The Chinese innovation system for wind energy: structure, functions and performance

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Declaration of originality

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Abstract

Energy technology innovation is critical to transitioning to a sustainable energy system. The energy R&D expenditure worldwide has increased recently to combat the challenges of climate change, energy security and energy affordability. Emerging economies play an increasingly important role in energy technology innovation. As the largest energy producer and consumer, China's energy technology innovation has an influential impact on the global energy system.

China has emerged as the largest investor and user of renewable energy technology. The country accounts for 33% of the global wind power capacity, far ahead of the USA (17%) and Germany (11%). Among the world's ten largest wind turbine producers, half of them are Chinese enterprises. China's rapid development of wind technology attracted wide interest. The two key questions are a) how does China compare with leading countries in wind technology innovation, and b) what factors have been responsible for China's successes and failures.

This thesis draws upon innovation systems theory and innovation metrics to answer these two questions. It is found that China has caught up fast in inputs and certain outputs but significantly lags the leading countries in other aspects especially outcomes. The relative weakness in invention capability represents China's most obvious bottlenecks. It demonstrates that the country's system performance is highly related to the fulfilment of the system functions which are affected by the presence and capability of the structural elements.

The thesis is offered as a comprehensive study on China's wind energy innovation system. It presents useful lessons on facilitating the generation, adoption and diffusion of renewable energy technology as well as the challenges that need to be addressed to smooth the energy transition globally. The research makes methodological, empirical and theoretical contributions to the innovation systems literature.

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Publications

Journal papers

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Conference/working papers

Rui Hu, Jim Skea, Matthew Hannon, 2016. *The drivers for China's wind energy innovation system*. BIEE 11th Oxford Research Conference, Oxford, United Kingdom.

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Rui Hu, 2015. *Innovation and technological capability of the Chinese wind turbine industry: An international comparative study*. Young Scientists Summer Program 2015, IIASA, Austria.

Book chapters

Chapter 3 Theorising energy innovation (co-author) in Energy Technology Innovation for the 21st Century: Accelerating Energy Revolution, Edward Elgar, 2017 (in progress).

Chapter 4 Measuring energy innovation (lead author) in Energy Technology Innovation for the 21st Century: Accelerating Energy Revolution, Edward Elgar, 2017 (in progress).

Chapter 9 Wind energy (lead author) in Energy Technology Innovation for the 21st Century: Accelerating Energy Revolution, Edward Elgar, 2017 (in progress).

Table of Contents

List of tables

List of figures

Abbreviations and acronyms

2DS	2°C Scenario
863 Plan	High Technology Research and Development Plan
973 Plan	Key Fundamental Technology Research and Development Plan
AMNEs	MNEs in advanced economies
BNEF	Bloomberg New Energy Finance
BP	British Petroleum
CAS	Chinese Academy of Sciences
CDB	China Development Bank
CDM	Clean Development Mechanism
CNY	Chinese Yuan (currency)
CO_2	Carbon dioxide
CPC	Cooperative Patent Classification
CWEA	Chinese Wind Energy Association
DOE	Department of Energy (USA)
DTU	Denmark Technical University
EIS	Energy innovation system
EMNEs	MNEs in emerging economies
EPO	European Patent Office
EU	European Union
EWEA	European Wind Energy Association
FIT	Feed-in-tariff
GDP	Gross domestic product
GJ	Gigajoules
GW	Gigawatt
GWEC	Global Wind Energy Council
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual Property Right
IRENA	International Renewable Energy Agency
IS	Innovation system
JPO	Japan Patent Office
koe	kilogrammes of oil equivalent
kW	Kilowatt
LCOE	Levelized cost of electricity
M&A	Mergers and acquisitions
MEP	Ministry of Environmental Protection (China)

MIIT	Ministry of Industry and Information Technology (China)
MITI	Ministry of International Trade and Industry (Japan)
MNE	Multinational enterprise
MOF	Ministry of Finance (China)
MOST	Ministry of Science and Technology (China)
MW	Megawatt
NDRC	National Development and Reform Commission (China)
NEA	National Energy Administration (China)
NIS	National innovation system
NREL	National Renewable Energy Laboratory (USA)
OECD	Organisation for Economic Co-operation and Development
PATSTAT	Worldwide Patent Statistical Database
PCT	Patent Cooperation Treaty
PIAS	Patent Information Analysis System
PPP	Purchasing power parity
PV	Photovoltaics
R&D	Research and development
RD&D	Research, development and demonstration
REN21	Renewable Energy Policy Network for the 21st Century
RSP	Renewable Standard Portfolio
S&T	Science and technology
SCI	Science Citation Index
SCIE	Science Citation Index-Expanded
SETC	State Economic and Trade Commission (China)
SIPO	State Intellectual Property Office (China)
SME	Small and medium-sized enterprise
SOE	State-Owned Enterprise
SPIC	State Power Investment Corporation (China)
t	Tonnes
TIS	Technological innovation system
TWh	Terawatt hours
UN	United Nations
USPTO	US Patent and Trademark Office
WoS	Web of Science
WTO	World Trade Organisation
WWII	World War II (or the Second World War)

Chapter 1 Introduction

1.1 Overview

This thesis is concerned with the structure, functions and performance of China's wind energy innovation system. It aims to answer: a) how does China compare with leading countries in wind technology innovation, and b) what factors are responsible for China's successes and failures. The analysis is built upon the innovation systems theory, particularly the frameworks of technological innovation system (Hekkert et al. 2007b) and energy technology innovation system (Wilson and Grubler 2014). A set of quantitative and qualitative methods (e.g. scientometrics, historical analysis, case study) are adopted to examine the innovation system in a historical perspective.

The research topic is motivated by four reasons. First, China has emerged as a global player in the energy sector, and the energy innovation delivered by China will have a profound impact on the global energy system. It is important to understand how energy innovation occurs in China, how effectively the energy innovation system operates and what lessons can be learnt. Second, China's economic development over the past decades has been highly related to the growth of technological capability. China's experience of technological catch-up and innovation may provide useful implications for other developing countries. Third, within a short period, China has developed as the largest user of wind energy and is closing technological gaps to the leading countries. The lessons learnt from China will provide useful lessons for facilitating wide-scale innovation in renewable energy technologies. Fourth, China exercises a strong degree of hierarchical control and emphasises state ownership, which makes its mode of technological innovation different from many Western countries. The analysis on China can reveal the differences in innovation patterns between a market and state-directed economy.

The thesis makes methodological, empirical and theoretical contributions to the scholarly liteature on innovation systems. To be specific, a) an indicator framework that consists of inputs, outputs and outcomes is proposed to assess the performance of energy innovation systems; b) an in-depth "structure-functional analysis" is conducted to understand the correlations between structural elements, functional patterns and system performance; c) a case study of a pioneering

Chinese firm (Goldwind) is carried out to illustrate how a particular structural element fulfilled and reacted to the specific system functions; d) a combination of quantitative and qualitative methods as well as insightful tables and diagrams are employed to produce convincing results; e) a wide range of English and original Chinese references (e.g. journal articles, magazines, newspapers and government documents) that have rarely been analysed are documented to provide new and more comprehensive evidence.

This chapter introduces the thesis. Section 1.2 presents the crucial importance of energy innovation and the contextual background in which China decarbonises electricity by developing renewable energy technologies especially wind power. Based on this, section 1.3 proposes two research questions that are to be answered throughout the thesis. Section 1.4 presents the main points of the thesis chapters.

1.2 Background

1.2.1 Energy innovation for mitigating climate change

Energy technology innovation is vital to mitigate global climate change, ensure energy security and stimulate economic prosperity (IEA 2015). The energy sector emitted about 80% of global carbon dioxide, highlighting the urgent demand for decarbonizing the energy system through innovative technologies (OECD 2015c). It is indicated that decarbonisation of electricity supply and increased efficiency of electricity end-use comprise the two key components of achieving the 2DS target[1] (IEA 2014).

Electricity will become the largest final energy carrier by 2050, with a share of over 25% in total final energy consumption (IEA 2015). In order to meet the 2DS target, a massive shift towards clean electricity production and efficient use of electricity are needed. Among the multiple clean energy sources of electricity, wind power and solar PV have the potential to reduce CO_2 emissions by 22% annually under the 2DS (IEA 2015). Thanks to technological innovations, the efficiency and reliability of wind and solar have improved significantly, and are almost ready to compete with fossil fuels (IRENA 2016).

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[1] The 2°C Scenario (2DS) refers to the carbon emissions trajectory that aims to limit the average global temperature increase to 2°C by 2100 with a 50% chance. It represents a prime focus of the Energy Technology Perspectives produced biennially by the International Energy Agency (IEA).

Technological innovation is a cumulative and continuous process. Government support in all stages of energy technology innovation (i.e. research, development, demonstration, deployment and diffusion) will play a crucial role in fostering novel energy technologies (Huenteler et al. 2016, IEA 2015). Identifying the most suitable policy tool is key to success. The recent research affirms that energy technology innovation should be analysed at the system level to avoid fragmented policies (Wilson and Grubler 2014).

The global transition to a low-carbon energy system requires cross-country cooperation. Multi-stakeholder initiatives set to mitigate climate change can create shared objectives and build greater confidence in ongoing development (IEA 2015, Suzuki 2015). Besides, international collaboration on knowledge and technology transfer, regulation and market analysis, and policy dialogue will support the scale-up of energy technology innovation (Noseleit 2017, IEA 2015). Collective activities strengthen the mechanism to inform the parties of technology innovation trends and facilitate local innovation.

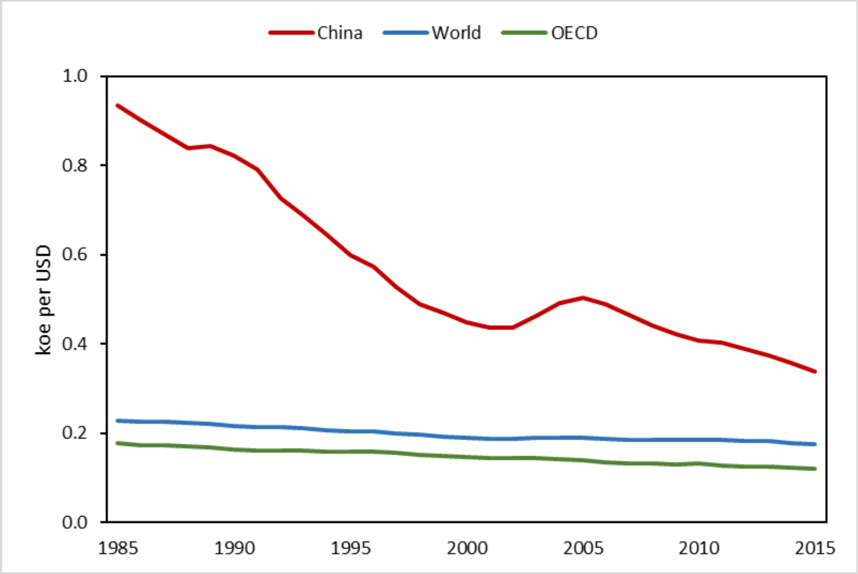
Emerging economies are playing an increasingly important role in energy technology innovation (FS-UNEP Collaborating Centre/BNEF 2016). The overall share of RD&D budgets in energy technologies by emerging economies is rising, and in some areas, the technology gaps are narrowed to some extent (IEA 2015). IEA (2015) argues that energy technology innovation in emerging economies could deliver the greatest and fastest advance towards the climate mitigation goals. A thorough analysis of a large emerging economy's energy technology innovation can provide useful lessons on how to spur wide-scale energy innovation.

1.2.2 China's role in the global energy system

China has grown to be the largest energy producer and importer. It overtook the USA as the world's largest oil importer in 2013, and over 60% of its oil consumption is imported (BP 2016). In 2014, China sealed a historic $400 billion gas deal with Russia to satisfy soaring energy demand (Anishchuk 2014). Energy security has been prioritised on the nation's policy agenda. The Chinese President Xi Jinping called for efforts to revolutionise the energy sector in the production, consumption, technology and regulation (Xinhua News Agency 2014).

A closer look at China's energy sector shows that a bigger issue may lie in its low energy efficiency. Among the world's ten biggest economies, China's energy intensity is the second highest (0.338 kilogrammes of oil equivalent per GDP, koe/GDP) after Russia (0.501 koe/GDP), nearly two times higher than the world average and 2.8 times more than the OECD member states (see Figure 1-1). Over the past decade, China produced 45% of the world's crude steel (World Steel Association 2016). The energy intensity of the Chinese steel industry is 23 GJ/t crude steel while that of the U.S. steel industry is 15 GJ/t crude steel (Hasanbeigi et al. 2014).

Figure 1-1 China's energy intensity compared to the OECD and world average



N.B. a) Energy intensity is calculated as energy use per unit of GDP; b) koe - kilogrammes of oil equivalent.

