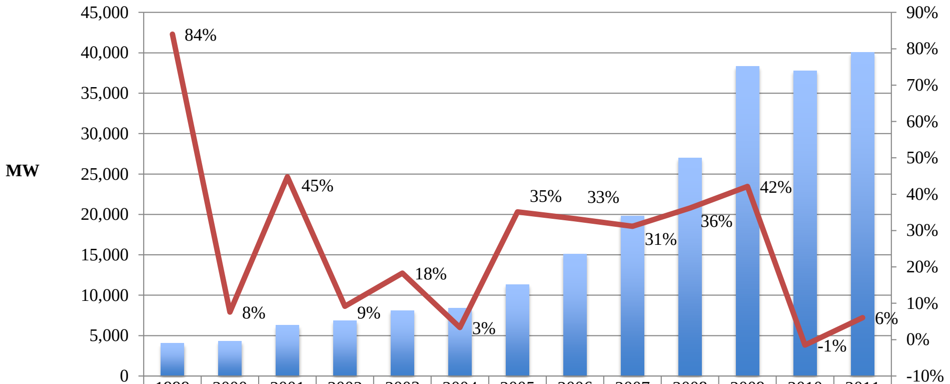


	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cumulative capacity	9,667	13,700	18,039	24,322	31,181	39,295	47,681	59,012	74,112	93,919	120,913	159,762	196,986	237,016
Growth rate	29%	42%	32%	35%	28%	26%	21%	24%	26%	27%	29%	32%	23%	20%

Source: Calculations based on data provided by WWEA (World Wind Energy Association) (2012)

The average growth rate is defined as the ratio of newly installed wind power capacity to the installed capacity of the previous year. Wind energy experienced a stable and high average growth rate of above 20% each year between 1997 and 2011. There was a downturn in 2009 due to the global financial crisis, but in 2011 new installations were able to take the cumulative total installed capacity to the historical high of 40 GW (WWEA 2012).

Figure 2: World new installed wind power capacity, 1997–2011 (MW)

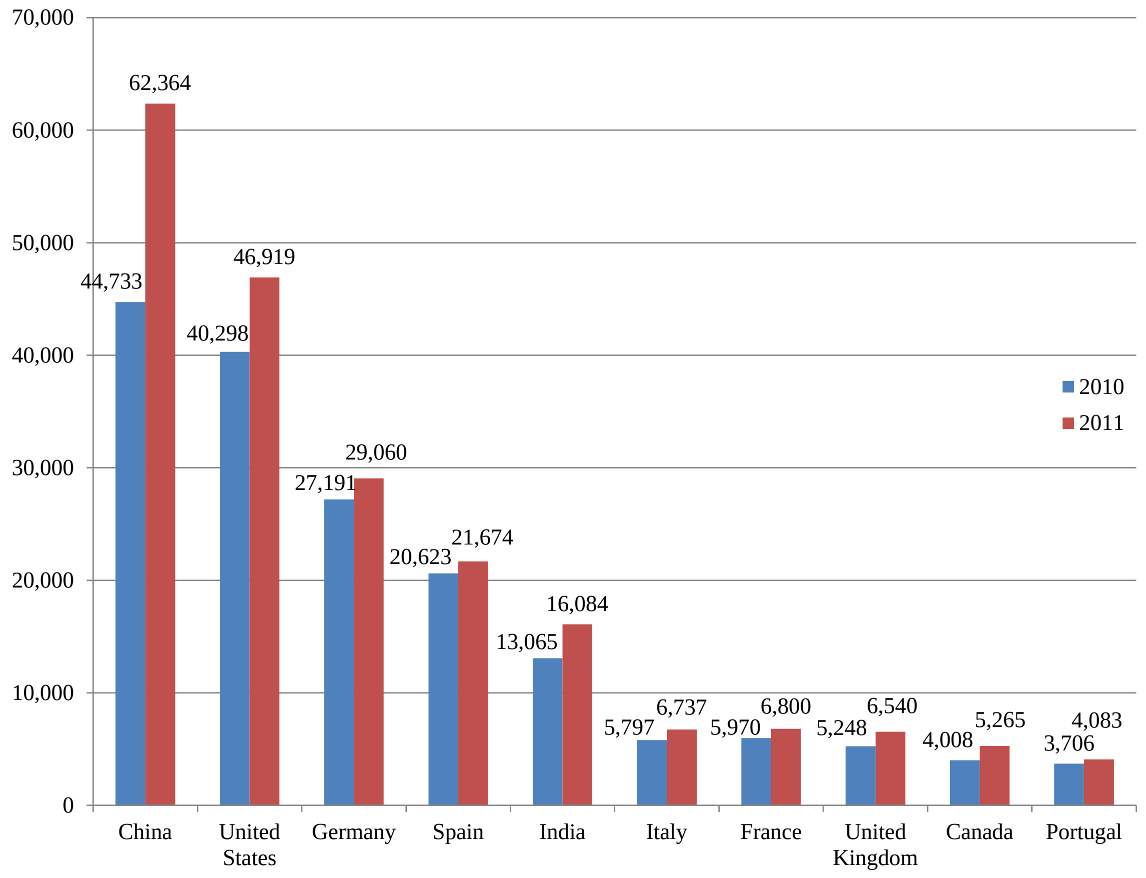


	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
New capacity	4,033	4,339	6,282	6,859	8,114	8,386	11,331	15,100	19,807	26,972	38,334	37,773	40,053
Growth rate	84%	8%	45%	9%	18%	3%	35%	33%	31%	36%	42%	-1%	6%

Source: Calculations based on data provided by WWEA (2012)

The world wind energy market has seen a clear shift in the distribution of production capacity and the scale of deployment during the past two decades. Initially, developed counties such as Denmark, the United States, the United Kingdom and Germany led the early attempts to develop wind power energy in response to climate change. Both technological and market development were dominated by these countries. Emerging economies, such as those of China and India, began to catch up around the end of the 20th century and rapidly gained a large market share. In 2011, both China and India were listed among the top five market owners in terms of accumulated installation capacity; indeed, China was ranked first (see Figure 3). The degree of market concentration continued to increase, with the top 10 countries holding 87% of the world market. Meanwhile, the distribution of the market was hard to predict as the growth rate of the emerging powers was dramatically higher than that of the 'traditional giants' (see Figure 4).

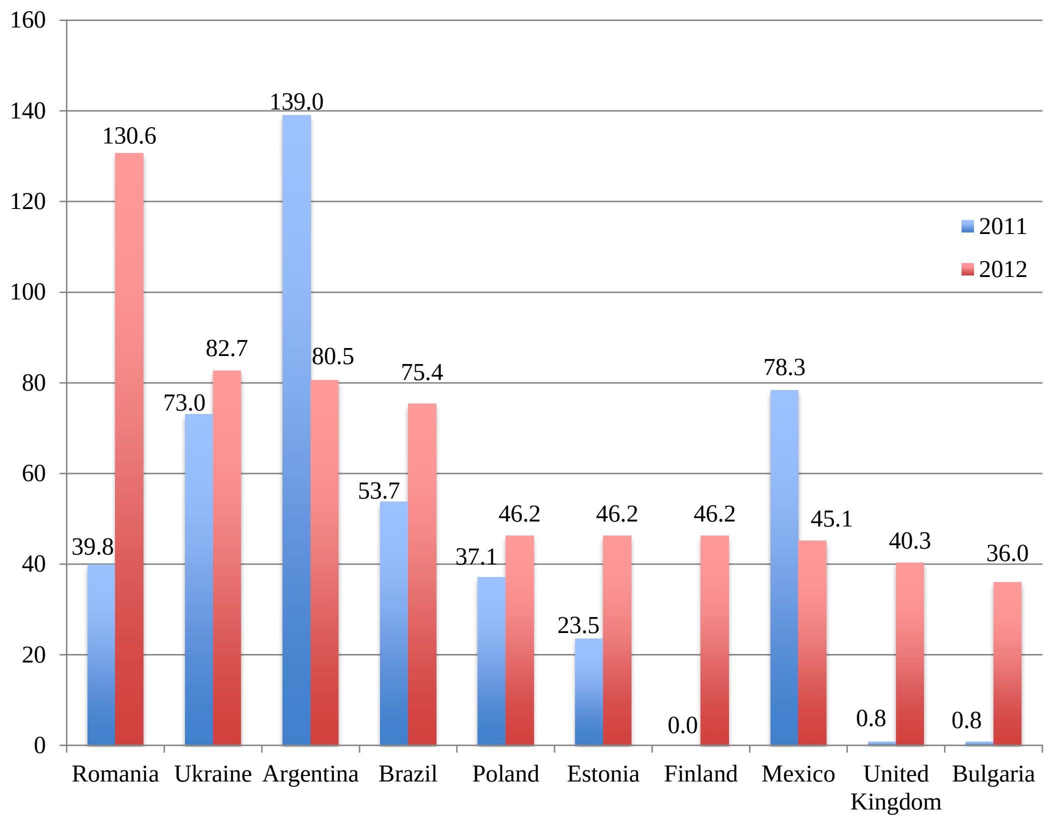
Figure 3: Top 10 countries by cumulative installed wind power capacity



Source: Calculations based on data provided by WWEA (2012)

Alongside manufacturing capacity, developing countries were also catching up in terms of cumulative deployment. Indicators such as installed capacity *per capita*, installed capacity per land area, and installed capacity per GDP (gross domestic product) describe the cumulative deployment level for different countries. The global average density of wind capacity per person is 34 W (watts). Denmark's density had reached 710.1 W/Cap in 2011, and Spain's, Ireland's, Portugal's and Germany's were 463.5 W/Cap, 434.9W/Cap, 379.5 W/Cap and 356.9 W/Cap, respectively. In 2011, China ranked 34th with 46 W/Cap, and India was 51st with 13W/Cap, below the global average. For installed capacity per land area, Denmark's and Germany's density had reached 91.1 kW/km^2 (kilowatt per square kilometre) and 81.4 kW/km^2, respectively, representing leading positions in large economies. For installed capacity per GDP, Denmark again maintained its leading position with 19.5 kW/million USD. Portugal's and Spain's indicators were 16.5 kW/million USD and 15.8 kW/million USD, respectively (WWEA 2012).