Source: Calculated from BP (2016)

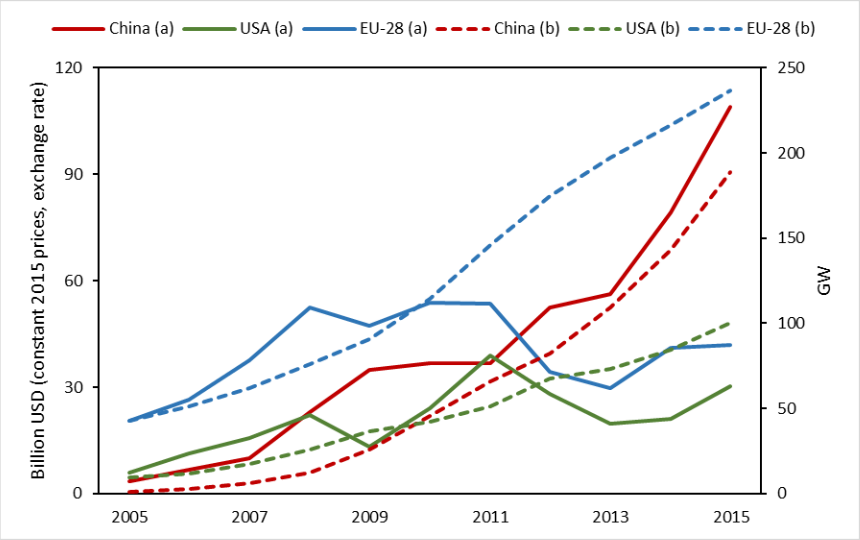
Energy efficiency is likely to address China's energy concerns as it can potentially double the country's economy with the current amount of energy consumption if it can be improved to the world average level. However, the improvement of energy intensity is not easy as it is highly related to the outlay of energy-intensive industries (Yu and He 2012) and China's present position in the global industry specialisations (Lin et al. 2014).

Environmental issues have become a major concern in the Chinese society. In 2015, 78.4% of the 338 prefecture-level cities performed below the national air quality standard, and 22.5% of the 480 monitoring sites suffered from acid rain (MEP 2016). Driven by the concerns of climate change, energy security and air pollution, China is transitioning towards a low-carbon energy sector. The share of coal in China's primary energy consumption dropped to 64% while non-fossil fuels climbed to 12% (BP 2016). In 2015, the country accounted for 38% of the world's investment in wind and solar energy, even larger than the US (17%) and the EU-28 (9%) combined (BNEF 2016). China spent about 110 billion USD on wind and solar energy R&D and asset finance, compared to 42 billion USD by the EU-28 and 30 billion USD by the USA (see

Figure 1-2). Regarding R&D expenditure, China already became the largest investor in wind and solar since 2012.

Given China's huge energy production and consumption as well as the tremendous investment and installed capacity of renewable energy technologies, the country's energy technology innovation has an influential impact on the global energy system. It is valuable to understand how energy technology innovation is delivered in China, how effectively the energy innovation policy works and what lessons can be learnt.

Figure 1-2 Wind and Solar energy investment (left) and installed capacity (right)



N.B. The investment refers to R&D expenditure and asset finance.

Source: BNEF (2016)

1.2.3 China's technological catch-up

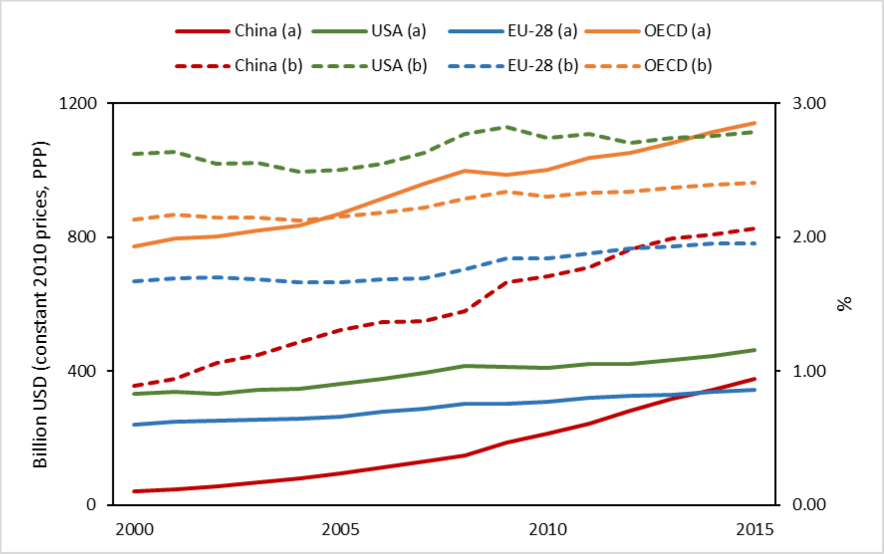
Following three decades of a high rate of economic growth, China has emerged as the second-largest economy globally. Among many successful factors, the openness of the national innovation system and the growth of technological capability may represent the real basis of China's economic miracle. The rise of Alibaba (Barreto 2014), Huawei (Shih 2014) and high-speed railways (The Economist 2013) affirms that China is an absorptive state and can innovate by improving infrastructures and capabilities with home-grown and foreign knowledge and technologies (Nesta 2013).

Institutional reforms have acted a central role in revolutionising China's innovation system. In 1978, a Chinese government delegation paid a visit to Western Europe. This visit impressed

Chinese policymakers with the prosperity of Western science, technology and business, and paved the way for cooperation between Chinese and Western enterprises afterwards. The well-recognised "economic reform and opening-up policy" embraces foreign capital and technology. Accession to the WTO integrates Chinese firms into global networks of production and innovation, through which they learn and develop technological and managerial capabilities. It is in this context that the Chinese manufacturing sector including the energy equipment industry has developed rapidly.

The economic growth model in the past that rested on energy and resource-intensive industries, low labour cost and pollution-intensive manufacturing is not sustainable now. China faces the challenges of promoting structural reforms and transforming into an innovation-driven economy. China's competitive advantage as a global manufacturer is challenged by increasing labour cost, the emergence of new technologies (e.g. automation) and environmental concerns. The *Medium-and-Long Term National Plan for Science and Technology Development (2006-2020)* established a set of targets and policies to build China as an innovative nation by 2020 (Chinese State Council 2010).

Figure 1-3 China's gross R&D expenditure (left) and R&D intensity (right)



N.B. R&D intensity is calculated as percentage of R&D expenditure per GDP.

Source: OECD (2016a)

China has strengthened R&D investment considerably since then. The country's R&D intensity climbed to 2.1% in 2015 (see Figure 1-3), surpassing the EU-28 (1.95%), slightly lower than the OECD average (2.4%). It is projected that China will head to be the top R&D spender by around 2019 (OECD 2014). The recently released *13th Five-Year Plan on Scientific and Technological Innovation (2016-2020)* aims to increase R&D intensity to 2.5% by 2020 (Chinese State Council 2016). In the field of the energy sector, China invested 13.7 billion USD in wind and solar power between 2005 and 2015, compared to 15.2 billion USD by the EU-28[2] (BNEF 2016).

R&D investment seems to be paying off. China ranks 2nd in publication citations (Chinese State Council 2016) and 3rd in PCT patent applications[3] (OECD 2016a). In 2015, China filed 26 thousand PCT applications compared to 53 thousand by the USA, 43 thousand by Japan and 18 thousand by Germany (OECD 2016a). The country has improved considerably in "hardware" for innovation such as physical and financial infrastructure but is still weak in "software" such as innovative entrepreneurship (OECD 2016b). China has developed as a science superpower that can compete with leading countries, but the efficiency and effectiveness of innovation depend on the improvement of "software" and the functioning of the innovation system. It is valuable to examine the innovation policy and innovation process of China in a particular technology field.

1.2.4 Ride the wind

Wind energy is one of the most mature renewable energy technologies and has become increasingly competitive against the traditional fossil fuels (IRENA 2016). China is a latecomer in wind energy but has caught up fast. The country's first grid-connected wind farm was not constructed until 1986 with three wind turbines imported from Denmark (He and Shi 2010, Shi 1997). China's wind power capacity increased from 1GW in 2005 to 145GW by 2015, accounting for 33% of global wind power capacity, far ahead of the USA (17%) and Germany (10%) (BP 2016). Wind power (3.2%) has surpassed nuclear (2.9%) and become China's third largest source of electricity generation, only after coal (72%) and hydro (19%). Regarding installed capacity, wind power (145GW) is five times larger than nuclear power plants (27GW) (CEC 2016).

The Chinese wind power industry has experienced three stages (see Figure 1-4): initial demonstration (1985-1996), early industrialisation (1997-2005) and widespread diffusion (2006-present). China started exploring wind turbine technology in the 1950s but had not integrated

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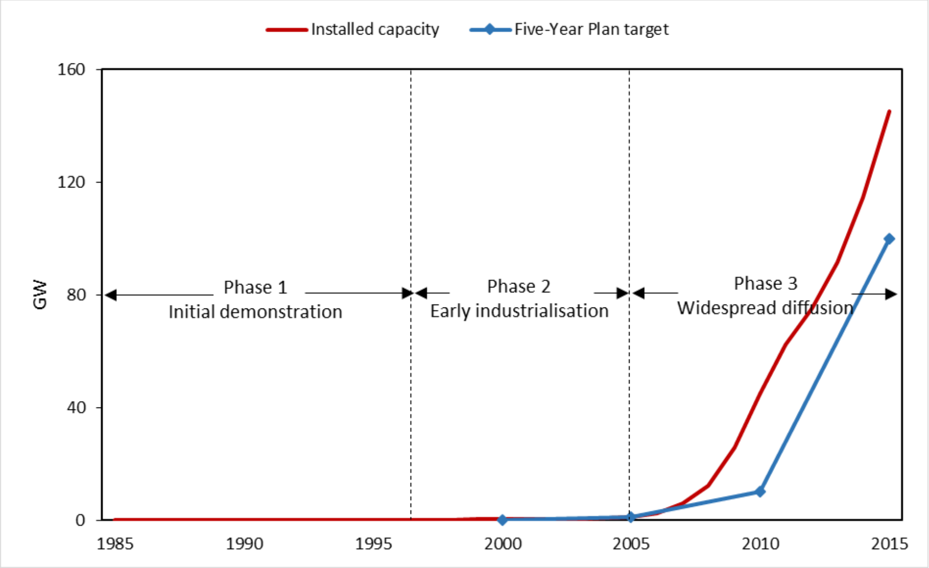
[2] The data includes R&D expenditure and asset finance and is converted into constant prices with 2015 as the base year.

[3] PCT refers to the Patent Cooperation Treaty. By filing one patent application under the PCT, applicants can simultaneously seek protection for an invention in about 150 countries.

wind power into the electricity grid until the late 1980s. Among many other reasons, technological deficits and the lack of regulation represented the most significant factors hindering China's development of wind power (Dai et al. 2014). In other words, an innovation system for wind energy was not well established.

Figure 1-4 China's cumulative wind power capacity



Source: Shi (2007) and CWEA (2015b)

Before 1996, few policies aimed at facilitating wind technology or the wind power industry. When the world's leading wind turbines reached 600kW in 1994, China had just begun to fund research on 200kW turbines. The Chinese government used foreign donations, grants and special loans to build demonstration projects, but the pilot wind projects had little influence on national policy for adopting wind power. By 1995, China heavily relied on foreign wind turbine technology, and only five experimental wind farms were operating in China, with a total capacity of 36MW.

After twenty years of the "economic reform and open-up policy", new strategies were called upon to avoid overdependence on technology licensing. Thus, technological innovation became a prime focus of the policy agenda. The "*Riding the Wind*" programme (1997) facilitated the establishment of two assembly plants for technology transfer through joint ventures. Goldwind was established in 1997 from a public research institute as the first domestic wind turbine producer. The *Guidelines for Speeding-Up the Localisation of Wind Turbines* (2000) was issued to accelerate technological catch-up.

To do so, China prioritised wind technology through some national major S&T programmes, such as "*High Technology Research and Development Plan (863 Plan)*", "*Key Fundamental Technology Research and Development Plan (973 Plan)*" and "*Torch Programme*". In parallel, Chinese wind turbine manufacturers attempted to grow technological capability via technology licensing, joint R&D, technology acquisition and indigenous innovation. Currently among the world's ten largest wind turbine makers, half of them are Chinese enterprises (REN21 2016). Component suppliers have achieved considerable progress too, particularly in the fields of the blade, generator and gearbox.

China is attempting to construct a wind turbine innovation system. It is very challenging for developing countries as many essential elements of the innovation system may be missing (Liu and White 2001). The thesis will show that China has built the necessary elements of the system. Recently, the *12th Five-Year Plan for Wind Power Development* (NEA 2012) used the term "wind technology innovation system" in a practical way to smooth innovation and strengthen China's technological capability in wind energy. The existing literature analysed China's wind innovation from different perspectives, but few have examined the wind turbine industry in a systemic approach. This thesis aims to narrow the gap by employing an innovation system approach with a set of quantitative and qualitative methods.

1.3 Research questions

The rapid development of China's wind turbine industry has attracted much interest. This thesis intends to unfold the technological change of China's wind energy innovation system by answering: a) how does China compare with leading countries in wind technology innovation, and b) what factors are responsible for China's successes and failures. The lessons learnt from China may provide useful lesson on facilitating the generation, adoption and diffusion of renewable energy technologies.

Question 1: How does China compare with leading countries in wind technology innovation?