Figure 4: Top 10 countries by growth rate of wind energy (%): markets bigger than 200 MW



Source: WWEA (2012)

According to the International Energy Agency, the wind energy industry will continue to grow. It is estimated that the share of electricity generated from wind could reach 12% by 2050. Meanwhile, two major trends are expected to affect the development of wind energy development. First, more countries will enter into competition and affect market share. For example, by 2030 non-OECD economies are predicted to produce 17% of global wind energy, rising to 57% in 2050. Second, technological improvements have a significant role to play. As technology is developed, investment costs are predicted to be reduced by 23% by 2050, equating to around 70 to 130 US dollars per MWh (IEA 2009).

With more developing countries entering into competition, it is important to review the new power distribution, especially in terms of innovation capacity. Will developing countries such as China gain sufficient innovation capacity to threaten the leading wind energy countries such as Denmark, Germany and the United States?

2.2 Development of the Chinese wind energy industry

2.2.1 Contextual background of wind energy development in China

The energy demands of China have increased alongside its rapid economic development. Total energy consumption for the nation rose from 987 million tons of standard coal in 1990 to 3.54 billion tons in 2010, making China the largest consumer of energy in the world (Wang 2012). China became a net oil importer in 1993 and a net coal importer in 2009, with more than 100 million tons of coal imported per year (Wang 2012). From 2006, the price of fossil fuel has fluctuated widely on the global market. China has thus experienced great pressure in terms of its reliance on, and security from, energy.

Historically, China relied on coal as its main source of energy due to its extensive coal resources. Coal's share of total energy consumption reached 70.5% in 2010. Massive coal consumption caused China to emit large quantities of CO_2, SO_2, NOx (carbon dioxide, sulphur dioxide, nitrogen oxide) and industrial dust. In 2009, the Chinese government promised to reduce CO_2 emissions to 40–50% of the 2005-level by 2020, and raise the share of non-fossil-fuel energy production to 15% (Wang 2012). Coming mainly from hydroelectric, nuclear and wind energy sources, in 2011 China's non-fossil-fuel energy only accounted for 284 million tons of standard coal, equivalent to 8% of total energy production (Wang 2012). Pressure to protect the environment is also pushing China to develop renewable energy rapidly.

The expansion of wind energy, which is regarded as a safe and renewable source of energy, attracted less political opposition than hydroelectric and nuclear power, which are associated with environmental risks and damage. In addition, the cost of wind energy had been reduced to a level that made it competitive with coal in the electricity market, far below the levels of photovoltaic and biomass energy. Moreover, the scale effect achieved by the massive production and deployment of wind energy would further reduce the cost of wind farm construction and operation. The development of wind energy was therefore a rational choice for China to achieve its energy plan for the 21st century.

2.2.2 Rapid development of the Chinese wind energy sector

China has vast wind resources within its territory.[3] It began to explore wind energy resources in the 1950s with the goal of providing a rural energy supply. Wind-powered water pumps were one of the developments of this period. Pilot studies and trial deployments of wind energy for the purpose of electricity generation began in the 1970s in response to the energy crisis. However, true industrialisation did not occur until 1986, when the first wind turbines began to generate electricity.

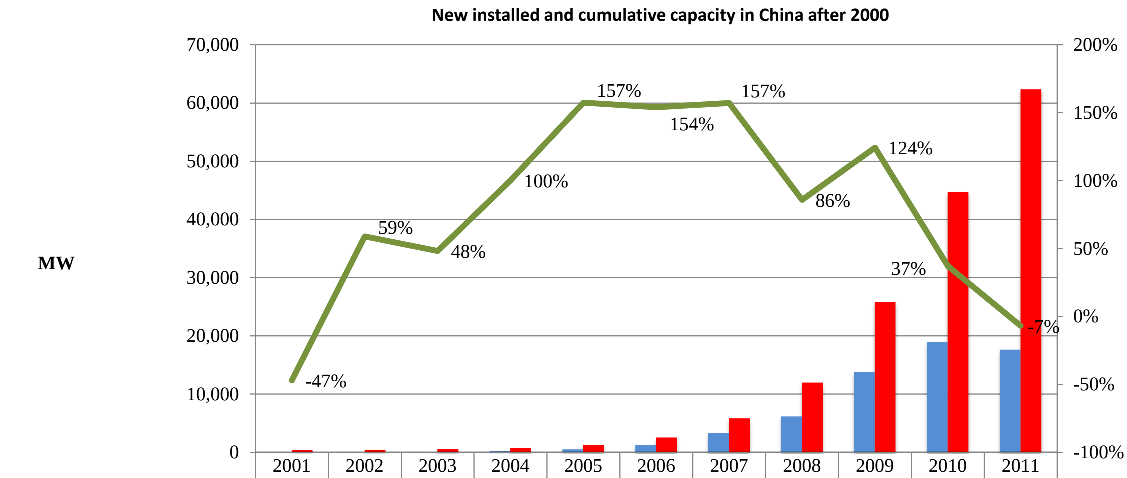
After the implementation of the Kyoto Protocol in 2003, the Chinese wind energy industry experienced rapid growth in both manufacturing capacity and installed capacity, alongside the expansion of the international wind market (Li et al. 2008; Li / Shi / Gao 2011). From

3 Data vary in different reports and documents. This paper cites the latest data obtained in a recent interview with the Center for Wind and Solar Energy Resources Assessment, China Meteorological Administration, on 17 Jul. 2012.

the manufacturing perspective, China became the world's largest wind energy manufacturer, with an average annual growth rate of 130% despite the worldwide financial crisis between 2004 and 2010 (see Figure 5).

In contrast to its solar electricity industry, China's wind energy sector relied on the domestic market for its development from the very beginning. With several 10 GW wind farms under construction (see Table 2), in 2011 grid-connected wind energy saved 22 million tons of coal from being burnt and thus reduced emissions by 360,000 tons of sulphur dioxide and 70 million tons of carbon dioxide. Based on household needs of 1,500 kWh per year, the grid-connected wind energy in 2011 satisfied the electricity demands of 4,700 households (Li et al. 2012).

Figure 5: Change in the Chinese installed wind energy capacity 2001–2011



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
New capacity	41.7	66.3	98.3	196.9	506.9	1,287.6	3,311.3	6,153.7	13,803.2	18,928.0	17,630.9
Cumulative capacity	381.2	447.5	545.8	742.7	1,249.6	2,537.2	5,848.6	12,002.2	25,805.4	44,733.4	62,364.3
Growth rate	-47%	59%	48%	100%	157%	154%	157%	86%	124%	37%	-7%

Data source: Li et al. (2012)

Table 2: Planned capacity of main wind bases	
Location	**Planned capacity (GW)**
Xinjiang Kumul	10.8
Gansu Jiuquan	12.7
Hebei	14
Jilin	23
Jiangsu coast	3 (onshore) 7 (offshore)
Eastern Inner Mongolia	20
Western Inner Mongolia	37

Source: GWEC (Global Wind Energy Council) (2012)

Compared with its onshore wind energy, the development of China's offshore wind farms was still in its infancy at this stage. By the end of 2011, the national offshore installed capacity was 242.5 MW. The Shanghai Donghai Bridge, Stage I project was the first large-scale commercial offshore wind farm in China, with a designed capacity of 102 MW (Li et al. 2012).

Table 3: Provincial cumulative installed capacity in 2011

Province	**Cumulative capacity (MW)**	**Province**	**Cumulative capacity (MW)**
Inner Mongolia	14,384.4	Shanghai	269.4
Gansu	5,551.6	Hainan	254.7
Hebei	4,991.3	Anhui	247.5
Liaoning	4,039.5	Shaanxi	245.5
Jilin	2,936.3	Henan	154
Shandong	2,718.6	Beijing	150
Heilongjiang	2,626.5	Hunan	133.8
Jiangsu	1,704.3	Jiangxi	133.5
Xinjiang	1,659.8	Tianjin	125
Ningxia	1,361.5	Hubei	115.4
Shanxi	1,035	Guizhou	60.9
Guangdong	933	Guangxi	49.5
Fujian	873.7	Chongqing	46.8
Yunnan	684.8	Sichuang	16
Zhejiang	320.6	Qinghai	14
Total			47,835.6

Source: Li et al. (2012)

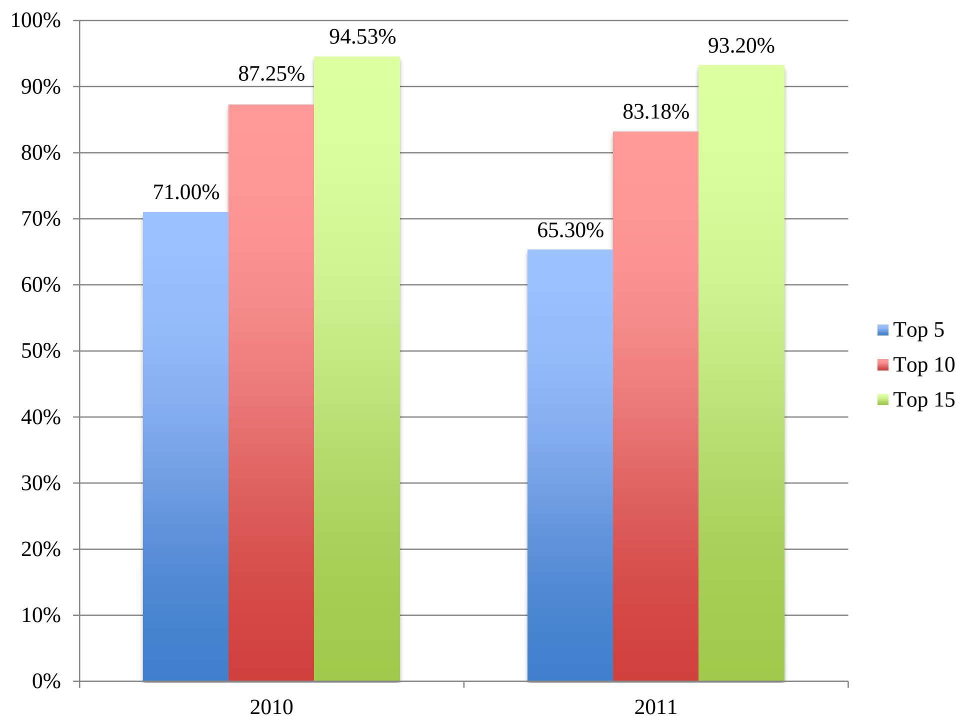
2.2.3 Booming wind market at a transition point

The development of wind energy in China began with the production of equipment. With a continually enlarging market, the wind energy equipment production sector became very large and prosperous. In 2011, more than 70 wind turbine manufacturers were registered in China, although only 29 of those had actual production. Compared with 43 manufacturers in 2009, the number of manufacturers is decreasing, reflecting more severe market competition and market concentration. The five biggest providers in 2011 were GoldWind (3,600 GW of capacity and 20.4% of the market), Sinovel (2,939 MW and 16.7%), United Power (2,847 MW and 16.1%), Mingyang Wind Power (1,177.5 MW and 6.7%), and Dongfang (946 MW and 5.4%) (Li et al. 2012).

This ranking is far from stable, however, and it would be hard to predict who the future leader in Chinese wind energy manufacturing will be. The increasingly heated competition in the wind energy market has generated a difficult situation for each producer. Besides Sinovel and GoldWind, United Power, Mingyang Wind Power, XEMC and Shanghai Electric have demonstrated increasing competitiveness through increasing their production capacity or using advances in technology. There are two types of newcomer: one type is represented by United Power, a utility provider that entered the industry to extend its business lines. The year 2011 saw a decrease in installed capacity from Sinovel, GoldWind, Dongfang, Vestas and Gamesa, but also the emergence of other firms. With its considerable growth rate of 73% in 2011, for example, United Power became the most outstanding enterprise in the Chinese market. Building on its background in utilities, United Power made wind turbine sales to its own wind farms and increased its risk management capacity. It began operating a 1.5 MW wind turbine in 2008 and installed 768 MW of wind energy equipment in 2009, making it the fourth biggest wind turbine provider in the Chinese market. United Power maintained its ranking, with 1,643 MW of installation in 2010, moving up to rank third in 2011. Moreover, United Power made considerable progress in R&D for new products. It first produced 3 MW turbines in 2010, and soon launched a 6 MW turbine in November 2011, only 6 months later than Sinovel.

Another type of newcomer is represented by XEMC, an engine provider that extended production to wind turbines. Formed in 2006, XEMC maintained stable and strong growth after launching its first 1.65 MW turbine in 2008. It moved into the top 10 with 451 MW of new installed capacity in 2011. Although they had less new installed capacity in 2011, GoldWind and Sinovel retained their positions as the first and second largest manufacturers in the Chinese market. GoldWind, Sinovel, United Power and Mingyang Power rose to be among the top 10 manufacturers in the world (Li et al. 2012).

Figure 6: Market share of top manufacturers in China



Source: Li et al. (2012)

The Chinese wind energy sector is at a transition point, with many uncertainties. Some firms are still gaining a greater share of the market using the advantage of low labour costs, while others are showcasing products with high added value. Some manufacturers have adopted a whole production chain strategy, while others are focusing on a single product. It is still too early to predict who will be the winners on the market. However, describing the main features of the industry's innovation path and achieving a full understanding of how that path formed would definitely assist policymakers in understanding the industry and making effective policy adjustments for the future.

2.3 The policy framework for wind energy innovation in China

As an emerging industry, the development of wind energy has depended on policy support in many areas. The existing literature indicates that the pattern of both manufacturing and deployment in the Chinese wind energy industry are strongly influenced by the concurrent policy framework (Li et al. 2008). Studies have, however, focused more on explaining the causal effect of development in the Chinese wind energy industry on certain policy contexts. The existing literature commonly adopted the three analytical dimensions of demand, supply, and policy environment. This paper, however, focuses on the path of innovation within the industry, and therefore places more emphasis on the changing trends in technological innovation and the influence of the concurrent policy framework. Policy instruments have included R&D investment, a market pull policy, environmental regulation, development planning, subsidies, and a tax deduction policy.

In each interview we asked the question "Which Chinese policy played the biggest role in boosting development of the wind energy industry?" Many policies were mentioned (see Table 4 for a detailed list of relevant policies). Of these, the Renewable Energy Law of 2006 (REL) is of particular importance and was mentioned by almost all of the interviewees. Passed by the National People's Congress (NPC) in 2005 and revised in 2009, the REL was a milestone in China's efforts to promote the development of renewable energy in the long term. The REL legislates for the direction of development of renewable energy and also the rights and commitments of participants. According to the REL, all levels of the Chinese government are obliged to set technology benchmarks and to issue technological data that are necessary for the market. Governments are also required to promote the connection of electricity from renewable sources to the state grid. The law permits enterprises and governments to cooperate in terms of franchising, and enterprises have obligations regarding technological development and price control. Electricity from renewable sources is to be subsidised so that it may be connected to the grid at the same price as traditional power. The subsidy comes from renewable energy funding, collected from end users via electricity utility bills. The law also calls for further study into special funds or tax incentives for the development of renewable energy (NPC 2006). The study interviewees all indicated that the REL provides a long-term guarantee for the development of the industry, which greatly influences the behaviour of all stakeholders.

Table 4 lists the other important policies for wind energy after 1994. A clear trend apparent from the policy framework is a shift from industrial policies to R&D and market policies.

The basic energy policy, along with national strategy and planning, set up an umbrella framework for all supporting policies. Starting with the REL, various energy policies to stimulate the development of renewable energy have been released by different ministries;

these include the policy Mid-Long Term Development Planning for Renewable Energy (2007), the 11th Five-year Plan for Renewable Energy (2008) and a revision of the REL in 2009. These policies are not necessarily specific to wind energy development, but the national emphasis on renewable energy has set the scene for wind energy to be developed.

Market exploration and deployment policies have been the most popular policy tools adopted by the Chinese government for wind energy development. Beginning in 2003, five rounds of concession projects were designed by the National Development and Reform Commission (NDRC) to enlarge the domestic market. Higher market targets were met by concession projects. Supplementary support provided by regulations on grid connection, wind-generated electricity prices and the management of renewable energy funding contributed greatly to the deployment and development of the industry.

China's R&D policy has particular features relating to the development of wind energy. In accordance with the national plan for the development of science and technology, research into wind energy has been included in the standard national research projects (e. g., the 863 Plan) ever since the 1950s. Until recently, there was no policy or research project designed specifically for wind energy. According to He Dexin, the President of the Chinese Wind Energy Association, more policies are available for technological improvement and indigenous innovation, for example, tax deductions for R&D funds and special research fund support for research into new types of wind turbine and wind blade. He also pointed out that national support for wind energy research is still mainly provided through universities and research institutes, and thus the overall R&D policy cannot be relevant until firms are motivated to join the R&D process as key players.

Last but not least, localisation policies abounded in the 1990s and early 2000s. These were all cancelled in 2009, marking the transition of the Chinese market to full competitiveness. Importantly, some of these policies required specific rates of adoption of domestic equipment in wind farm construction. While any items contravening free-trade principles were cancelled in 2009, the Chinese government continues to support domestic manufacture and indigenous innovation through R&D funding or the setting of technology standards. We have therefore included a column for 'localisation' in Table 4 to mark the relevant policies.

Table 4: Key wind energy policies in China

Policy	Year	R&D	Manu-facturing	Deploy-ment	Locali-sation	Remarks
Regulation on grid-connecting operation in wind farms	1994			√		Regulatory measure
Regulations on supporting further development of wind power	1999		√	√	√	Regulatory measure, price supporting
10th Five-year Plan for new and renewable energy	2001		√	√		Planning
Management measure on preparatory work of wind power concession projects	2003			√		Regulatory measure
Measures on formulating pre-report of availability of wind farms	2003			√		Regulatory measure

Table 4 (cont.): Key wind energy policies in China						
Policy	**Year**	**R&D**	**Manu-facturing**	**Deploy-ment**	**Locali-sation**	**Remarks**
Technological regulation on selection of wind farm location	2003			√		Regulatory measure
Technological regulation on measurement and assessment of wind resources	2003			√		Regulatory measure
Technological regulation on detailed engineering geological investigation of wind farms	2003			√		Regulatory measure
Measures on formulating investment estimations of wind farm projects	2003			√		Regulatory measure
National technological regulation on assessment of wind resources	2004			√		Regulatory measure
Notification on relevant requirements for wind power construction management	2005			√		Regulatory measure
Notification on relevant suggestions for accelerating localisation of wind power construction	2005	√	√		√	Planning & subsidy
Interim measures on regulation of land and environment protection management in wind power construction	2005			√		Regulation
Interim measures on special fund management for development of renewable energy	2006	√				Subsidy
11th Five-year Plan for renewable energy development	2008			√		Planning
Circular of the Ministry of Finance on the adjustment of import tax policies governing the High Wind Power Generator Units and their key parts and raw materials	2008	√	√			Tax rebating
Interim measure on management of special funds for wind power industrialisation	2008		√		√	Subsidy
NDRC notification on improving price policy of grid-connected wind electricity	2009			√		Price supporting
NEB interim measure on management of offshore wind power development	2010			√		Planning & regulation
Views on accelerating smooth development of wind equipment industry	2010	√	√		√	Planning
Source: Authors checked wind-related policies using the Government Policy and Document Database that is maintained by the School of Public Policy and Management, Tsinghua University.						