Currently, only a limited number of studies have discussed China's wind innovation capability, and there exists a mixture of opinions regarding whether China has grown as a leading innovator. While some hold that China experienced technological leapfrogging (Ru et al. 2012b), others, however, argued that China remained dependent on foreign technology (Zhao, Guo, and Fu

2014). The inconsistent conclusions like this are partly caused by the lack of quantitative metrics and data. Many studies have merely relied on qualitative analyses, which makes the results highly subject to personal conceptions

To adequately characterise China's progress in wind technology innovation, an indicator framework consisting of inputs, outputs and outcomes will be developed and applied to the wind turbine industry across China, Denmark, Germany and the USA. It is used to identify China's position in terms of cross-country comparisons. To minimise the impact of country size on the results, comparisons will be made at both national and firm levels. National-level comparison describes the country's aggregate performance, whereas firm-level assessment reflects innovation gaps across firms. A combination of national and firm-level comparisons enables conducting a more robust evaluation.

Question 2: What factors are responsible for China's successes and failures?

An innovation system (IS) may suffer from systemic problems (Bleda and del Río 2013, Negro, Alkemade, and Hekkert 2012a). The technological innovation system (TIS) (Hekkert et al. 2007b) has proved to be a useful tool for identifying the systemic problems. This research will adopt the TIS framework to understand the factors that affect China's wind energy innovation by studying the structural elements and the system functions.

Firms are the focal agents of a TIS. Many IS studies have focused on macro institutional structure but overlooked the roles played by particular firms in the emergence and take-off of the TIS. Chinese manufacturers have striven to catch up with the frontiers via technology imitation and innovation. In some cases, they evolved from a wind farm developer to a wind turbine maker or even changed technological trajectory to realise technological catch-up. Investigation of a firm's innovation dynamics uncovers the interactive relationships between a structural element and the system functions.

China's wind energy innovation occurred in the historical context of global networks of production and innovation. This has obviously affected China's energy innovation strategy and policy. Chinese firms improved technological capability by taking advantage of both national and international factors. A conductive national innovation system is necessary but may not be sufficient for international technology transfer (Lewis 2007). The thesis will include transnational linkages into the analysis of China's wind energy innovation system.

1.4 Thesis outline

The thesis consists of 10 chapters organised around four central dimensions of a TIS – system performance, functional patterns, structural elements and dynamics of innovation in a firm. The main points of each chapter are summarised as follows.

Chapter 2 conducts a comprehensive literature review on wind energy innovation in China and other countries. There is not a consensus about whether China has become a leading innovator in wind technology. This is due to the lack of quantitative metrics. Existing research explains China's rise in wind power from different perspectives and emphasises differing aspects that they considered most relevant. A systemic approach is needed to avoid the fragmented evidence. The chapter also reviews the innovation stories of other countries across Europe, North America and Asia. Some research gaps and opportunities are identified.

Chapter 3 derives the analytical framework for this thesis based on the understandings of the multiple IS approaches, namely national innovation systems (NIS), technological innovation systems (TIS) and energy technology innovation systems (ETIS). ETIS is used to derive an indicator framework for measuring system performance, and the "structure-functional analysis" of the TIS framework along with the incorporations of transnational linkages and micro-level dynamics inspired from NIS studies are employed to examine the structural elements and functional patterns of the system.

Chapter 4 describes the research design and analytical methods for the thesis. To appropriately answer the proposed questions, a "mixed methods" approach consisting of six concrete methods is employed to generate both quantitative and qualitative evidence. These methods are bibliometric analysis, patent analysis, scaling analysis, historical analysis, semi-structured interviews and case study. It discusses the usefulness and limitations of the proposed methods, and how they are used in this research. A list of data sources for studying China's wind technology innovation is presented.

Chapter 5 derives an indicator framework that incorporates *input, output and outcome* metrics into the energy technology innovation chain (i.e. research, development, demonstration, market formation and diffusion) for measuring the performance of EISs. It covers the whole innovation chain and allows to identify the strengths or weaknesses across different innovation stages. It represents a conceptual and methodological contribution to metrics for energy innovation system (EISs).

Chapter 6 applies the proposed indicator framework to the wind turbine industry across China, Denmark, Germany and the USA. The quantitative results from national and firm level comparisons are very consistent. They point to the fact that China has made remarkable achievements in certain inputs, outputs and outcomes, but there still exists a considerable innovation gap with respect to leading countries in many other aspects. Suggestions are proposed for future research on improvement of indicators and methods.

Chapter 7 maps out the structural elements (i.e. actors, networks and institutions) of China's wind turbine innovation system, describes their presence and status quo and summarises their key features. It shows that China has built the necessary elements of the innovation system, and the current challenge is to improve the capability or quality of individual elements. The features observed from the structural analysis can partly explain China's performance in wind turbine innovation (as indicated in Chapter 6). The structural problems may inspire policymakers to formulate innovation policy.

Chapter 8 measures the system functions via a set of quantitative and qualitative indicators. The results show that there exists a close correlation between the presence and capability (quality) of structural elements, the functioning of the innovation system and the system's overall performance. To be specific, China's functional patterns are different from developed countries; the system performance depends on the fulfilment of the system functions; the system's functionality relates to the presence and capability (or quality) of structural elements.

Chapter 9 conducts a case study on the dynamics of Goldwind's technological learning and innovation in a historical perspective. It shows that the success of Goldwind's transition from a technology imitator to an innovator owed to the fulfilment of and the firm's interactions with the system functions, particularly Entrepreneurial Activities, Knowledge Networks and Resource Mobilisation. This chapter contributes to the scholarly literature on the interactive relationships between a structural element and the specific system functions.

Chapter 10 presents the major conclusions, policy lessons and contributions in terms of novelty. The competence of China's wind energy innovation system has yet to be improved by better governance in the areas of structural elements and functional patterns. China's experience demonstrates that developing countries can achieve technological catch up through adequate innovation strategy and policy, but it can be a hard and slow process. The findings improve our understandings of innovation systems theory, the methods and data used for analysing innovation systems, and wind technology innovation in China.

Chapter 2 Literature review

The last chapter described the background for China's development of wind energy and proposed the research questions. This chapter turns to review the scholarly literature on China's wind energy innovation to identify the research gaps and opportunities. The literature that discussed wind energy innovation in Europe, North America and Asia is also examined to show the differences between developed and developing countries in innovation patterns and catch-up processes.

Section 2.1 presents the debate on China's technological capability of wind turbine industry. Section 2.2 reviews the mechanisms that Chinese firms have used to absorb technology developed in foreign countries. Section 2.3 focuses on the transnational linkages of China's wind energy sector while section 2.4 examines the literature about the drivers and barriers in China's wind energy innovation. Section 2.5 reviews wind innovation patterns across Europe, North America and Asia. Section 2.6 summarises the main findings of the literature review.

2.1 China's technological capability in wind energy

There is a mixture of opinions on whether China has become fairly competitive in the technological capability of wind turbine industry. Some hold that China has experienced a technological leapfrog, others, however, argue that the technological capability of Chinese wind turbine industry remains limited. The existing studies have mainly relied on qualitative interviews that are often subject to personal conceptions. A few scholars quantified China's ratio of home-made technologies but failed to identify the technological gap (e.g. patent filings, turbine sizes and time lags) to foreign leading players. Quantitative metrics are required to make more accurate evaluations.

Ru et al. (2012b) argue that China has experienced a technological leapfrog in wind energy but lags behind the leading players in developing leading turbines. Klagge, Liu, and Campos Silva (2012) argue that China is still reliant on foreign technology while Gosens and Lu (2013b) address that China needs to import core components, especially high-quality steel bearings and control systems that are often of high values. Zhao et al. (2012) contend that Chinese manufacturers lag foreign leading enterprises in most aspects (e.g. technology advance, component supply, product range, performance & reliability, certification) except price and factories layout.

Gosens and Lu (2013b) conducted interviews with Chinese firm managers who argue that Chinese firms have caught up in the capability of producing multi-MW turbines, but a quality gap with the global leaders remains. Zhao, Guo, and Fu (2014) also emphasise the quality gap that thousands of turbines were out of order during the wind power accidents in 2011. They conclude that China lacks the ownership of key Intellectual Property Rights (IPRs) and that the quality and reliability of wind turbines have to be improved (Zhao, Guo, and Fu 2014).

Urban, Nordensvärd, and Zhou (2012) reveal that foreign companies are sceptical about whether indigenous innovations are happening in China. They think that Chinese firms are mainly involved in technology licensing and acquisition (Urban, Nordensvärd, and Zhou 2012). China's wind energy sector relies on international technology transfer and joint R&D in the first stage and on local content requirements to reduce competition from foreign firms in the second stage (Urban, Nordensvärd, and Zhou 2012). Currently, the reliance on both factors has decreased, and some Chinese firms have become competitive as a result of strong state leadership and financing (Urban, Nordensvärd, and Zhou 2012).

Zhou et al. (2012) argue that before 2005 Chinese firms were unable to imitate foreign technology and had less motivation to innovate, so they just licensed technology from foreign companies. After having improved manufacturing capability through licensing, they were eager to build design capability (Zhou et al. 2012). Compared to independent R&D, technology collaboration with foreign companies allows them to develop technology quicker and probably less risky. Zhou et al. (2012) argue that joint R&D has helped Chinese firms train technicians and improve technological capability – they filed more patents after partnering with foreign firms.

However, the gap between Chinese and foreign firms in technological capability as well as the Chinese firms' short-term pursuit of profits rather than improvement of technological capability have caused joint R&D to be less effective than expected (Zhou et al. 2012). Zhou et al. (2012) argue that joint R&D is just an enhanced version of technology licensing. Chinese companies must pay foreign companies 20 million USD on average for using even the basic technology although the Chinese firms provide most of the funds for the joint R&D projects (Zhou et al. 2012). Also, Chinese companies must pay a royalty of 7% per turbine on average and an additional 5% of sales if exporting overseas (Zhou et al. 2012). Regarding IPRs, Chinese companies may own the IPRs of the joint R&D projects or share with their partners, but they cannot sell them without the authorization of the foreign partner who may license the technology freely (Zhou et al. 2012).

Wang, Qin, and Lewis (2012) find that Chinese firms independently develop about 43% of turbine models, jointly develop 21% with foreign firms, and acquire the remaining 36% from foreign technology licensing or domestic technology transfer. Wang, Qin, and Lewis (2012) warn that Chinese firms' innovation capability is unlikely to sustain the industry's further development as few Chinese firms are capable of producing world-class innovations and many rely on foreign designs that do not suit well the local Chinese climate conditions.

2.2 China's technology-seeking approaches

China is a latecomer in wind turbine technology. The firms adopted a variety of methods to obtain the technical know-how and improve technological capability. This section reviews the types of technology-seeking approaches the Chinese firms used.

Lewis (2007) argues that the limited technological capability of developing countries makes their entry to a new technological field difficult. International technology transfer may be a solution, but it is unlikely that leading companies will transfer proprietary knowledge to companies which may become potential competitors (Lewis 2007). It is even risky to transfer technology to developing countries where an identical but cheaper turbine may be manufactured (Lewis 2007). How companies in developing countries can acquire the technological know-how and IPRs, how domestic and international factors shape their technology development strategies, and how different strategies may result in differing performance are important issues for catching-up countries (Lewis 2007).

Zhou et al. (2012) argue that technology licensing has made Chinese firms rely heavily on foreign companies. It is unsustainable for China to develop the industry by just sticking to the supply of expensive foreign technology. Qiu, Ortolano, and Wang (2013) report that licensing contracts involve an up-front fee and maybe royalties as a fraction of the revenues from sales, but exporting is usually prohibited. Brown (2002) reveals that Goldwind was charged about €5,000 royalty per turbine produced (600kW) for using Repower's technology and was prohibited from exporting to overseas markets.

Compared to technology licensing, joint R&D involves more advanced technologies, does not require royalty payments and allows the IPRs solely or jointly owned by the Chinese firms (Qiu, Ortolano, and Wang 2013). It represents an attractive option for Chinese firms which are eager to narrow the technological gap between the leading companies. Qiu, Ortolano, and Wang (2013) find that joint R&D projects usually take place between a Chinese manufacturer and a foreign R&D focused company. The foreign firms are often design companies and do not carry out manufacturing, so they are less concerned about competition from Chinese manufacturers (Qiu, Ortolano, and Wang 2013). The cooperation enables the foreign partners to gain market access to the Chinese market, earn extra profits and stimulate technological upgrading (Qiu, Ortolano, and Wang 2013). For the Chinese side, they can acquire advanced technology, learn design capability, save royalty payments and own the IPRs (Qiu, Ortolano, and Wang 2013).

In recent years, a few Chinese firms embarked on international development by establishing R&D units in innovation-intensive regions or acquiring foreign design companies that encountered development bottlenecks. In 2008, Goldwind owned 70% of Vensys' share to develop 3 MW turbines. In 2009, XEMC purchased Darwind for €10 million (Yan 2009). Mingyang established an R&D centre in Demark to cooperate with Risø-DTU (Mingyang 2010) and launched an offshore R&D centre at North Carolina University in the USA (Quilter 2012). Ru et al. (2012b) argue that Chinese firms may enhance their technological capability by tapping into foreign knowledge bases, but the central issue is whether they can absorb and integrate the dispersed knowledge.