3 The innovation path for Chinese wind energy development

3.1 The innovation path for core wind energy technology

The factors affecting the innovation path of Chinese wind energy can be divided into three aspects.

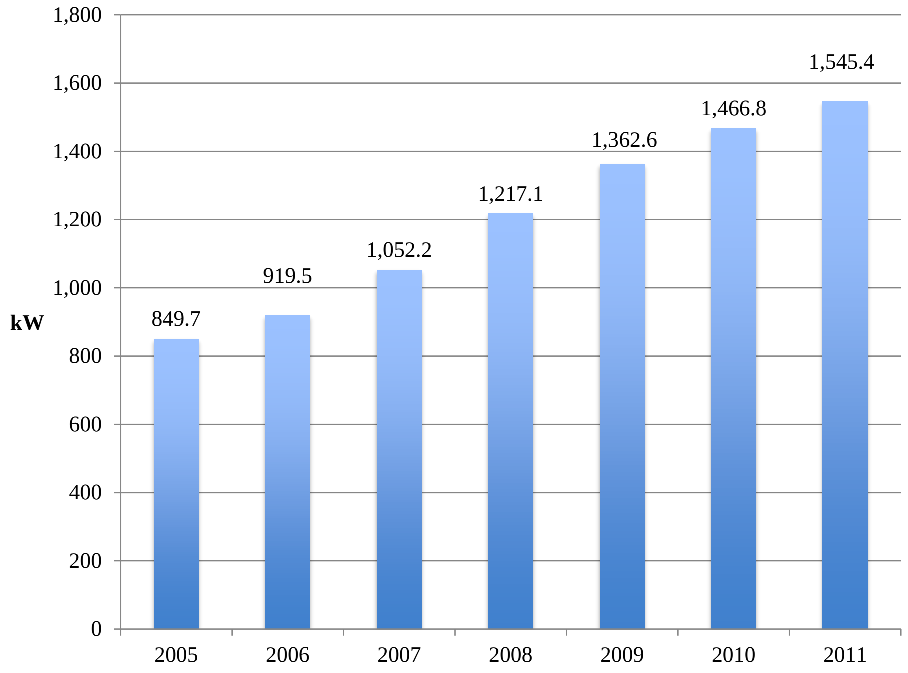
3.1.1 Moving from a strategy of 'preferring lower prices' to one of 'preferring higher quality'

International competitors have expressed the strongest feelings about this trend. During the interviews, the director of government relationships at Vestas China stated that the company's prices were higher than those of domestic companies, which prevented local projects focusing on short-term installation goals from choosing Vestas products. However, Vestas placed emphasis on high energy production and life-cycle efficiency, concepts that have gradually been accepted by Chinese governments. International competitors used to lose projects to lower bids based on cheaper domestic wind energy equipment, although the excellent operational performance and reliability of their turbines has helped international manufacturers to maintain a significant market share in China. Vesta and Gamesa are examples. Wind farm operators have given turbine security and reliability of the control system the highest priorities. Domestic manufacturers have therefore been urged to invest more in core technology R&D to increase the quality of their equipment and maintain market share.

3.1.2 Moving from 'small turbine' to 'large turbine' technology

Currently, 1.5 MW and 2.5 MW turbines dominate the wind energy deployment market in China. Before 2005, wind turbines with unit capacities of 250 kW, 600 kW and 850 kW were installed. Lacking any large-scale wind farms, various demonstration projects and small commercial wind farms selected different turbine units. Imported wind turbines with capacities above 1 MW were introduced into the Chinese market during the first and second rounds of concession bidding between 2003 and 2004, and were widely adopted in wind farm projects with similar unit capacities. 1.5 MW wind turbines then became the dominant unit capacity; in marked contrast, according to Vestas, to the world market, in which 1.2 MW wind turbines were dominant (Vestas interview). 2 MW wind turbines soon joined the market, becoming very popular and occupying a large share of the market. Up to 2007, wind turbines with unit capacities above 1 MW comprised about 51% of those installed annually and took the average capacity to 1.05 MW. This average rose to 1.47 MW in 2010 and 1.646 MW in 2012 (Navigate Research 2013). More recently, large wind turbines have become available: 2.5 MW, 3 MW or even larger wind turbines have gradually reached the commercialisation stage and entered the market. 3 MW wind turbines were put into mass production and have been successfully installed in a variety of wind farms. Domestic manufacturers were testing pilot 5 MW and 6 MW wind turbines in 2011.

Figure 7: Development trend of the average unit capacity of wind turbines



Source: Li et al. (2012)

3.1.3 Moving from 'imported technology' to 'indigenous technology'

Chinese domestic manufacturers have gradually come to dominate the Chinese domestic market and have begun to gain a favourable international reputation during the process of internationalisation. Table 5 shows that local firms have gained a large share of the domestic market. According to Wyman (2012), four Chinese wind turbine manufacturers were listed among the world's top 10 producers of wind energy. Sinovel, founded in 2006, was ranked as the world's second largest wind energy manufacturer in 2011, capturing 11.1% of the total market.[4]

Table 5: New installed capacity and cumulative capacity (MW) of the Top 15 manufacturers in China*

Enterprise	Annual production (2010)	Cumulative production (2010)	Annual production (2011)	Cumulative production (2011)
GoldWind	3,735	9,078.85	3,600	12,678.9
Sinovel	4,386	10,038	2,939	12,977
United Power	1,643	2,435	2,847	5,282
Guangdong Mingyang	1,050	1,945.5	1,177.5	3,123

4 Sinovel has experienced a downturn since 2012, falling out of the Top 5 in market share in 2013. In 2012, it was still ranked seventh in the world market.

Table 5 (cont.): New installed capacity and cumulative capacity (MW) of the Top 15 manufacturers in China				
Enterprise	**Annual production (2010)**	**Cumulative production (2010)**	**Annual production (2011)**	**Cumulative production (2011)**
Dongfang Electric	2,623.5	5,952	946	6,898
XEMC	507	1,089	712.5	1,801.5
Shanghai Electric	597.85	1,073.35	708.1	1,781.5
Vestas	892.1	2,903.6	661.9	3,565.5
China Creative Wind Energy	486	682.5	625.5	1,308
CSR Zhuzhou	334.95	465.3	451.2	916.5
General Wind Power	210	1,167	408.5	1,575.5
CSIC Haizhuang Windpower	383.15	479.25	396	875.3
Zhengjiang Windey	129	723	375	1,098
Gomasa	595.55	2,424.3	361.6	2,785.9
Envision	250.5	400.5	348	748.5
Total	**17,823.6**	**40,857.15**	**16,557.8**	**57,415.1**
* Companies are ranked according to annual production in 2011.				
Source: Li et al. (2012).				

3.2 The innovation path for wind energy deployment

China experienced two major shifts in the development of the innovation path for wind energy deployment.

3.2.1 The shift from a centralised deployment pattern to a de-centralised pattern

The pattern of deployment involved ‘large-scale deployment strategy’ and ‘diverse wind deployment strategy’ stages.

Rich wind resources are located in Northern China, Northeastern China and Northwestern China. However, these areas are sparsely populated with underdeveloped local economies, and have low levels of electricity consumption. The industrialised areas, such as those in the east and southeastern parts of China, are distant from wind-rich areas. The initial wind demonstration projects were mainly located in Xinjiang, Hebei and Inner Mongolia; when China increased the pace of development of wind energy technology in the late 1990s, the economic advantages provided by low land costs and rich wind resources in these areas drove the adoption of a large-scale, concentrated, mono-operator and long-distance transmission model for wind energy deployment.

From 2008, based on national investigation into wind energy resources and distribution, China scheduled the building of seven wind energy bases in Gansu, Xinjiang, Hebei, Western Inner Mongolia, Eastern Inner Mongolia, Jilin, Jiangsu and Heilongjiang.[5] By the end of 2011, construction had begun on the seven bases: Gansu Jiuquan 10 GW base Stage I, Inner Mongolia Tongliao Kailu 10 GW Base, Bayanur Urat Middle Banner Base, Baotou Darhan-Muminggan Base, Hebei-Zhangbei Base Stages I and II, Hebei Chengde Base and Xinjiang Kumul Base. Another six wind energy bases received construction approval and entered into the early preparation stages.

However, large-scale deployment raised the problems of grid-connection and long-distance transmission. As China was among the first adopters of large-scale wind energy deployment globally, it encountered many technological obstacles. For example, grid connection was a major issue. Key technological questions included the following: How could the grid control system be improved to eliminate the turbulence generated by wind power? How could efficiency in long-distance electricity transmission be ensured? Should an ultra-high voltage (UHV) transmission line be built? Should the grid be upgraded as a whole to a smart grid? Without suitable technical solutions to these questions, the electricity generated in the large wind bases would be subject to severe generation overabundance. According to statistics from the State Electricity Regulatory Commission (SERC), in the first six months of 2010 Inner Mongolia curtailed the most electricity, equivalent to 75.68% of the total wind energy that could be generated in that area (Li et al. 2012).

While engaging in R&D for large-scale wind energy deployment, China also began to develop widely distributed, smaller-scale wind farms, especially in the south-western part of the country. There were two advantages: First, while these areas had slower wind speeds, they also had high population densities and developed economies, and the electricity generated from the small wind farms was therefore close to the end users and could readily be accepted by the grid. Second, due to the progress in turbine technology, low-speed wind turbines were close to being commercialised and therefore there were no technical obstacles to developing a distributed deployment model (NDRC 2012).