To mitigate global climate change, the United Nations has encouraged developed countries to transfer low-carbon energy technology to developing countries through the Clean Development Mechanism (CDM). Lema and Lema (2013) find that as of April 2009, China and India had been the largest receivers of CDM projects in wind energy. It was estimated that technology licensing and international trade accounted for 56% and 29% of China's CDM projects respectively (Lema and Lema 2013).

The CDM acts as another path to gain access to advanced foreign technology, but there is a gap in the literature on the effectiveness of these CDM projects on the development of local technological capability. Lema and Lema (2013) point out that the required capability may have been developed independently of CDM because the identified transfer mechanisms had been adopted by China and India in wind power projects before the occurrence of CDM. The transfer mechanisms identified by Lema and Lema (2013) are a bit conventional. Many MNEs now use new mechanisms such as collaborative R&D and M&A to acquire the technology they need.

The literature shows that Chinese firms are transitioning from simply licensing the technology to conducting joint R&D with foreign companies in the hope of acquiring more advanced technologies. A few firms have ventured to acquire foreign design companies and even established R&D subsidiaries in overseas knowledge clusters to accelerate technological growth. However, the effect of these technology transfer mechanisms on the development of technological capability deserves further research.

2.3 The international linkages for China's innovation

China does not develop wind technology in isolation but has learnt technology and policy experience from other countries. The transnational linkages of China's wind turbine industry have underpinned Chinese firms' technology-seeking approaches. This section reviews the literature that highlighted the role of international linkages (not contained to the wind energy sector) in facilitating China's technological innovation.

Slepniov et al. (2015) describe how Envision Energy built links to the Danish innovation system. The firm was established in 2007 and has developed as the world's 9th largest wind turbine manufacturer (REN21 2016). Three years after its establishment, the firm acquired its first research subsidiary in Denmark. The local presence allows the firm to access skilled R&D personnel and excellent test facilities in Denmark (Slepniov et al. 2015). Envision Energy has also managed to set up R&D centres in the USA and Japan and attracted world-class engineers from recognised MNEs (Slepniov et al. 2015).

The international linkages of China's innovation system are not limited to wind energy sector but also to many other industries. Zhang and Gallagher (2016) hold that solar PV technology innovation in China has been a process of combining national and international innovation segments. One notable example is the international flows of human resources - entrepreneurs and scientists return with advanced knowledge (or technology) to found or enter new firms. Zhang and Gallagher (2016) find that over 61% of the board members of the three largest Chinese PV firms have studied or worked abroad.

Fan (2015) argues that returnee companies in the high-technology industries play an important role in facilitating China's access to global financial and technology resources that otherwise may not be available in domestic Chinese market. The companies had sourced finance from foreign capital markets when the Chinese ones were not mature enough. These returnee companies have transformed or significantly facilitated the development of the respective areas (Fan 2015).

Jin, Zhang, and McKelvey (2015) have examined four start-ups in nanotechnology in Suzhou Industrial Park (SIP). They find that the founders and many co-founders have studied or worked abroad, especially in the USA and Japan. Also, knowledge diffusion takes place between governments regarding public policies. The SIP is jointly managed by the Chinese and Singaporean governments, through which Chinese administration officers can learn experience from their Singaporean partners (Jin, Zhang, and McKelvey 2015).

Gifford et al. (2015) have studied Geely and Huawei's technology seeking in Sweden, namely Geely's purchase of Volvo Cars and Huawei's hiring of Ericsson employees. Volvo Cars Corporation (VCC) is recognised for high quality and safety while Geely produces lower-quality vehicles. Shufu Li, Founder and Chairman of Geely, said that the acquisition gave VCC access to Geely's low-cost production lines and market convergence in China, while Geely was able to take advantage of VCC's high-quality brand and advanced technologies (Gifford et al. 2015).

Gifford et al. (2015) argue that the acquisition of key personnel by Huawei is 'surgically precise'. The firm once faced the challenge of the lack of talent in telecommunication R&D. This type of talent was relatively abundant in Sweden thanks to the supply of trained engineers from local universities and the location of the telecommunication giant Ericsson. Huawei offered favourable conditions (nearly 50% more salary) to hire Sweden's skilled labour, particularly those who previously worked in Ericsson and were the company's key personnel (Gifford et al. 2015).

Zhang and Gallagher (2016) argue that by locating their operations in innovation-intensive regions, Chinese firms may be able to access technical knowledge and market information that cannot be available from the domestic innovation system. Gosens and Lu (2013b) hold that technological innovation is a transnational phenomenon in the low-carbon energy sector. The lagging domestic innovation system can benefit from technology diffusion from the leading innovation systems (Gosens and Lu 2013b).

Narula and Zanfei (2005) emphasise that no country can provide world-class competence in all technological fields, even for the most advanced countries. Relying merely on home country competence may lead to a sub-optimal strategy, especially in the age of multi-technology products (Narula and Zanfei 2005). Firms may acquire technology from abroad through licensing or venture abroad to internalise aspects of foreign countries' innovation systems

(Narula and Zanfei 2005). However, no firms may exit completely, rather preferring to maintain both domestic and foreign presence simultaneously (Narula and Zanfei 2005). In this sense, few countries have truly 'national' systems. Some innovation systems are more 'national' than others, so the term is more indicative than definitive (Narula and Zanfei 2005).

Chinese firms have tapped into the global networks of production and innovation. They have R&D units abroad, and many foreign companies have set up production facilities or R&D subsidiaries in China. It is difficult to determine how 'truly domestic' the Chinese innovation system is. The literature shows that it is important for follower countries to improve technological capability by building linkages to the innovation systems of advanced countries.

2.4 The drivers and barriers for China's wind innovation

Existing research has addressed the drivers or barriers in China's wind energy sector from different aspects, with a few having adopted a systemic approach. This section summarises the main points of the current studies.

Gallagher (2014) argues that finance is one of the most important factors that have enabled China to acquire, modify, develop, manufacture and export clean energy technology. Many American firms identify financing as a central challenge in developing clean energy technologies, whereas Chinese firms rarely consider financing as a constraint (Gallagher 2014). Gosens and Lu (2014) find that the China Development Bank (CDB) extended credit lines of $6 billion to Goldwind and $5 billion to United Power to develop wind farms in Pakistan.

Zhao, Guo, and Fu (2014) estimate that China's subsidy for renewable energy was about 33.4 billion CNY between 2006 and 2011 split by wind power (36%), biomass (35%) and solar PV (29%). For wind power, the subsidy increased from 227 million CNY in 2006 to more than 9 billion CNY by 2011 (Zhao, Guo, and Fu 2014). Hu et al. (2013) warn that the government's financial burden will rise significantly in the long run as more electricity is generated from wind turbines.

Surana and Anadon (2015a) compare two models of resource mobilisation between China and India, concluding that resource mobilisation is less efficient in China's wind power industry. The liberalised market in India (vs. China's State-Owned Enterprises model) allows greater competition between foreign and domestic firms and contributes to international competitiveness and substantial exports (Surana and Anadon 2015a). However, the study did not examine the quantified impact of the two models, such as generation capacity, manufacturing capability, market share, patents and job creations.

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

Gosens and Lu (2013b) argue that the relatively short operational history of Chinese wind turbines acts as the major barrier to entering the European and North American markets. The Chinese operational records are not considered by foreign developers even if the turbine models are manufactured based on licenses from globally recognised designs (Gosens and Lu 2014). Gosens and Lu (2013b) argue that the requirement of having a long and solid operational history is disadvantageous for developing economies and will also squeeze out emerging players from the European and US markets.

China's wind energy innovation system has been criticised for several failures. Klagge, Liu, and Campos Silva (2012) note that China suffers from ineffective coordination between industry and innovation policies, few collaborations between industry and university, and the lack of skilled labour and IPR protection. The Renewable Standard Portfolio (RSP) is concerned with installed capacity rather than power generation, so the market is orientated towards cost rather than technology and quality (Gosens and Lu 2014). Collaboration between universities and enterprises is rather weak, and the contribution of universities and institutes to wind technology is quite limited compared to foreign counterparts like Risø-DTU (Klagge, Liu, and Campos Silva 2012).

Gosens and Lu (2014) find that the Institute of Wind Energy at the Shenyang University of Technology acting as a knowledge supplier in China has applied for few patents and has no license arrangements with any foreign clients nor any expectations of such arrangements. Klagge, Liu, and Campos Silva (2012) argue that the number of project contracts commissioned by firms to universities is rather small compared to that granted by the government. University researchers are more interested in publishing papers than establishing links between their research and industrial use (Klagge, Liu, and Campos Silva 2012).

Klagge, Liu, and Campos Silva (2012) hold that the education and training systems related to wind energy develop slowly. '*Wind Energy and Power Engineering*' was not set as a separate discipline at six universities until 2006 (Klagge, Liu, and Campos Silva 2012). There is a severe shortage of skilled labour, especially qualified scientists, technicians and managers. As such, Goldwind has to build its college to educate and train technical professionals (BJX 2011).

Bureaucracy in SOEs represents another barrier. Gallagher (2014) note that the leaders of SOEs are 'politically appointed' and responsible for the firm for a few years rather than 10-20 years. They do not have the personal incentive to make the long-term investment but maximise returns in the short term (Gallagher 2014). Klagge, Liu, and Campos Silva (2012) point out that the large SOEs have relied heavily on foreign technology and been more willing to establish links with foreign partners than domestic universities and institutes. A huge amount of capital is spent by the SOEs to purchase foreign technologies, which crowds out indigenous R&D activities (Gallagher 2014).

Gallagher (2014) argues that overinvestment and scaling-up have characterised China's industrial development in clean energy technology. When an emerging industry shows sign of success, the local governments provide incentives to set up local factories for job creation and GDP growth (Gallagher 2014). In many cases, almost every province pursues the same industry, leading to serious overcapacity. When the products become oversupplied, firms have to compete on cost.

Gallagher (2014) concludes that China's experience is unique and may not be easily replicated. Firstly, the Chinese market is huge which makes the location of almost all kinds of advanced technologies sensible to both Chinese and foreign firms. Secondly, the concerns of energy security and environmental pollution push China to have a longer-term perspective and greater motivation to develop clean energy technology than other countries. Thirdly, the Chinese government has accumulated a huge amount of capital that can be used to develop new technologies. Thus financing is not a big issue. Lastly, China has built a strong industrial base with fast-improved infrastructure and relatively skilled labour, making it easier to quickly import and export technologies.

The existing literature indicates that economic resources, industrial base and public policy, etc. have played a crucial role in stimulating China's wind technology, but the innovation system suffers from some severe problems, including the deficits in knowledge development, interactions among actors and governance of SOEs. These have addressed parts of the innovation system, and a systemic approach is required to identify the systemic problems and avoid partial views.

2.5 Historical lessons from other countries

Wind power has developed as a global industry. The modern wind turbine technology originates in Europe and has diffused to North America and Asia. This section reviews the innovation patterns in these regions to learn historical lessons.

2.5.1 Europe

In 1891, a Danish engineer invented the first wind turbine for generating electricity (Cleveland and Morris 2013). Since the 1980s, the speed of wind power deployment began to accelerate. Denmark, the Netherlands and Germany represent the European pioneers in utilising wind power. Kamp, Smits, and Andriesse (2004) compare the innovation patterns between Denmark and Netherlands in the early years, concluding that the interactions among researchers, turbine producers and users characterised their respective effectiveness of innovation.

Kamp, Smits, and Andriesse (2004) argue that the Dutch government was science-oriented and provided R&D subsidies for ten years so that Dutch engineers can use the pre-existing knowledge of aerodynamics. However, there were not many turbine users until the implementation of investment subsidies in 1986, and after this time, most of the energy companies were not enthusiastic about wind energy (Kamp, Smits, and Andriesse 2004). The misalignment of policies undermined “learning by interacting” among researchers, producers and users. As a consequence, the research results pushed by science were not well transformed and implemented (Kamp, Smits, and Andriesse 2004).

The situation in Denmark was very different (Kamp, Smits, and Andriesse 2004). Learning by searching was much less supported by the innovation system as far fewer R&D subsidies were available in Denmark. However, the other types of learning mechanisms (i.e. learning by doing, learning by using and learning by interacting) performed much better than in the Netherlands. For example, while it was small, investment subsidies were provided at an early stage, which created a larger group of users. The various actors organised themselves through formal and informal networks, which greatly stimulated learning by using and learning by interacting (Kamp, Smits, and Andriesse 2004).

In particular, Kamp, Smits, and Andriesse (2004) emphasise the role of step-by-step learning in Denmark's technology development process. Danish research institutes had a close relationship with turbine producers. They even altered the nature of technology to suit the producer's needs. science-based knowledge gradually replaced hands-on knowledge in contrast to the Dutch system that supplied sophisticated knowledge at the beginning (Kamp, Smits, and Andriesse 2004). Kamp, Smits, and Andriesse (2004) conclude that the actors in the Danish innovation system fitted each other's needs better, which was one of the main reasons for the Danish success.