3.2.2 The shift from a partial production chain to a whole production chain strategy

Wind farm operators have gradually engaged in the manufacture of wind energy equipment. Globally, wind farm development, wind farm operation and wind energy equipment manufacture are typically carried out by different firms that specialise in these different areas and together form a competitive market. In China, the situation is different. Although the electricity market is undergoing a process of market reform, it is still monopolised by large state-owned enterprises that naturally became the main operators of wind farms. Following the rush into wind farm construction after 2009, private investors have gradually entered the scene and have gained a small market share. Currently, wind

5 Then, the NDRC extended the 10 GW wind base name list to 9 in the 12th Five-year planning for wind energy development in 2012.

farm projects are being operated or constructed by more than 60 enterprises, most of which are central state-owned enterprises.

Wind farm operators in China can be categorised into four groups: central state-owned enterprises, local state-owned enterprises, private or foreign enterprises, and wind energy manufacturers who have extended their value chains to wind farm operation. Table 6 lists the major wind farm operators in each of these categories.

Table 6: Four types of wind farm operator in China

Type of wind farm operator	Key operators
Central state-owned enterprises	Guodian Longyuan, China Datang, China Huaneng, China Huadian, China Power Investment, Guangdong Nuclear Power, National Offshore Oil, CECEP, Shenhua (Guohua), Three Gorges Corporation, China Resources, State Grid, Sinohydro, and HydroChina
Local state-owned enterprises	Beijing Jingneng, Tianjin Jinneng, Shanghai Shennneg, Shandong Luneng, Guangdong Yudean, Ningxia Electric Power, Hebei Construction & Investment (Suntien Green Energy), Fujian Energy, and Fujian Investment & Development
Private or foreign enterprises	Heilongjiang Zhongyu, China Wind Power, Golden Concord, Shanxi Yunguang Wind Power, Wuhan Kaidi, Daoda Marine Heavy Industry, HKC New Energy, Honiton Energy, and UPC
Wind energy manufacturers	GoldWind, Gomesa, Zhejiang Huayi (HEAG), Tianwei Group, Shandong Changxing, Universal Wind Energy, and XEMC

Sources: Data collected from various different reports from the Chinese Wind Energy Association (2010; 2011; 2013)

Similar to the Chinese wind turbine market, the market for wind farm operation has also experienced dramatic changes. There are two main trends: First, state-owned enterprises are more likely to operate large-scale wind farms. In 2011, the top 10 wind farm operators installed a total capacity of 13.43 GW. Although this was 660 MW less than that installed in 2010, these top 10 enterprises held 1.8% more of the total new installed capacity than the previous year. A similar centralisation occurred with the top operators. For example, despite an average decrease in new installed capacity in 2011, the Guodian Group, which includes Longyuan and Guodian Electric, had 370 MW more installed capacity than the previous year, maintaining its position as the largest wind farm operator in the country. Almost no private sector enterprises have entered into competition in this area due to the high investment costs.

Second, a market for smaller-scale distributed wind farms with no dominant enterprises is emerging. In many of the areas with lower-quality wind resources there is motivation to develop low-speed wind farms. Similar to wind farms in Germany and Denmark, many of these projects are of a smaller scale with distributed features, and are closer to end consumers. Through such projects, China’s wind energy industry would potentially open up to private investment or foreign enterprises.

Table 7: Top 10 wind farm enterprises with the largest new installed capacity in 2011

Wind farm operator	Capacity (MW)	Market share (%)
Guodian Group	3,860.5	21.9
Datang Group	2,235.1	12.7
Huaneng Group	2,229	12.6
Huadiang Group	1,104	6.3
Guohua	1,094.5	6.2
China Power Investment	866.3	4.9
China Resources	796.1	4.5
Guangdong Nuclear Power	527	3
Beijing Jingneng	372	2.1
Suntien	343.6	1.9
Others	4,202.9	23.9
Total	**17,630.9**	**100**

Sources: Li et al. (2012)

Table 8: Top wind farm enterprises with the largest grid-connection capacity in 2011

Wind farm operator	Capacity (MW)
Guodian Group	9,812.9
Datang Group	6,581.0
Huaneng Group	5,743.0
Huadiang Group	2,353.0
Guohua	2,837.1
China Power Investment	2,200.6
China Resources	2,124.0
Guangdong Nuclear Power	1,382.8
Beijing Jingneng	1,340.3
Others	13,460.4
Total	**47,835.6**

Sources: Li et al. (2012)

4 A description of specific cases of innovation

This research adopted two criteria for case selection. First, to describe an innovation path event, the case had to be a detailed event that led to change in China's technology path. Second, the case had to contain sufficient information to show the key influencing factors that made this change in innovation path happen. The cases would hopefully also illustrate the causal relationship between the influencing factors and the change in the technology innovation path.

4.1 GoldWind 1.2 MW turbine technology development

4.1.1 Background information

GoldWind was founded in 1998 and has its headquarters in Xinjiang. As one of the earliest wind energy corporations in China, it developed many wind energy businesses, including wind turbine design and manufacturing, wind resource assessment and wind farm operation. According to 2011 and 2012 data, GoldWind is the largest manufacturer of wind turbines in China and the second-largest globally. With strong, internationalised R&D capabilities, GoldWind has become the world's largest manufacturer of permanent magnet direct drive (PMDD) wind turbines. Currently, GoldWind has branches and factories located in six continents.

GoldWind experienced several key technology innovation events during its development. This case describes how GoldWind obtained its technological capacity and illustrates GoldWind's changes in innovation direction historically and for the future.

The process of accumulating GoldWind's innovation capacity was long, with three important stages. The first stage dated back to the 1980s when GoldWind began developing and marketing 600 kW and 750 kW units that led the Chinese wind energy market. From this small innovation capacity base, GoldWind then established a joint research mechanism with Vensys to develop 1.5 MW and 2.5 MW direct drive wind turbines, which occupied around 20% of total production capacity in 2012. These wind turbine models will dominate the market in China for the next 3 to 5 years (Maximilian Hinz, Copenhagen Business School, interview 2012). During this second stage, GoldWind initiated an international collaboration strategy that had a significant influence on its later development. In Stage Three, after implementing its internationalisation strategy, GoldWind is developing in-house innovation capacity for key products for the future, including 6.0 MW and 10 MW wind turbines for offshore operations.

4.1.2 Technological innovation event of the 1.2 MW wind turbine

The first joint research project, on a 1.2 MW wind turbine, is the most important of the above events, and provides an example of how China is obtaining advanced wind power technology through international research collaborations.

GoldWind had begun learning from foreign technologies long before its joint research on the 1.2 MW turbine. In 1997, the Xinjiang New Wind Company, the predecessor of

GoldWind, licensed 600 kW wind turbines from Jacobs to obtain the capacity to build what were then the largest wind turbines in China. Soon afterwards, GoldWind obtained a license from Repower for its 750 kW turbine. In both cases, GoldWind insisted that technician and researcher training was included in the contract. Chinese engineers were sent to Germany for operational training, while experts from Jacobs and Repower went to China to provide on-site training. Through mutual communication and a hands-on teaching process, GoldWind greatly improved its technological capability and successfully produced 600 kW and 750 kW turbines in 1999 and 2001, respectively. These experiences formed the foundations for collaborative research in 2004. Wu Gang, the CEO of GoldWind, realised that GoldWind did not have sufficient R&D capacity for independent innovation at that time, and promoted a 'dumb-bell' business model for the firm. At one end, the firm would develop its design and assembling capacity to meet market needs; at the other, market investigation and service would be central to competitiveness.

In 2003, GoldWind embarked on the collaborative design of 1.2 MW magneto-electric direct drive wind turbines with Vensys. Unlike the manufacturing firm Repower, Vensys was a design firm that was looking for a partner with the manufacturing capability to realise its turbine design. The decision to collaborate with GoldWind, however, was not straightforward. GoldWind had previously produced doubly fed induction generators of 600 kW and 750 kW, but Vensys only designed gearless turbine technology (direct drive, gearless wind turbines) which was uncommon in terms of both technology and markets. GoldWind needed to consider many factors before choosing this new technology as a key innovation path. The advantages were that gearless turbines have less weight, lower costs, and fewer parts for maintenance and replacement. GoldWind finally decided to take up the challenge, and by 2005 had built a prototype 1.2 MW turbine and installed it in the Da Ban City wind farm for pilot testing. This became the first wind turbine of more than 1 MW produced in China.

GoldWind learned much from the collaboration and improved the magneto-electric direct drive technology to independently produce 1.5 MW (2007), 2.5 MW (2009) and 3.0 MW (2009) turbines, having already commercialised the 2.5 MW and 3.0 MW products. In summarising the key factors for the success of GoldWind, Wu Gang , the CEO of GoldWind, emphasised that *"insisting on collaborative research, rather than licensing technology or purchasing turbine design solutions, made GoldWind strong in independent technology development,"* (Media interview 2010).[6]

GoldWind continued its internalisation process by purchasing Vensys in 2008. With 70% ownership, GoldWind gained control over the direction of future R&D and access to Vensys' intellectual property. Wu Gang believes that it was important to give Vensys sufficient freedom in design and technology transfer to maintain its top design capacity. At the same time, GoldWind invested in Vensys to build new manufacturing capacity in Europe to compete in foreign markets. This was also very useful for Vensys, as it could improve the quality of its designs through 'learning by doing'. GoldWind has now established a global R&D network of three research centres, in Beijing, Xinjiang and Germany, and has a strong indigenous design ability along with a large number of patents.

6 http://blog.sihna.com.cn/wpsp89600

4.1.3 Summary and conclusions

GoldWind represents a successful Chinese wind energy manufacturer that has obtained the most up-to-date technology and enlarged its market share both domestically and internationally. Similar patterns appear when we study how other Chinese wind energy manufacturers obtained their core technology, although slight differences exist between the cases. In the 1980s and 1990s, technology was mainly obtained through donation by foreign governments or equipment imported using loans from foreign governments. Although in-house innovation has consistently been supported by national research plans, the poor innovation capacity of firms prevented them gaining cutting-edge technology through indigenous innovation. The 2000s saw the pattern of technology gain changing to a commercial merger model: Chinese wind energy manufacturers used the profit they gained from manufacturing equipment to purchase R&D labs or companies with design capacity or to license the latest technology from international competitors. This trend came to a gradual halt recently, as mature technology is no longer available for purchase or licensing. Chinese wind energy firms, actively or passively, turned to the strategy of indigenous innovation.