Andersen and Drejer (2008) investigated the changing patterns of knowledge exchange in the Danish innovation system. They find that the formation and evolution of knowledge networks have been dominantly affected by actors' interests. During the formative stage of an industrial field, firms had incentives to share knowledge and solve problems jointly because they had a shared interest in gaining the basic know-how of the emerging technology and in challenging the established mature technologies. As the industry became mature, the interests of actors changed, and the alignment of interests declined, which ultimately changed the practices of knowledge-sharing. In other words, technological innovation evolved from small networks of like-minded and non-specialised participants to more distributed and inter-organisational networks (Andersen and Drejer 2008, Lema et al. 2014).

Nielsen and Heymann (2012) argue that Germany suffered the same problem as the Netherlands in the early years. When developing and commercialising wind technology, Danish engineers not only established informal and professional networks to exchange information but also actively introduced the technology to the general public. In contrast, social networks in Germany were more fragmented, less established and less effective. Technical ideas and designs varied widely among the German practitioners. Ineffective communication led to early failures in Germany (Nielsen and Heymann 2012).

There were also commonalities between Denmark and Germany. According to Lewis and Wiser (2007), Denmark and Germany had most extensively used export credit assistance, development aid loans or grants to foster the use of their wind turbines in developing countries. Denmark was the first country that promoted aggressive quality certification and standardisation programmes in wind turbine technology. In the early era of the wind industry, the use of Danish-manufactured turbines was mandated, making it very difficult for outsiders to enter the Danish market (Lewis and Wiser 2007).

Lema et al. (2014) argue that country-specific factors (e.g. national policies) caused the similarities in innovation pathways between Denmark and Germany, but firm-level strategies or even international factors affected the differences between them. Public policies are crucial to facilitate innovation but have less impact on the specific choices of innovations (Lema et al. 2014). The decisions on R&D strategies and technological trajectories are primarily determined by private firms (Lema et al. 2014).

Lema et al. (2014) hold that Denmark and Germany have experienced a constant increase in turbine size and quality and their key difference lies in turbine designs - Danish wind turbines include gearboxes while German turbines are gearless (direct drive). In Germany, the direct drive trajectory was shaped by the research carried out at the University of Saarbrücken (Lema et al. 2014). The government partly funded the Danish research on wind turbines, but the designs were shaped by initial and incremental innovations implemented by firms (Lema et al. 2014).

At the international level, Vestas wind turbines have almost become a globally dominant design. However, the partnership between Goldwind and Vensys (based in Germany) have made direct drive the sole technological trajectory of Goldwind, and gearless wind turbines are massively installed in China and potentially diffusing to other countries (Lema et al. 2014). Therefore, innovation pathways are influenced by national policies but may be ultimately determined by firm-level strategies and even international factors (Lema et al. 2014).

The European experience shows that learning by doing, learning by using and learning by interacting has been crucial for wind technology innovation. As the technology becomes more and more mature, the knowledge networks may evolve into other forms. Firm-level strategies have shaped the technological trajectory, but national policies have to a large extent ensured the success of the industry.

2.5.2 North America

The US wind turbine industry started in the early 1970s, driven by incentive policies such as investment tax credits and production tax credits. However, due to the lack of technological advance, the price of wind turbines remained high, and the reliability and performance could not be guaranteed (Guey-Lee 1998).

Norberg-Bohm (2000) compares the two research models of the USA in advancing wind turbine technology - ‘big science’ effort (known as Mod Program) and ‘practice-driven’ innovation. The National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE) jointly administered the Mod Program while the National Renewable Energy Laboratory (NREL) managed the practice-driven component innovation. The NASA and DOE-led program was aimed to apply American expertise in high-technology to build large, reliable and cost-competitive wind turbines (3-5MW). Nearly half of federal spending on wind energy ($200-300 million) was invested during the 1970s (Norberg-Bohm 2000). In comparison, the NREL sponsored innovation for advanced components required that the cost be shared by the private sector so that private firms’ technological innovation can supplement federal-funded research. The consequence was that the big science effort failed to bring about large wind turbines while continuous component innovations proved effective (Norberg-Bohm 2000).

Loiter and Norberg-Bohm (1999) argue that demand-side policies were vital to facilitate the diffusion of wind technology but innovation in the technology per se was greatly required. A series of tax subsidies were carried out to create niche markets (Guey-Lee 1998), but when the tax credits expired, the wind market diminished considerably (Norberg-Bohm 2000). Norberg-Bohm (2000) argues that the market-pull policy was too short to create a sustainable wind power industry. Most manufacturers went bankrupt after the removal of the incentives and were unable to develop the next generations of product designs (Norberg-Bohm 2000).

Regarding technology-push policy, Norberg-Bohm (2000) holds that the inconsistency in funding led to the loss of technological capability and the subsequent need to build that capability, which eventually resulted in the failures of long-term technology development and diffusion. The government must create a long-term and consistent market for an emerging technology, and act simultaneously to support both technology development and market formation through both technology-push and market-pull policies (Norberg-Bohm 2000).

Bird et al. (2005) find that the substantial growth of wind power in the USA since 2000 can be attributed to national policies particularly the Renewable Portfolio Standard (RPS). They emphasise that national policies should take into account the wider context of the energy sector. McDowall et al. (2013) argue that public policies should go beyond “technology-push” and “market-pull” to pay closer attention to the institutional framework.

The story from the US wind power industry tells that there must be alignment between technology-push and market-pull policies. In the early phases of technology development process, incremental and practice-driven innovation may work better than a top-down and big science approach. Institutional change (e.g. creation of legitimacy) may be necessary to adapt to the development of novel energy technologies.

2.5.3 Asia

Wind power technology developed much later in Asia. China and India built their first wind farms in 1986 with Vestas wind turbines while Japan[4] and South Korea emerged recently. The innovation processes have been quite different.

According to Awate, Larsen, and Mudambi (2014), Suzlon, a pioneering Indian firm founded in 1995, established a technology licensing agreement with Südwind at the beginning. When Südwind went bankrupt, Suzlon hired its engineers and started manufacturing in India. In 2000, Suzlon acquired a bankrupt Dutch firm AE-Rotor which had competence in mould and blade design. It then acquired a bankrupt American firm Enron Wind, giving Suzlon the state-of-the-art production lines and technical support. In 2002, Suzlon set up an R&D subsidiary in Germany by acquiring a German firm AX 215 Verwaltungs GmbH.

In 2004, Suzlon set up a joint venture with one of its generator suppliers, Elin Motoren GmbH of Austria. In 2005, Suzlon set up an R&D unit in Denmark to focus on aerodynamics and wind turbine design. In 2006, it acquired Hansen Transmissions of Belgium, the second largest gearbox manufacturer in the world, allowing Suzlon to own the most sophisticated technology for gearboxes and drive trains. In 2007, it acquired a German firm Repower whose product portfolios included the largest multi-megawatt offshore wind turbine. Awate, Larsen, and Mudambi (2014) conclude that Suzlon has incorporated technologies developed elsewhere into its knowledge and technology base.

South Korea entered the wind power industry much later, but Korean manufacturers have rapidly leapfrogged to focus on advanced offshore wind by technology licensing, joint R&D and M&A (Lewis 2011). Lewis (2011) observes that Daewoo acquired German manufacturer DeWind, which gave the firm access to a 1.25 MW model and two 2 MW models, along with R&D facilities and production lines in Germany and the USA. Samsung began co-developing a 2.5 MW onshore wind turbine with UK design firms Romax and Garrad Hassan in 2008 (Lewis 2011). The

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[4] Wind power did not gain much attention in Japan until the nuclear accidents in 2011. Mitsubishi Heavy Industries (MHI) and Hitachi were among the few Japanese firms that produced turbines mainly less than 3.0MW. In 2013, MHI and Vestas established a joint venture to develop offshore wind technology based on Vestas' V164 8.0MW turbine.

company now operates R&D centres, production plants and after-sales service centres in Europe and the USA.

Lewis (2011) highlights that Korean firms have collaborated with or acquired foreign firms that are usually small while Korean companies are often huge conglomerates with significant industry experience and worldwide client base. These advantages ensure them premium financial resources for M&A (Lewis 2011). Due to land availability and wind resource constraints, Korean firms focus on offshore wind and aim at exporting to overseas markets (Lewis 2011).

Lewis (2011) observes that China, India and South Korea have all benefited from national policy support for wind power, but there are limits to understanding their successes based only on a national system of innovation. Technology development strategies adopted by the firms to acquire the technology outside national borders, and the linkages between the origins of technologies among companies in different countries require a wider perspective to study innovation systems (Lewis 2011).

By investigating the national policies implemented by China, India and South Korea, Lewis and Wiser (2007) identify two types of policies - direct and indirect policies. Direct measures target at local manufacturing while indirect policies support wind power utilisation (Lewis and Wiser 2007). Direct support mechanisms include the local content requirement, financial and tax incentives, customs duties, export credit assistance, quality certification, and R&D; indirect support mechanisms include feed-in tariffs, mandatory renewable energy targets and government tendering.

China and India have accumulated technological capability step-by-step, but Japan and South Korea have leapfrogged rapidly to focus on advanced offshore wind technology. The pre-existing industrial base between industrialised and industrialising countries may have a significant influence on technological catch-up, especially when considering that wind turbine involves a range of scientific and technological fields.

2.6 Summary

There has not been a consensus as to whether China has developed as a leading innovator in wind technology. Many of the existing studies have relied heavily on interviews which are subjective and may be influenced by personal conceptions. For example, the opinions from domestic and foreign interviewees are quite different. Quantitative metrics combined with in-depth documentary analysis are required to produce more convincing results.

China's wind energy innovation has been criticised for having severe problems, but the identified problems have appeared to be fragmented and lack data evidence. A systemic approach with quantitative data is needed. Also, the dynamics of innovation at the firm level, as well as the international linkages between domestic and foreign innovation systems, have not been well studied.

The historical lessons from Europe and North America imply that energy innovation policy must pay attention to both technology-push and market-pull sides. A big science approach may not work better than practice-driven methods (see Norberg-Bohm (2000), Kamp, Smits, and Andriesse (2004)). The interactions among researchers, producers and users are extremely important. National policies and institutions are pivotal to facilitate innovations, but firm-level strategies ultimately shape the technological trajectory.

Industrialised and industrialising countries may vary significantly in innovation strategies and innovation pathways. China and India have built technological capability step by step while Japan and South Korea leapfrogged rapidly to advance offshore wind technology. The pre-existing technological capability and industrial base may have a significant impact on a country's technological catch-up.

Based on the literature review, the research gaps and opportunities are identified:

- Quantitative indicators are required to evaluate the performance of a country's energy innovation system. The existing studies have suffered from merely relying on qualitative interviews which may be quite subjective.
- The scholarly literature has emphasised parts of the problems in China's wind energy innovation system. A systemic approach is needed to diagnose the systemic problems and avoid the fragmented evidence.
- The innovation pathways between developed and developing countries can be very different. The functional patterns and international linkages of innovation systems in developing countries have not been well studied.
- The existing research has mainly focused on the macro institutions and policy analysis and lacks micro level analysis of the innovation dynamics of a firm embedded in the wider innovation system.

This thesis aims to narrow these gaps by employing an extended TIS framework and carrying out the analysis by both quantitative and qualitative data. The next chapter is to derive an analytical framework for studying China's wind energy innovation system.

Chapter 3 Theoretical foundations

Many studies have analysed China's wind energy innovation from different angles and emphasised the factors that they considered most relevant (see Chapter 2). However, innovation is systemic in nature (Fagerberg 2005), requiring a systemic perspective to identify systemic problems.

Academic views on the innovation process have shifted from the traditional linear model to innovation systems (ISs), such as national innovation system (NIS), regional innovation system (RIS), sectoral innovation system (SIS), technological innovation system (TIS) and energy innovation system (EIS). The multiple ISs may be regarded as variants of a single generic IS approach (Edquist 2005). When the analysis is focused on the geographical dimension, a particular country or region determines the boundaries of the system; in other cases, the main interest is a sector or technology (Edquist 2005). Whether the context should be national, regional, sectoral or technological, depends on the questions to be addressed. This thesis is concerned with the structures and processes that stimulate or hamper innovation in a technological field. Thus, the NIS and TIS frameworks suit better[5].

This chapter intends to derive an adequate framework for studying China's wind energy innovation system by drawing upon the IS approach. In the first place, section 3.1 defines the concept of innovation. The conceptual elements of NIS, TIS and EIS frameworks are presented in sections 3.2 3.3 and 3.4. Section 3.5 proposes the analytical framework for the thesis. Section 3.6 summarises the main points of this chapter.

3.1 The concept of innovation

The concept of innovation was coined by Schumpeter (1934) who regarded economic development as a dynamic process driven by innovation. Schumpeter saw innovation as 'a new combination of existing resources'. The scholarly literature on innovation studies has grown

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[5] Cooke (1992) and Malerba (2002) have respectively coined the terms "RIS" and "SIS".

tremendously (Fagerberg and Verspagen 2009), but the boundary of the concept of innovation has become ambiguous (Fagerberg 2004).