The clear movement from importing technology to commercial mergers and then to indigenous innovation illustrates the innovation path taken by Chinese wind energy development over the past 30 years.

4.2 Jiuquan wind farm construction – a large-scale deployment project in China

4.2.1 Background information

Located in the northwest of China, Gansu province has rich wind resources. Jiuquan City lies in the west of Gansu province, near the border of Xinjiang province. Jiuquan has a land area of 19.2 km^2, with potential wind resources of 210 GW and currently available storage of 82 GW. It is geographically and climatically suitable for large-scale, concentrated wind farm construction.

Of the seven planned state wind bases, Jiuquan Wind Base was the first wind base of more than 10 GW to be constructed. In May 2008, the NDRC approved the construction of Jiuquan Base in its 11th Five-year Plan. To begin Stage I, with a designed capacity of 3.8 GW, the construction of four wind farms commenced in Changma, North Bridge, Ganhekou and Qiaowan. In 2009, construction began on another 16 Stage I wind farms. By the end of 2011, 3600 MW of capacity had been installed and connected to the grid, with 200 MW still under the connecting process. Once the Jiuquan Stage I projects were progressing smoothly, the NDRC began planning for the Stage II projects with a designed capacity of 5 GW. In May 2011, the preparatory work for Jiuquan Stage II was approved by the National Energy Bureau. By the end of February 2013, the program passed a technology test and was ready for implementation.

Stage I of the 10 GW Jiuquan Wind Base, with a built capacity of 5,500 MW, was completed in 2010. Stage II is gaining construction approval through the NDRC. Each stage involves construction of wind farms at different places within the wind base, for example, North Bridge, a site with good wind resources. The three main Stage I wind farms are owned by the State Development and Investment Corporation (SDIC), the China

Power Investment Corporation (CPI) and HydroChina, respectively. At North Bridge SDIC Wind Farm, 66 turbines of 1.5 MW each, manufactured by Dongfang Electric, were installed. Construction began in 2009, with connection to the grid in 2010. By the middle of 2012, North Bridge had generated a total of 410 million kWh of electricity. At the CPI Wind Farm, 200 turbines of 0.75 MW each, manufactured by GoldWind, were installed in its first and second stages. In its third stage, installation continued with 134 turbines of 1.5 MW each, manufactured by Sinovel. The HydroChina Wind Farm was begun in 2009 with the installation of 67 GoldWind 1.5 MW turbines and 67 Sinovel 1.5 MW turbines. The project was connected to the grid at the end of 2009, and had generated 4.87 million kWh of electricity by the middle of 2012. There are detailed schedules for the second stage of construction of each wind farm, and also project concessions for each. An open bidding process attracted various equipment manufacturers and electricity companies, independently or jointly. For example, Sinovel won an 1,800 MW contract for the first stage of construction of the Jiuquan Wind Base.

4.2.2 The innovation path for deployment at the Jiuquan Wind Base

According to data from local Gansu governments and investigations by the Chinese Academy of Engineering (CAE), Jiuquan Base mass-installed domestic 1.5 MW turbines, supplemented with a few larger foreign turbines. Construction of the wind base began around 2008, at a time when domestic manufacturers had started producing 1.5 MW wind turbines. Domestically produced turbines were cheaper than foreign products and more adaptive to the local environment. Therefore, although the foreign turbines are larger, the domestic turbines become the mainstream equipment in the early stages of China's large-scale wind energy deployment. With the scale of wind farm construction increasing and standards of technological stability and security improving, foreign companies such as Vestas and Gomesa are now more involved in large-scale wind farm construction. Both foreign companies and technology experts believe that foreign turbines are more competitive in the China wind energy market due to their life-cycle cost advantages.

4.2.3 Technological difficulties at the Jiuquan Wind Base

The main problems at the Jiuquan Wind Base and other large-scale wind deployments relate to electricity storage and transmission. The majority of the electricity generated at the wind base is transmitted to Lanzhou, the capital city of Gansu province 1,000 km away, through a 750 KV line. This line was built in 2010 when the total generation capacity in Jiuquan was only 1,390 MW. With a wind energy generation capacity of 4,040 MW in 2011, this 750 KV transmission line is far from sufficient.

Jiuquan Base also has to face other technological challenges: Unlike some of the European countries, Gansu province does not have consistent wind resources. Wind resource prediction technology is sorely needed to make better use of Gansu's resources and for connection to the grid with sufficient control. However, it is not possible to simply use existing technology because China has wind distributions that no other country has encountered. Also, off-grid accidents have occurred when wind farms have been unable to pass the low voltage ride through (LVRT) test (Wang 2012). Problems relating to LVRT have been solved by top foreign manufacturers, especially in small-scale wind turbine applications; however, Chinese turbines have only passed tests in the laboratory. In practice, turbines in China are often affected by unstable wind power and grid voltages.

4.2.4 Summary and conclusions

Gansu Jiuquan Wind Base is a typical example of the particular characteristics and problems of large-scale wind energy development in China. Large-scale wind farms require systematic innovation that combines wind turbine manufacture, electricity generation and grid connection. The weakest link puts the whole deployment process at risk. Without a careful verification process, the pattern of large-scale deployment was selected mainly on the basis of geographical and resource quality considerations and, together with quick development, generated many obstacles that became apparent later. Some were technological obstacles, while others related to the mechanism for electricity administration China.

Currently, three main technological issues are expected to affect the pattern of large-scale deployment. Meeting the LVRT standard is essential for wind turbine manufacture, as it will ensure the stability of electricity generation and reduce large-scale curtailment. In terms of grid connection, wind energy relies heavily on the state grid system; it is this system that decides which wind farms can sell electricity to the grid. Therefore, transmitting wind-generated electricity to a grid that is short of energy and providing a stable electricity supply are two main technological targets for wind farms. Additionally, gaining local support for wind farm construction is also essential; public opinion and local government taxation are two main concerns for the industry (Dai / Xue 2014).

4.3 Hui Teng (HT) blade design and manufacture

4.3.1 Background information

Hui Teng is a world-class producer of wind blades in China. Founded in the Baoding Development Area of High-tech Industry in 2001, HT is held by Baoding Huiyang (45% share), China Aviation Group (30% share) and US Meiteng (25% share). Hui Teng began business by producing 600 kW wind blades based on imported technologies, sponsored by a national innovation programme during the 9th Five-year Plan (1996–2000). Its success in producing 600 kW wind blades led to HT being the first Chinese enterprise to have an independent production capacity. However, HT still lacked an accumulation of core technologies, and was experiencing difficulty in finding suitable foreign alliances with which to cooperate on innovation. Thus, HT continued to develop 600 kW and 750 kW wind blades based on imported technologies, and focused on developing customised products that met China’s specific demands, such as low temperatures and dusty environments. These endeavours made HT a strong competitor in the local market. Hui Teng then began to work with various foreign alliances (e. g., CTC in the Netherlands), and used the advances in design to develop large-scale, technologically advanced wind blades. In 2005 and 2006, HT successively launched 1.2 MW and 1.5 MW wind blades. When the Chinese government set goals for localisation and innovation for the wind energy industry in the early 2000s, HT’s market share increased rapidly and in 2006 reached 90% in the 600 kW sector. These achievements cemented HT’s position as the leader in the Chinese market and a significant player in global markets. After 2006, HT initiated a new globalisation strategy. In terms of material provision, HT controlled costs through collaborating with the German company Degussa. In terms of wind energy technology, HT bought out Holland CTC in 2009 and thus acquired top technological innovation and worldwide service provision abilities. Building on the achievements of its global strategy, HT continued to progress in innovation and production. In 2007, after launching its 2MW blade, HT further narrowed the gap between domestic and foreign producers in unit capacity. In 2009, HT's production levels successively broke through 6,000 and 7,000 units. Eight countries, including the United States, Japan and South Africa, were adopting HT's products. Currently, HT has 11 series of products comprising 29 types of blade in total, and is now focusing on R&D for 5 MW offshore wind blades.

Government intervention played a significant role in China's wind market boom and in the growth of innovation capability in local firms. As a representative case, HT has seen benefits not only from its own endeavours but also from influential policies at both the central and local government levels.

4.3.2 Key elements of HT's technological innovation path

R&D support policies

Hui Teng was not able to develop its innovation capacity without governmental R&D support, especially in the initial stages when its technological capacity was weak. In 1999, as a manufacturer of aviation propellers, HT undertook a scientific and technological project of national significance – research into a 600 kW large wind turbine blade. The first prototype was produced in May 2000 and lowered the price of blades to 46% (Hui Teng interview, 2012). Hui Teng then applied for funding for commercialisation from the National Torch Program (Huo Ju Ji Hua). In April 2001, HT's 600 kW blade entered mass production, ending China's total reliance on imported blades.

Through all of the important stages of HT's development, including the design and manufacture of its 750 kW, 1.2 MW, 1.5 MW, 2 MW and 3 MW wind turbine blades, national and local R&D programmes played essential roles. Table 9 lists the major R&D projects undertaken by HT with government support.

Taxation and finance policies

The central Chinese government used taxation policies to promote wind energy. In 1997, the State Council reduced the value-added tax (VAT) for joint ventures and multi-national companies in the energy industry, and reduced import tariffs to stimulate the importation of advanced wind energy technologies. In 2000, the government further exempted wind power equipment for large-scale wind turbines from tariffs and importation VAT, and decreased the VAT on grid-connected wind power from 17% to 8.5%. In 2001, 50% of the VAT applying to wind energy generation was cut to encourage the establishment of joint ventures in China. Import tariffs had been adjusted in 2005 and 2006 to encourage the importation of parts for local assembly. By 2008, Chinese firms had become comparatively competitive, and the government removed the restrictions on import tax rebates and later removed the tax policy interventions for the wind energy industry.

Table 9: Major Hui Teng research projects supported by the government

<table>
<tr><th>Code</th><th>Project period</th><th>Objective of R&D subsidy</th><th>Funding organisation</th><th>Technology</th><th>Date</th></tr>
<tr><td>PR1</td><td>1995-2000</td><td>Blade design for 600 kW wind turbine system</td><td>Ministry of Science and Technology (MoST)</td><td>0.6 MW</td><td>2001.4</td></tr>
<tr><td>PR2</td><td>2003-2005</td><td>Blade design for 1 MW wind turbine</td><td>MoST</td><td>1.2 MW</td><td>2005.5</td></tr>
<tr><td>PR3</td><td>2004-2006</td><td>Blade design for 1.3 MW wind turbine</td><td>MoST</td><td>1.5 MW</td><td>2006.5</td></tr>
<tr><td>PR4</td><td>2006-2009</td><td>Blade for 1.3 MW wind turbine (onshore)</td><td>MoST</td><td>1.5 MW (onshore)</td><td>2007.8</td></tr>
<tr><td>PR5</td><td>2006-2008</td><td>Blade for 2.0 MW wind turbine</td><td>He Bei Bureau of Science and Technology</td><td rowspan="2">2.0 MW</td><td rowspan="2">2007.10</td></tr>
<tr><td>PR6</td><td>2004-2006</td><td>Huge-size wind turbine blade</td><td>MoST</td></tr>
<tr><td>PR7</td><td>2006-2008</td><td>Monitoring technology of wind turbine blade</td><td>MoST</td><td rowspan="5">2.5 MW, 3.0 MW</td><td rowspan="5">2009.2</td></tr>
<tr><td>PR8</td><td>2007-2010</td><td>Technology of advanced wind turbine airfoil</td><td>MoST</td></tr>
<tr><td>PR9</td><td>2007-2009</td><td>Moulding of huge-size wind turbine blade</td><td>State Commission of Science and Technology for National Defence Industry</td></tr>
<tr><td>PR10</td><td>2007-2009</td><td>Blade for 2.5 MW wind turbine</td><td>Baoding Bureau of Science and Technology</td></tr>
<tr><td>PR11</td><td>2009-2011</td><td>Blade for 3.0 MW wind turbine</td><td>Baoding Bureau of Science and Technology</td></tr>
</table>

Source: Hui Teng interview

Finance policies are rarely used directly by central government, although in 1999 the Notice of Further Support for Renewable Energy offered discounted loans for renewable energy projects. Local governments use finance policies more often. For example, Baoding has issued China Electricity Valley bonds and seeks to encourage national- and provincial-level projects to invest in Baoding's wind industry.

Localisation policy

In 2003, the Wind Power Concession Project, issued by the NDRC, set a mandatory minimum localisation rate for newly installed wind turbines of at least 50% in 2003 and 70% after 2004. From 2003 to 2007 five rounds of concession projects were carried out, totalling a cumulative installed capacity of 3,350 MW, which significantly improved the level of localisation rate and promoted the use of wind energy resources by creating a huge market demand.

China repealed the localisation regulation in 2009. *"There was no need for a localisation requirement any more after 2009,"* stated Gao Hu, an expert in the NDRC, during the interview, *"because all Chinese turbines naturally meet the requirement. And foreign turbine manufactures set up local production lines to meet the requirement also."*

Other policies

The central government also introduced a series of policies to promote the rapid, long-term and healthy development of the wind power industry, such as the Renewable Energy Law (NPC 2005), the Mid- and Long-Term Plan for Renewable Energy Development (NDRC 2007) and the 11th Five-year Plan for Renewable Energy Development (NDRC 2008). The government also aimed to establish a wind power industrial service system, equipment standards, a testing and certification system, and national wind turbine and spare part R&D centres through the Document on Promoting Wind Power Industry Development (NDRC / Chinese Ministry of Finance 2006).

4.3.3 Summary and conclusions

Consideration of HT's case indicates that, in the context of global innovation, China's wind policy has had a profound effect on the wind industry, ranging from direct R&D support, through managing imports and localisation, to constructing a market-oriented environment for competition.

For HT, central government R&D funding support was the main driving force for its development during the early stage. From the late 1970s to 1995, there was major support for wind turbine manufacturing from R&D subsidies. Hui Teng derived benefits from these national projects and quickly became a leader in wind turbine blade manufacturing in China. In the second stage, HT established a partnership with a German company to design blades for turbines over 1 MW, and also a close partnership with a Dutch company on a contractual basis. In June 2006, HT's 1.5 MW blade was successfully produced, giving HT a clear development direction that established its leadership in the China wind power market. In the third stage, enterprise internationalisation and R&D globalisation became the main trends, and HT acquired the Dutch company CTC to enhance its blade-design capability.

5 Key elements of the formation of the Chinese wind energy innovation path

The previous sections have explored the overall innovation path taken by Chinese wind energy development, and the individual cases have answered the first research question: it has been clearly shown that the Chinese wind energy sector took a different innovation path from its EU counterparts. In this section, the key elements that brought this innovation path about are explored, with particular focus on contextual changes from the aspects both of policy and of socio-economic development.

Elements that influence innovation path formation normally arise from three aspects: local policy, technological base, and the social and political context. All three factors have influenced the formation of the Chinese wind energy innovation path, playing different roles at different times.

5.1 The role of foreign products and imported technology

The Chinese wind energy sector might not have been developed had there been no foreign technological input. Imported products/technologies had three stages of effect:

5.1.1 Stage One: Foreign donated wind farms served to 'jump-start' the development of Chinese wind energy technology in the 1980s

China began using wind energy equipment in rural areas as an alternative supply of energy. These independent energy systems cannot be counted as 'true' wind energy deployments. At this time, domestic wind energy R&D and scattered pilot wind turbines mainly existed for research purposes. Commercial deployment did not occur until foreign governments began to donate wind turbines to China for the purposes of market exploration and build wind farms in various places in the late 1980s. The Xinjiang Wind Energy Company, the predecessor of GoldWind, was formed to operate Dabancheng Wind farm using a loan from the Danish government. Other wind farms were built in provinces such as Shandong and Zhejiang, and were connected to the grid for the first time in 1988. This milestone represented not only an innovation path change in the sense that China had large wind turbines (over 100 kW) for the first time, but also a deployment innovation path change: given that China had its first commercial wind farm, the operation process served as a training programme for technicians and wind farm experts who later became the backbone of Chinese wind energy R&D.

5.1.2 Stage Two: Imported products and collaborative R&D advance the development of Chinese wind energy technology from the late 1990s to the early 2000s

Imported wind turbines allowed Chinese wind energy development to take a short-cut to advanced technologies. Domestic R&D was only at the 55 kW level when 150 kW and 250 kW wind turbines were purchased using foreign government loans. Such purchases provided Chinese engineers and researchers with access to advanced wind energy technologies from other countries. Reverse innovation was also used for this purpose, leading to several key changes in the technological innovation path. For example, from

1992 to 1995, the Xinjiang Wind Power Plant produced key components of the 300 kW wind turbine based on knowledge gained through reverse innovation. In the mid-1990s, China's first batch of 100 kW wind turbines was successfully produced through a coalition between the Zhejiang Institute of Mechanical and Electrical Engineering and the Hangzhou Power Equipment Plant, using a reverse design from the 120 kW turbines imported from the Danish firm Bonus.

Firms with a relatively strong R&D base began to collaborate with foreign firms on R&D projects. The most successful practitioner of licensing was GoldWind. Based on licensing agreements relating to 600 kW turbines from Jacobs and 750 kW turbines from Repower, GoldWind quickly gained knowledge of key technology and know-how to enhance its technology capability, and successfully produced 600 kW and 750 kW turbines in 1999 and 2001, respectively, using local design and local parts. As in other industries, the process of 'importing technology, digestion, and absorption' became a valuable model through which the wind industry could make technological improvements (Dai / Xue 2014).

Many wind turbine manufacturers established joint-venture projects and carried out collaborative research. For example, GoldWind and the German firm Vensys began a collaborative project on 1.2 MW turbines in 2004. Garrad Hassan collaborated with Zhejiang Windey and Baoding Tianwei, and Aerodyn collaborated with Shanghai Electric, CSIC Haizhuang, United Power and Guangdong Mingyang. However, leading wind energy technology companies such as Vestas and GE preferred not to set up joint ventures with Chinese firms, but built their own branch factories in China to protect their intellectual property. Meanwhile, the costs of wind turbines decreased rapidly.

Early on, Chinese wind companies had overcome technological gaps through importing, but this stage did not last long because the high cost of imported wind turbines prevented China from increasing the scale of deployment. Lowering the cost of wind turbines through localisation therefore became the main goal for the following period.

5.1.3 Stage Three: Foreign firm acquisition improves the indigenous innovation capacity of the Chinese wind energy sector around 2008

Foreign technology played a different role when domestic firms became more mature in terms of their technology capacity. Up until 2008, domestic wind turbines had a 75.6% share of the local market, and leading domestic players gradually gained the capacity to conduct indigenous R&D at each stage of the wind turbine life-cycle.

Mergers and acquisitions (M&A), especially in relation to foreign R&D sectors or wind design companies, were key methods for domestic firms to take a short-cut to core technologies and a share in foreign markets, and to speed up their building up of indigenous innovation capacity. For example, GoldWind acquired a 70% share of Vensys, its former partner in collaborative design, in 2008 and then began to establish a global R&D network of three research centres, in Beijing, Xinjiang and Germany. In doing so, it became a leading wind energy company with strong indigenous R&D and design abilities and independent intellectual property rights. Not only did these lead to foreign sales of USD 140 million in 2009, but they also provided GoldWind with the long-term competitiveness that helped it regain its leadership in the domestic market in 2013.