Innovation has been conceptualised by a variety of labels, such as radical innovation, incremental innovation, discontinuous innovation, imitative innovation, as well as architectural, modular, improving, and evolutionary innovations (Garcia and Calantone 2002). The concepts of social innovation (Amable 2000, Mumford 2002), eco-innovation (Pujari 2006, Rennings 2000), sustainable innovation (Schot and Geels 2008), and grassroots innovation (Seyfang and Smith 2007) gained much interest recently. However, the lack of consistency in operationalizing innovation may lead to "*incongruent categorizations of innovation typology and widespread confusion as to what empirical studies are reporting*" (Garcia and Calantone 2002).

The Oslo Manual to a large extent bridges the gap by clarifying the concept of innovation. It compiled internationally-agreed rules on how to collect and interpret innovation data. According to the manual, "i*nnovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations"* (OECD and Eurostat 2005). Innovation is categorised into four types: product innovation, process innovation, organisational innovation, and marketing innovation.

The generations of innovation are often related to R&D efforts, but innovation can occur without directly conducting R&D. Non-R&D activities can play an important role, such as acquiring patents and licenses, purchasing new technology and taking advantage of consultancy services provided by external entities (OECD and Eurostat 2005, OECD 2009a). Likewise, without organisational and (or) marketing innovation, product and (or) process innovation may not achieve final success.

The degree of novelty of innovation varies from 'new to the firm' to 'new to the market' to 'new to the world' (OECD and Eurostat 2005). The impact of innovation on society stems from the diffusion of innovation undertaken by firms. Hence, the type of 'new to the firm' represents the basic form of innovation diffusion. However, when making cross-country comparisons, the 'new to the market' or 'new to the world' type of innovation may work better. A golden rule is that which kind of novelty should be referred to depends on the research questions.

This thesis mainly focuses on product innovation, namely technological innovation in wind turbines. The novelty of technological innovation defined in this research refers to 'new to the market' or 'new to the world' when it is national level analysis, and 'new to the firm' at the company-level analysis.

3.2 National system of innovation

The notion of NIS emerged concurrently in academic and policy communities in the early 1980s, facilitated by the scholars affiliated to the OECD (Sharif 2006). The purpose was to draft policy guidelines to achieve long-term economic growth. In published form, NIS was firstly used by Freeman (1987) in his monograph '*Technology Policy and Economic Performance: Lessons from Japan*'. Two other pioneering volumes on this concept are '*National Systems of Innovation: Toward a Theory of Innovation and Interactive Learning*' (Lundvall 1992) and '*National Innovation System: A Comparative Analysis*' (Nelson 1993a). These works build the theoretical foundation of NIS.

3.2.1 Origin of NIS studies

In the early 1970s, almost all advanced industrial nations slowed down in economic growth, whereas Japan emerged as a major technological and economic power. The relative decline of the USA and the widespread concerns in Europe about falling behind led to intense discussions on whether technological capability represented the key source of a nation's international competitiveness, and whether these capabilities can be cultivated by national actions (Nelson and Rosenberg 1993).

The USA far led the world in all R&D activities measured by both absolute and relative numbers in the early post-WWII period, but Japan fast closed this gap by the early 1980s. For instance, the US civil R&D expenditure as a percentage of GDP in 1967 was 26% higher than Japan, but as of 1983, Japan surpassed the USA by 35% (Freeman 1987). Between 1975 and 1985, the share of Japanese patents granted in the USA increased by two times; in contrast, the US share shrank from 65% to 56% (Freeman 1987).

To illustrate the innovation process of Japan, Freeman (1987) coined the concept of 'national system of innovation', arguing that Japan's technological and economic success owed to a combination of technological, institutional, and social innovations. Nelson (1967) found that a technological gap between Europe and the USA had existed for nearly a hundred years and was reinforced by continuous investment in equipment capital and education of the USA.

Freeman (1987) described the NIS as "*the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies*". The evolution of the world's science and technology hub shifting from Britain to Germany and then to the USA involves significant changes in institutions (Freeman 1987). The core objective of an NIS is to create favourable institutions to incentivise the heterogeneous actors to interact with each other to generate, adopt and diffuse new concepts and technologies (OECD 1997).

3.2.2 Determinants of a successful NIS

There is numerous literature discussing NIS while the most cited volumes have been the ones by Freeman (1987), Lundvall (1992) and Nelson (1993a). This section draws upon these original works to understand how the actors, interactions and institutions facilitate innovation and technological change. The recent development of NIS studies will be presented in section 3.2.3.

Freeman's reflections on Japan's success

Freeman (1987) analysed the roles of the Japanese Ministry of International Trade and Industry (MITI), of enterprise R&D strategy about imported technology and "reverse engineering", of national education and training system, of major social changes, and of technological forecasting. Freeman (1987) concluded that apart from the increasing scale of R&D activities, the way in which the resources were managed and organised at both enterprise and national levels was critical to speed up technical change and to improve the international competitiveness of Japanese firms.

A strong impetus of MITI in pursuit of long-term strategic goals has been crucial to facilitate institutional and technological changes. Europe and the USA accepted this kind of technology responsibility much later (Freeman 1987). Japanese firms were good at modifying the best technologies imported abroad. Reverse engineering provided a window of opportunity for Japanese firms to overcome quality deficits that they encountered. Japanese factories produced few radical innovations, but they made many incremental innovations such as the 'just-in-time' system.

The scale of the qualified labour force may represent another major change in Japan. Japan overtook West Germany and Britain in absolute numbers of graduates with a degree in science and engineering (Freeman 1987). The availability of an abundant good-quality workforce ensured its success in the modification of imported technologies and eventually the generation of in-house innovations.

Changes in social aspects and organisational practices underlay Japan's competitive strength (Freeman 1987). Japanese conglomerates promoted cooperation and information flows between industrial groups. Commercial banks were included in the conglomerates so that Japanese companies could obtain financial capital to support development when the funds for industrial investment were in short supply in other countries.

The capability of Japanese governments and firms to identify generic technology and to use advanced new technology in both established areas and new product groups was vital for Japan's success (Freeman 1987). The MITI collaborated closely with science, technology and industry communities, which facilitated the exchange of technology and market information. The stakeholders were fully aware of the broad development trends and could be able to response appropriately.

Japan has been the most successful country in accelerating the rate of technical change after WWII. The Japanese experience indicates that a competent innovation system enables a technology follower country to make rapid progress through appropriate adaptation of imported technology (Freeman 1987). The performance of an NIS can be affected by a variety of factors, among which the flexibility of institutions may perhaps be the most crucial element (Freeman 1987).

Nelson's analysis of industrialised nations

Nelson (1993a) and his colleagues analysed the success or failure stories of fifteen industrialised nations, aiming to find out the common elements that promote technological advance or cause cross-country variations. The research confirms that institutions, universities, institutes and corporate R&D labs, as well as the connections among them, are essential for analysing NISs (Nelson and Rosenberg 1993).

Nelson (1993b) argued that institutional continuity should be considered in analysing NISs as the basic national objectives and conditions have continuity. For countries with a relatively short history, the institutions supporting innovation have their origins in those of several decades ago. For countries with longer histories, the institutional continuity is even more striking. Britain in the 1990s continued many institutional characteristics that appeared in the 1890s. Of the countries with longer histories, the USA has made the most dramatic changes in institutions after the WWII.

Another factor causing cross-country differences is the education and training system that provides firms with qualified labour (Nelson 1993b). Some countries have a highly qualified workforce while other countries may have failed to train such skilled labour. The availability of qualified labour enabled Korean and Taiwanese firms to produce more sophisticated products in the 1980s. American and German universities more consciously trained students with an eye to industry needs.

Over protection for emerging industries may lead to failures (Nelson 1993b). Some emerging industries can grow up quickly under protection, but others may fail. Electronics and automobiles represent successful examples of Japanese and Korean emerging industries that grow up rapidly in a protected market. However, French electronics never managed to compete advantageously with international rivals. The reason may be that the government failed to encourage firms to compete on world markets when they should have.

The global production networks enable an MNE's R&D centre, manufacturing base and marketing hub located in different countries to maximise profits and take advantage of local knowledge and skills (Nelson and Rosenberg 1993). Inter-firm connections across borders are common for sharing R&D cost, exploring potential market or removing government-made barriers. A nation's attempts to protect and develop its domestic industries may be frustrated because of internationalisation.

For catching-up countries, innovation involves the learning of imported technology, adaptation to local circumstances and diffusion across sectors (Nelson and Rosenberg 1993). Firms may start by learning how to produce a product or employ a technology that is commonly seen in advanced economies. This practice (reverse engineering) is important for technological laggards to catch up with technological leaders.

Nelson and Rosenberg (1993) conclude that cross-country differences in innovation are major differences in economic, political circumstances and development priorities. They are caused by history, culture and social values, including the timing of entry into industrialisation, which profoundly influences a nation's institutions, laws and policies. Certain good practices in one country can diffuse to other countries, but when a nation attempts to borrow the system, it may eventually build a very different one.

Lundvall's theoretical building of NIS

Lundvall (1992) criticised the limitations of neo-classical economics that had focused on the factors of scarcity, allocation and exchange in a static context, leaving other aspects of the real world in obscurity. He held two assumptions: a) the most fundamental resource in the modern economy is knowledge and accordingly the most important process is learning; b) learning is predominantly an interactive and socially embedded process which cannot be understood well without considering institutional and cultural contexts (Lundvall 1992).

Lundvall (1992) and his colleagues argued that information flow, learning process and interactions played an essential role in fostering innovation. Innovation is a collective achievement that requires efforts from a variety of agents. A firm cannot innovate in isolation but needs to interact with external partners and institutional environment (Lundvall 1988). The interactions with external actors help identify the need for practices, knowledge, technology, financial and human resources.

Lundvall (1992) defined an innovation system as the arrangement of various elements and their relationships which interact in the production, diffusion and utilisation of new and economically useful knowledge. A narrow sense of NIS focuses on the major organisations and institutions (e.g. firms, universities and institutes) involved in exploring and searching innovations. A broader definition encompasses all aspects of the economic system and institutional setting-up that affect the exploring and searching of innovations, including the sub-systems of production, marketing and finance in which interactive learning takes place.

The definition of NIS should be flexible regarding the core components and relationships (Lundvall 1992). In different historical periods, some sub-systems and their relationships may play an important role in the process of innovation. It is necessary to identify the most relevant elements (or sub-systems) based on historical observations. It may be dangerous to insist upon one single approach as the only legitimate one. Different approaches and perspectives may unveil different aspects of the system (Lundvall 1992).

3.2.3 Recent development on NIS

NIS studies begin to shift to competence-building (Borrás and Edquist 2013, Lundvall 2002), systemic problems (Edquist 2011, Chaminade et al. 2009) and micro-level dynamics of innovation (Lundvall 2007, Lundvall, Joseph, et al. 2009). The international linkages of innovation systems (Marin and Arza 2009, Carlsson 2006, McKelvey and Bagchi-Sen 2015) which gained much attention recently are to be discussed in section 3.3.3.

Competence-building

Liu and White (2001) studied the evolving structure and dynamics of China's innovation systems before and after the economic reform. It was found that there were obviously missing building blocks in the early stage of China's NIS and many of them had not been in place after the reform. They argued that the ex-post concept of NIS developed in advanced countries may not be easily applied to developing countries where many essential elements of NIS were missing or still taking shape.

Lundvall (2007) acknowledged this concern but observed that some of the most important elements in the concept came from the literature on development issues in the third world. Follower countries can catch up through a combination of importing, licensing, reverse engineering and international collaboration. While challenging, it can be seen as a process of system (or competence) building (Lundvall 2007). Then the NIS approach can be adapted to the situations in developing countries where national innovation and competence building system may exist. Competence-building was the other side of the process of innovation (Lundvall, Joseph, et al. 2009).

Borrás and Edquist (2013) defined competence-building as the process of formal or informal development and acquisition of specific competences (e.g. knowledge, skills and expertise). Learning is the individual or organisation's own ability to adapt, make and change the specific competencies from internal and (or) external sources (Borrás and Edquist 2013). The core issues of innovation systems are to build, maintain and use competencies (Borrás and Edquist 2013).

In this sense, NIS can be seen as an evolutionary concept concerning how different national systems create diversity, stimulate variation and select routines (Lundvall 2007). The focus is to examine how the enduring relationships and patterns of dependence and interaction are dissolved and established as time passes. The strategic roles of this process are knowledge creation, learning and innovation. Lundvall (2007) proposed seven assumptions to support this argument:

- Knowledge is localised and cannot be easily moved from one place to another.
- Knowledge is embedded in minds, artefacts, routines and relationships.
- Learning and innovation are best understood as the outcome of interactions.
- Interactive learning is a socially embedded process for which a purely economic analysis is insufficient.

- Learning and innovation are strongly interconnected (but not identical) processes.
- National systems differ in the knowledge base and the specialisation of production and trade.
- National systems are systemic in the sense that different elements are interdependent and interrelationships matter for innovation performance.

Systemic problems

System failures may occur in both developed and developing economies due to systemic problems (Chaminade et al. 2009). In the Oxford Handbook of Innovation, Edquist (2005) presented a hypothetical list of activities (functions) to diagnose systemic problems. These activities include: 1) research and development; 2) competence building; 3) formation of new product markets; 4) articulation of user needs; 5) creation and change of organisations; 6) knowledge networks; 7) creation and change of institutions; 8) incubating activities; 9) financing innovation; and 10) consultancy services (Edquist 2011). The respective importance of these activities may vary in different ISs across different time periods (Edquist 2005).