5.2 The role of public policy

5.2.1 Long-term wind energy policy guarantees continuous technology innovation

In addition to specific policies aimed at stimulating the wind energy industry, the overall national strategy on renewable energy development also effectively ensures investment in this industry. China began adjusting its development strategy immediately after 1993 when the Kyoto Protocol was implemented, and since then the design and implementation of low-carbon development has been repeatedly emphasised in various policies. This long-term, stable policy framework set up strong incentives for domestic and foreign firms to invest in the technology and the market.

Foreign wind energy firms were highly motivated by China's consistent wind energy policies.

> *A long-term policy supporting wind energy development makes us [Vestas China] not worry about the future market. For example, the 2020 target of emission reduction, various five-year plans, the Renewable Energy Law and many national development targets set up the policy framework to ensure the quick development of the industry here in China* (Tom Pellman, Government Relationship Department, Vestas, China).

Beginning with the REL in 2006, China's renewable energy policy is unlikely to be weakened or cancelled. Such strong confidence in the Chinese market encourages foreign wind energy companies to invest more in local R&D and market exploration. During the downturn in the Chinese wind energy market around 2009 and 2010, foreign firms did not reduce their input into China with a view to future market competition.

5.2.2 Deployment policy influences formation of the technology innovation path

Deployment strategy had a clear pull effect on core technology development. Chinese wind deployment technology has been dominated by few models, mainly those of 1.5 MW and 2.5 MW capacity. Two factors of the deployment process led to this. First, when designing and constructing a large-scale wind farm, it is vitally important to investigate the location. Given a large piece of flat land in the northwestern part of China with its rich wind resources, wind resource distribution data showed only small differences within the area. Thus, the same type of wind turbine could be adopted throughout the area without loss of efficiency (interview with Zhu Rong, China Meteorological Administration). It would therefore be easy for wind farm developers to select the most popular wind turbine within their budget. The large-scale deployment strategy was pursued from 2004 when 1.5 MW wind turbines were starting to dominate the international and domestic markets. Similarly, 2.5 MW wind turbines dominated wind farm construction projects when domestic manufacturers became capable of providing cheap turbines through reverse innovation or joint R&D projects.

Second, the rapid speed of wind farm development in the nation left little room for developers to slow down the construction process while they waited for better turbine technology to appear. This partially explains why larger wind turbines, such as those of 3 MW capacity, have been little used in the over 10 GW wind bases.

The unit size of wind turbines has continued to increase. Before 2005, wind turbines with unit capacities of 250 kW, 600 kW and 850 kW dominated the Chinese market. Imported wind turbines above 1 MW were introduced during the first and second concession bidding and were quickly adopted: in 2007 about 51% of the annual newly installed market were held by wind turbines above 1 MW. The average wind turbine capacity rose to 1.0489 MW and in 2010 increased to 1.4668 MW, when large wind turbines became mainstream products. More recently, there has been considerable progress in multi-MW wind turbine production and application in China. A 3 MW wind turbine has been put into mass production and installed successfully, and a prototype 5 MW wind turbine has been produced.

5.2.3 Assorted policy instruments jointly influence indigenous innovation

Government interventions are viewed as effective measures for expediting the innovation process of an emerging technology, starting from early-stage development. In China, government intervention in the wind energy industry took the form of a range of innovation policies. This package of policy instruments included R&D activities, market exploration policies, a strategic agenda, tax and financial policies, technology standards for shaping innovation capabilities, and incentives to attract private investment. Various policies were adopted in the various different developmental periods of the Chinese wind energy industry with the goal of creating the largest wind market in the world, and influenced the technology innovation path. The content of this package of policies is very similar to national policies in the EU and India.

The policies cover three stages in the development of wind energy technology. First, a mature market for climate technology was not possible in the early stage, and the government therefore had to intervene to form an initial market. At the embryonic stage of wind energy development, the Chinese government focused on manufacturing capacity by encouraging the importation of production lines. Subsidies and tax deductions were offered to encourage the importation of wind energy technologies. With almost no domestic market existing in the 1980s, a commercialisation policy (i.e., demonstration projects) functioned as the initial market formalisation tool. When China took steps to enlarge the domestic market, more policies were adopted, such as the five rounds of concession projects. Detailed policy tools were selected that considered specific contexts, such as the distribution and quality of wind resources, the technological base, and the share of state-owned enterprises.

Second, after the climate technology market emerged, the government began to adopt a policy instrument package. For example, R&D might stimulate research capacity and generate a technology push effect; tax incentives, the national energy policy and environmental regulations might generate a market pull effect; technological standards could provide a fair and competitive environment for the market. At this stage, climate technology was to be encouraged in the same way as other important technologies.

It is worth noting that the innovation path for Chinese wind energy technology is still developing. There is evidence of different features from the corresponding path in the EU but, as yet, no evidence for concluding that these paths will be different in the long run. As Chinese wind energy technology develops to a more mature stage, R&D activities will be encouraged and the power of low-price competition may be reduced. The process of internationalisation and global competition requires advanced technology, high-quality processes and a competitive environment, and this may influence China’s future wind energy technology.

5.2.4 Administrative changes to influence the future of wind energy innovation

In 2013, China restructured the energy authority by combining the Energy Bureau and the State Electricity Regulatory Commission. The new agency is emphasising the significance of the wind energy industry and its corresponding development strategies. In addition, the new agency is committed to working with the relevant ministries to increase R&D subsidies on renewable energy, and it is hoped that many specific solutions will be developed to improve the large-scale wind farms in the northwest, solving the wind energy curtailment and grid connection difficulties. Many firms in China (including foreign firms) will also benefit from the government's plans to build distributed networks in the southeast of China and wind farms offshore.

5.3 The role of economic development and internationalisation

5.3.1 Internationalisation as the main mechanism influencing the path of innovation

China's wind energy industry obtained its technology improvements in a different way to the EU and India. Innovation events have been influenced by features of the wind energy industry and China's developmental context.

The wind energy industry involves production process at both the lower and upper levels of the value chain. Tower manufacture, for example, is a simple mechanical engineering process with very little value-added technology. At the other extreme, blade design, turbine design and manufacture, and control system design are all high-technology features. Therefore, while a strong technological background is not necessary to enter the industry, a strong technological capacity is required to lead the industry.

China's wind energy industry began in a similar way to other manufacturing industries, such as toy manufacture: by importing production lines, gaining a share in international markets via low prices (usually with a low-quality product), and gradually gaining the core technological capacity to move towards the higher end of the value chain. At the same time, because the Chinese wind energy industry began growing in the late 1980s, it also learned lessons from other manufacturing industries. For example, China knew that the industry would have a low resistance to uncertainty if the core technology was not obtained. The goal for advancing the innovation path of the wind energy industry was very clear: the ultimate aim was indigenous innovation capacity. This could be achieved through internal R&D, technology transfer, or commercial mergers, and China considered all three methods. Being a 'latecomer facing a fast-growing market' in wind energy development, it was impossible to rely on internal R&D to bring China up to the first rank. Technology transfer, while useful, has embedded shortcomings – a company or a country will never become a leader by using transferred technology without a strong capacity for internal R&D. Commercial mergers can solve this problem to some extent by greatly narrowing the technology gap between the purchaser and the purchased. Purchasing a research design company or a firm with a strong R&D capacity would also increase future research competitiveness.

China now has another potential innovation path, in which more domestic companies will push the development of wind energy technology through internal R&D. A recent example is GoldWind, the Chinese wind turbine manufacturer with the strongest R&D capacity, regaining its leading place in the market in 2011 and 2012 while its largest competitor, Sinovel, lost this leading position due to rapid expansion and reduced R&D capacity. The path of technology innovation for deployment is not as clear as that for core technology because commercial deployment only began in 2003 after a strong push from the government. Technology innovation in the deployment sector is still under exploration by both the industry and different levels of government. The last section therefore mainly sketches the current deployment patterns and ongoing changes, and indicates how deployment innovation may influence the development of core technology.

5.3.2 National economic paradigm influenced wind energy innovation path

The wind energy sector does not exist independently of other economic sectors. Equipment manufacturing, materials, transportation, and even city planning influence and are influenced by its development. The developmental strategy for the wind energy sector is therefore inevitably influenced by strategies in other sectors.

For example, when the Chinese wind energy market started to boom in the early 21st century, it was still low in technological capacity and small in market size. Wind energy began to form a sector after the ‘Ride the Wind (Cheng Feng) Project’ with the clear sectoral goal of upgrading domestic technology capacity (Lew 2000). In this period, the sectoral goal was fulfilled by policy initiatives influenced by a macro policy framework. After 20 years of economic reform, new strategies were called upon in all sectors to avoid overdependence on foreign technologies under the original equipment manufacturer (OEM) model. This period saw two major changes at the macro policy level: the ‘success through quality’[7] and ‘promote trade through science and technology improvement’[8] policies introduced in 1996 and 1999, respectively, which placed improvement in domestic technology on the policy agenda. Meanwhile, the concept of ‘science and technology is the primary productive force’ was still guiding other policies at the macro level. At the level of specific policy initiative design processes, it became essential to understand, absorb and re-invent domestic manufacture technologies based on imported technologies. As a result, technological improvement became embedded in the macro policy framework.

This change in macro strategy guided the strategic re-direction of the wind energy sector. This period saw much importation activity. China not only imported wind turbines from front-runners such as Denmark and Germany, but also gained access to advanced technologies via technology licensing and joint ventures. These enabled China to bypass wind energy technologies below 600 kW and increase its technology-absorbing capacity (Li et al. 2008; Xie et al. 2011).

It is therefore expected that, under the current national strategy emphasising indigenous innovation, the wind energy sector will also follow this general trend in making an increase in R&D capacity a higher-priority sectoral strategy.

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7 Source: State Council 1996 ‘Programme for Quality Revitalisation’.

8 Source: ‘Action plan to promote trade through science and technology improvement’, issued by the MoST and MoFTE (Ministry of Foreign Trade and Economic Cooperation) in 1999.

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