Negro, Alkemade, and Hekkert (2012b) concluded a list of systemic problems that occurred in renewable energy innovation, including market structure problems, infrastructure problems, institutional problems, interaction problems and capability problems. Wieczorek and Hekkert (2012) attempted to diagnose systemic problems by linking system structures with system functions (Hekkert et al. 2007b, Bergek et al. 2008), which represents a new approach to analyse system failures.

Micro-level dynamics

NIS approach has mainly focused on macro structures and institutions and paid little attention to firm-level activities. Lundvall, Vang, et al. (2009) argue that changes at the system level are the outcome of changes at the micro level, whereas the system shapes the learning, innovation and competence-building at the micro level. Without knowledge about the micro-structures, it seems impossible to operate institutions and organisations at the meso- and macro-level (Lundvall, Vang, et al. 2009).

Firms are the central agents that bring up innovations. It is important to analyse what takes place inside firms in the process of system-building and innovation (Lundvall, Vang, et al. 2009). The role played by a particular firm (e.g. IBM), a state lab (e.g. Risø, Danish National Laboratory for Sustainable Energy) or a mission-oriented R&D programme (e.g. Manhattan Project or

Project Apollo) may be much larger than their peers in the industry. A micro perspective is vital to examine how the organisations or entrepreneurs create diversity, stimulate variation and select routines in competence-building (Lundvall 2007).

3.3 Technological innovation system

Despite the usefulness of the NIS framework, it suffers from several drawbacks. Firstly, it lacks an operationalised definition, which makes it look more like a policy tool rather than a theory (Edquist 2005). Secondly, the NIS contains too many elements and relationships, which means the structure and dynamics of the system can hardly be mapped out. Thirdly, the NIS analysis is often constrained within a national border and overlooks the transnational linkages of innovation systems.

Based on the earlier work on the technological system by Carlsson and Stankiewicz (1991) and the functions of innovation systems by Edquist (2005) and other scholars (e.g. Jacobsson and Johnson (2000) and Jacobsson and Bergek (2004)), Hekkert et al. (2007b) and Bergek et al. (2008) proposed the framework of the technological innovation system (TIS). This section presents the definition and analytical components of TIS.

3.3.1 Definition of TIS

In 1988, the Swedish Board for Technical Development initiated a research programme to study what was called Sweden's Technological System (Sharif 2006). Carlsson and Stankiewicz (1991) coined that "*a technological system is a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology*".

The technological system is the precedent of the recently developed TIS framework. Hekkert et al. (2011) define the TIS as the set of actors and rules that determine the rate and direction of technological change in a specific technology area. The primary focus of TIS is to understand how the system can identify, absorb and exploit (global) technological opportunities. National borders do not necessarily determine the boundaries of the system. A country contains many (at least several) TISs, and they coevolve over time regarding the components, relationships and properties (Carlsson et al. 2002).

Components are the operating part of a system (Carlsson et al. 2002). They can be of a variety of types such as individuals, firms, universities, research institutes and governmental bodies. They can be physical or technological artefacts such as R&D laboratories, libraries, wind turbines and solar panels. Also, they can be institutions in the forms of laws, rules, norms, routines and established practices.

Relationships are the links (or interactions) between components (Carlsson et al. 2002), which Lundvall and his colleagues discussed extensively in their serial research. When the interactions are investigated at the international level, transnational relationships characterised by technology transfer or technology spill-over constitute one of the core aspects of TIS (Carlsson et al. 2002).

Properties refer to the capabilities or qualities of components and their relationships which characterise the system. The properties and behaviour of each component depend on those of other components and can have an influence on the properties and behaviour of the whole system. Because of this interdependence, the components cannot be analysed independently but should be considered as a whole.

A technological system is not static but evolves over time regarding technologies and products (Carlsson et al. 2002). New sub-technologies may emerge, which may alter the configurations of actors, relationships and properties of the system. The boundary of the system always changes due to this dynamic character. Sometimes, the system is broadened; at other times, it is narrowed. Even technological specialists may not agree which technologies should be included in a period. Historical analysis is useful for redefining the system boundary (Carlsson et al. 2002).

Determining the boundaries of a TIS is challenging. Carlsson et al. (2002) argue that a system can be analysed at three levels: a) a technology within a knowledge field; b) a product or artefact; c) a set of related products aimed at a particular objective such as health care or transport (Carlsson et al. 2002). With technology as the level of analysis, all entities having competence within that technological area will be included, regardless of its application. Taking a product or artefact as the perspective, the actors are those within an industry, with their primary interest lying in the diffusion and use of the technology. When it expands to a set of related products, the actors may come from several industries, and the focus is on the actors and institutions supporting products to the market.

3.3.2 Functions of TIS

An innovation system is considered to have a set of functions. Edquist (2005) presented a list of functions to diagnose systemic problems, which somewhat supplements the less operationalised NIS approach that pays little attention to the dynamics of innovation. The literature suggests several lists of system functions, but it is hard to say which functions are the most important ones. Markard, Hekkert, and Jacobsson (2015) argue that the identification and incorporation of new functions would mean a step forward in TIS development.

Table 0-1 Functions of technological innovation systems

Functions	Refers to
F1: Entrepreneurial experimentation	The core role of entrepreneurs is to translate knowledge and technology into commercialised innovations. Without entrepreneurs, the innovation system may not even exist.
F2: Knowledge development	Knowledge is the fundamental resource for innovation. Knowledge development relates to the build-up of knowledge stocks through learning.
F3: Knowledge exchange	Knowledge exchange through networks allows to disseminate knowledge, develop mutual understandings and adjust the surroundings.
F4: Guidance of search	Guidance of the search is to shape the needs, requirements and expectations of actors to achieve socio-technical transitions when various technological options exist.
F5: Resource mobilisation	Human and financial resources are the basic inputs to the innovation process. The mobilisation of sufficient resources is essential to fuel the innovation system.
F6: Market formation	As new technologies can hardly compete with incumbents in the existing regime, a protected market is needed to incubate technological innovation.
F7: Creation of legitimacy	Novel technologies must become part of an incumbent regime by legitimising them via laws and regulations to counter the resistance to change.

Source: adapted from Hekkert et al. (2007b) and Bergek et al. (2008)

The TIS functions proposed by Hekkert et al. (2007b) and Bergek et al. (2008) have been the most widely-used ones (see Table 3-1), but "*even Bergek herself developed multiple variants of her first list…therefore the lists of system functions need to be confirmed (or rejected) by empirical evidence*" (Suurs 2009). This thesis adopts the seven functions proposed by Hekkert et al. (2007b), Bergek et al. (2008) and their collaborators.

Function 1. Entrepreneurial activities

The existence of entrepreneurs is of prime importance, and without entrepreneurs, innovation will not take place, and innovation systems may even not exist (Hekkert et al. 2007a, Negro 2007). Entrepreneurs can be new entrants to the market or incumbents who recognise the new opportunities. They can also be public sectors as long as they carry out market-oriented activities with an emerging technology (Suurs 2009). The core role of entrepreneurs is to translate knowledge and technology into business opportunities and eventually innovations.

Function 2. Knowledge development

Knowledge development involves learning which is central to the innovation process (Lundvall 1992). There are various types of learning activities, such as learning by doing, learning by using and learning by interacting (Lundvall 1992). New knowledge can stem from original R&D activities, an innovative combination of old and new knowledge or recombination of old knowledge by imitation (Negro 2007). From an evolutionary perspective, knowledge development relates to variety creation and is the prerequisite for the development of new technologies (Suurs 2009).

Function 3. Knowledge diffusion

Knowledge diffusion through networks involves partnerships among technology developers, university scientists and policy makers. Knowledge networks act as the channel that connects actors and facilitates knowledge exchange. The channels can be meetings, conferences, projects or programmes (Suurs 2009). Networks enable the heterogeneous actors to develop mutual understandings of an emerging technology and to make adjustments to the surrounding institutions (Suurs 2009, Negro 2007).

Function 4. Guidance of the search

Guidance of the search refers to the activities that shape the needs, requirements and expectations of actors (Suurs 2009). An example is that the government's announcement on reducing CO_2 emissions may stimulate investment in renewable energy and energy efficiency technologies. The actors outside the system may join in because of the effect of this guidance. The essence is to allocate resources to develop the mutually agreed technology when various technological options exist.

Function 5. Market formation

A protected space or niche market may be needed to cultivate technological innovation. The market formation is often taken up by firms through competitive products, but renewable energy technologies can hardly compete advantageously with established technologies without public support especially in the early stage. In this case, the market formation function needs to be fulfilled by the government via supportive policies such as subsidies, tax incentives, minimal consumption quotas or public procurement (Suurs 2009, Negro 2007).

Function 6. Resources mobilisation

Resources mobilisation refers to the allocations of financial, material and human capital (Suurs 2009). They can be investments in infrastructure, incentives and subsidies for R&D or public procurement. It may be difficult to determine whether the resources are sufficient as this information is usually based on the actors' perceptions. Entrepreneurs may complain that the resources are insufficient, but incumbent companies may insist the resources are over-provided (Negro 2007).

Function 7. Creation of legitimacy

The rise of a new technology often encounters resistance from incumbents (Suurs 2009). Actions must be made to counteract this inertia and facilitate the development of an emerging TIS. The purpose is to obtain legitimacy and create a favourable environment for the emerging technology. In this sense, the function is a special form of guidance of the search. This function can be accomplished by advocacy coalitions or lobbies to urge authorities to reorganise institutional configuration.

The functions are not isolated from each other, but each has an influence on several others. some functions may perform better than others, but as a whole, the system may not function as successfully as expected (Markard, Hekkert, and Jacobsson 2015). For example, the guidance of search influences resources mobilisation and market creation, and in turn, they may reinforce the shared visions of the new technology.

3.3.3 International linkages of TIS

Since national borders do not determine the boundaries of TIS, one TIS may connect more than one country in a global perspective, increasing transnational connections among firms and countries require a global perspective for TIS studies. The interplay between domestic and foreign TISs, the influence of leading TIS on the dynamics of lagging TIS, and the strategies for the lagging TIS to benefit from the global TIS are very interesting research topics.

The functions of a TIS may be influenced by both domestic and international factors. It is, therefore, valuable to consider the impact of international linkages on the competence and evolution of the domestic TIS. There are not many studies linking international linkages to the TIS framework, but based on the existing literature, this section intends to emphasise the role of international linkages in strengthening knowledge development, knowledge exchange and entrepreneurial activities.

Marin and Arza (2009) argue that international involvement may enable the country to have easier access to technological and managerial competence originated outside the national system, but also to be part of international knowledge creation and diffusion. This statement can be verified through the Chinese examples in Chapter 2. Knowledge diffusion from developed countries to less developed countries is recognised as a critical source of productivity growth (Du, Harrison, and Jefferson 2012). A potential channel of such diffusion is knowledge spillovers from foreign direct investment (FDI).

Lundvall (1992) emphasises that NIS should not be exclusively localised inside national borders. It is necessary to be more explicit about the relationships between globalisation and national systems, e.g. how globalisation has affected the process of system building in developing countries (Lundvall 2007).

The extent of internationalisation of innovation systems is controversial. Patel and Vega (1999) showed that more than 75% of firms located technology abroad in their core technologies where they were strong at home, and only 10% went abroad to exploit the technological advantage of the host country rather than compensate for their weakness at home. Patel and Vega (1999) argued that what happened in a home country mattered in the creation of global technological advantage even for most internationalised firms. By examining 345 MNEs' patenting activities, Bas and Sierra (2002) confirmed that 70% of MNEs located their R&D activities abroad in technological fields where they were strong at home. Foreign location of R&D activities of MNEs was a consequence of home country advantage or according to the host country strength (Bas and Sierra 2002).

Patel and Vega (1999) explained that the reason why firms involved in the production for the world market kept most of the technology close to the home base might be because knowledge is mind-embodied. The most efficient way is to locate the majority of R&D at home while establishing small foreign laboratories for adapting R&D or monitoring the technological development of foreign countries (Patel and Vega 1999). Understanding country-specific factors, such as competitive climate, financial system, education and training system, and research institutions, in influencing national technological advantage is crucial for innovation (Patel and Vega 1999).

Bas and Sierra (2002) categorised the strategy for internationalisation of R&D into four types: a) technology-seeking R&D; b) home-base-exploiting R&D; c) home-base-augmenting R&D; and d) market-seeking R&D. Which strategy should be adopted depends on the relative technological strength at home and abroad (Bas and Sierra 2002). Technology-seeking R&D is to offset home country weakness by locating R&D activities in a host country with proven technological strength. The firms set up local R&D units to tap into the host country's proven technological capabilities or obtain the technology through acquisitions. Home-base-exploiting R&D is the opposite of technology-seeking R&D. The rationale is to exploit technological competence in foreign markets where the desired technology is weak. Foreign R&D units are used to adapt the established technology to the needs of foreign customers and (or) help foreign customers to use that technology. Home-base-augmenting R&D is to locate R&D activities abroad in a technological field where both home country and the host country are strong. It is intended to strengthen the core competence or strategic positioning of the investing firms. Market-seeking R&D corresponds to situations where a firm invests R&D abroad in a technological field where both home country and the host country are weak. The motivation for this strategy is not technology-oriented but market access.

Ambos (2005) observes that German MNEs increasingly invest in international R&D for capability augmenting opposed to capability exploiting. This finding underlines the prior predictions that the future challenge for MNEs will be the global sourcing, melding and leveraging of dispersed knowledge around the global (Ambos 2005). A firm may engage in more than one type of international R&D strategies. Certain countries may attract both capability-augmenting and capability-exploiting R&D at the same time (Ambos 2005). Narula and Zanfei (2005) also finds that MNEs increasingly internationalise their R&D activities, excluding a few exceptions, most notably Japanese MNEs. Along with adaptive R&D, asset-augmenting R&D to gain access to local competencies becomes more and more important (Narula and Zanfei 2005).

It is worth noting that Patel and Vega (1999) and Bas and Sierra (2002) focused on the MNEs in advanced economies (AMNEs) and did not take into account the MNEs in emerging economies (EMNEs). The globalisation of innovation was not as obvious as today. The MNEs from emerging economies play a more active role, and AMNEs begin to locate part of their R&D centres in these countries like China and India. Another issue is that Patel and Vega (1999) and Bas and Sierra (2002) drew upon a restricted number of patent offices, either from the USPTO or EPO. China, Japan and South Korea have filed a considerable proportion of the world's patents. Partial patent statistics may affect quantitative results.

Krishna, Patra, and Bhattacharya (2012) emphasise that the paradigm of offshoring R&D has changed significantly over the last two decades. India has emerged as an important destination for innovation in ICT and biopharmaceuticals. The country is emerging as an innovation partner of AMNEs (Krishna, Patra, and Bhattacharya 2012). Many foreign R&D units in the ICT industry are developing products from India for their global product portfolios. As a result of economic and market growth, Indian firms are expanding business and linking up with the global network of innovation through M&A (Krishna, Patra, and Bhattacharya 2012).

Awate, Larsen, and Mudambi (2014) argue that internationalisation of R&D activities by AMNEs can be explained by competence exploitation and competence creation, while EMNEs' R&D internationalisation is rooted in accessing established-foreign knowledge. In the field of wind technology, Vestas adopts a global innovation strategy by accessing engineers, technical know-how and capabilities from different locations to push their technology frontier (Awate, Larsen, and Mudambi 2014). In 2009, Vestas established a research centre in Texas to tap into the local pool of knowledge and competence in aerodynamics and electricity. In 2010, Vestas built an R&D unit in Beijing to take advantage of the local expertise in high-voltage engineering and software development.

A major change in today's global landscape of innovation is the rising role of emerging economies. These countries have integrated themselves into the global networks of innovation and production. The international linkage between countries acts as the bridge smoothing the cross-border flows of goods, capital, information, technology and labour. The impact of globalisation on innovation capability may vary across countries, but for certain catch-up countries, they do have improved technological capability in the era of globalisation. It is necessary to consider the role of international linkage in the process of energy technology innovation.

3.4 Energy innovation system

Given the grand challenges of climate change, energy security, energy affordability and environmental degradation, technological innovation is vital to building a more secure and sustainable energy system (IEA 2015, GEA 2012). Academic research on energy innovation started around the 1980s (see Haustein and Neuwirth (1982), Zimmerman (1982), and Darley and Beniger (1981)). The early studies mainly focused on R&D (Sagar and Holdren 2002), and recently scholars like Gallagher, Holdren, and Sagar (2006b), Grubler, Aguayo, Aguayo, et al. (2012) and Wilson and Grubler (2014) adopted a systemic approach to studying energy technology innovation process, inspired by the IS approach. This section discusses the emergence and conceptual elements of the energy innovation system (EIS) framework.

3.4.1 The emergence of EIS

When analysing innovation in transport infrastructure, Grubler (1990) described the long-term development of energy technologies as a process of birth, growth, saturation and eventual decline (also known as an S-shaped curve). Innovation was closely related to organisational and social adaptation processes (Grubler 1990).

In the book "*Technology and Global Change*", Grubler (1998) particularly emphasised the role of diffusion. Technological diffusion was considered as the primary interest of global change because, without widespread diffusion, there would be no impact (Grubler 1998). Technology clusters - sets of interrelated technological, infrastructural and organisational innovations - play a vital role in fostering technological diffusion, but it is affected by the diversity of firms and their objectives, abilities to learn as well as attitudes towards risks (Grubler 1998).

In the 1990s, renewable energy technology (RET) enjoyed double-digit growth, but the transformation of the energy system was slow, painful and uncertain (Jacobsson and Johnson 2000). Neij (1997) argued that the adoption of RETs, with special emphasis on wind turbines and solar photovoltaics (PV), would increase if policy instruments were used to facilitate diffusion.

In the field of energy efficiency technology, Newell, Jaffe, and Stavins (1999) found that enforced standards had a significant impact on innovation while the direction of innovation was responsive to energy prices for some products but not for others. Popp (2002) also observed that energy prices and knowledge quality had positive effects on energy efficient technology innovations.

Jacobsson and Johnson (2000) and Jacobsson and Bergek (2004) employed an IS perspective to explain the speed and direction of RETs in the transformative process of the energy system. The framework comprised four elements - firms, networks, markets and institutions, which represented an earlier version of TIS. Foxon et al. (2005), Jacobsson and Lauber (2006) and Lewis and Wiser (2007) adopted similar analytical elements in their research.

Gallagher, Holdren, and Sagar (2006b) described energy innovation as a process with multi-dynamic feedbacks between different stages, namely fundamental research, applied research, development, demonstration, pre-commercial and niche deployment and widespread deployment (diffusion). Grubler, Aguayo, Aguayo, et al. (2012) applied the IS approach to studying energy technologies and proposed the EIS framework. Grubler and Wilson (2014) then offered detailed empirical analyses of energy technologies by using the framework.

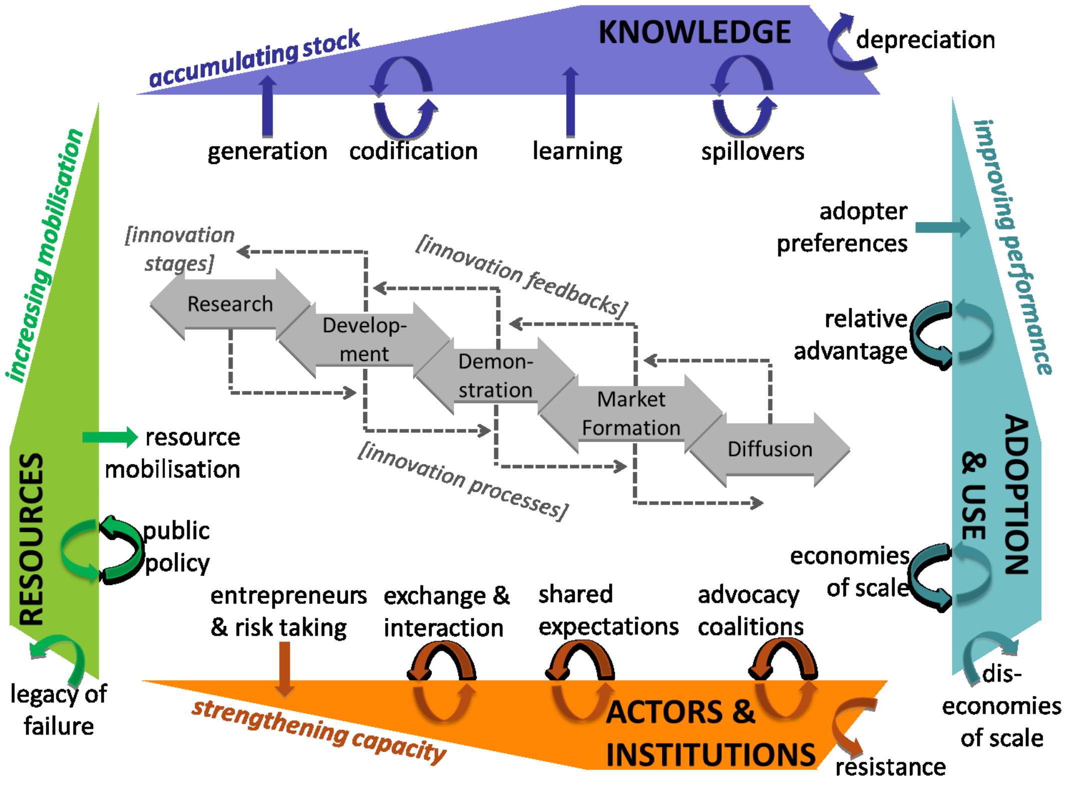
3.4.2 The components of EIS

Many energy technology innovations have been crude, imperfect and expensive at the initial stage (Wilson and Grubler 2014). The distance between R&D and market formation is called the 'valley of death' (Mills and Livingston 2005). It is often caused by high cost, difficulty in scaling up or the lack of a clear perceived demand (Wilson and Grubler 2014). It takes many years for a novel technology to become widely diffused. This may be because a technology does not exist in isolation but depends on related technologies and infrastructures as well as business models, a wider market and social institutions (Hughes 1983).

Energy innovation involves novel applications of materials and knowledge. The energy innovation process starts from laboratory research to development, demonstration, deployment and diffusion. Wilson and Grubler (2014) argue that a systemic approach can overcome the shortcomings caused by partial or fragmented analyses. The EIS framework is proposed to help understand the key stages, processes and drivers of energy innovation in a systemic manner.

Essentially, the EIS describes: a) the stages of energy technology innovation process; b) the feedbacks between these stages; c) the drivers of energy technology innovation, namely technology-push and market-pull; d) the relevance of energy supply and energy end-use technologies; e) analytical dimensions of energy innovation, namely knowledge, resources, actors, institutions and adoption (see diagram 3-1).

Diagram 3-1 The analytical framework of energy innovation systems



Source: Wilson and Grubler (2014)

Knowledge is the most fundamental resource in the modern economy (Lundvall 1992). Wilson and Grubler (2014) have emphasised the exclusive characteristics of knowledge dimension, including knowledge generation, knowledge codification, knowledge flows, knowledge spill-over, knowledge depreciation and learning.

Resources are the key input to innovation systems. They include financial, human and intellectual property-related assets as well as the time involved (Wilson and Grubler 2014). Resources mobilisation is a core function of the TIS framework. Public policy acts as a direct resource and facilitates the mobilisation of resources (Wilson and Grubler 2014). However, resources mobilised that have failed to bear fruit may cause a vicious cycle with fewer resources leading to less success and vice versa.

Actors and institutions are the core analytical elements in IS studies. Wilson and Grubler (2014) have emphasised the factors that may affect the property or behaviour of actors and institutions, including entrepreneurship, shared expectations, advocacy coalitions and resistance to change. These characteristics are in line with the relevant functions of the TIS framework (Hekkert et al. 2007b, Bergek et al. 2008).

The adoption and use of technology are the ultimate measures of a successful innovation (Wilson and Grubler 2014). The widespread diffusion of a particular technology is affected by relative advantage, adopter preferences and economies of scale (Wilson and Grubler 2014). The relative advantage can be efficiency, reliability, cost and environmental impact.

The EIS framework has corresponded to the need for a systemic perspective to study energy technology innovation. It has absorbed fruitful elements from IS studies particularly the TIS. The multi-dynamic stages characterise the generic process of energy technology innovation.

3.5 The analytical framework for the thesis

The goal of an innovation system is to facilitate the generation, adoption and diffusion of economically useful knowledge and technology. The purpose of employing the IS approach is to measure, understand and explain the complexity and variations in innovation performance across countries, regions or sectors. The multiple IS approaches share some common grounds, but they differ regarding the analytical frameworks. Also, many IS studies have been static, less empirical and paid little attention to the dynamics of innovation in a firm. An adequate framework is important.

Bergek et al. (2008) propose a six-step scheme for analysing TIS – a) defining the boundary of a TIS, b) identifying the structural components, c) mapping the functional pattern, d) assessing the functionality of the TIS and setting process goals, e) identifying inducement and blocking mechanisms, and f) specifying key policy issues. Wieczorek and Hekkert (2012) propose a five-step scheme for analysing TIS – a) mapping structural dimensions and their capabilities, b) coupled structure-functional analysis, c) systemic problems, d) systemic goals and e) systemic instrument design.

Wieczorek and Hekkert (2012) suggest explaining systemic problems by linking structure to functions, holding that the functionality of a TIS is fulfilled through the presence and capabilities (or qualities) of structural elements. Without the alteration of a structural element, the fulfilment of functions can hardly be achieved (Wieczorek and Hekkert 2012). In this sense, the systemic structure acts as the ground base of a TIS, upon which the functions are developed and work as functional intermediaries towards the goal of facilitating technological innovations.

Table 3-2 Structural elements and the relevant problems

Structural elements	Structural problems
Actors	Presence: actors are absent Capability: actors lack capability or competence (e.g. to learn or utilise resources) to identify their needs and develop strategies
Networks	Presence: networks are absent Quality: strong network (e.g. strong involvement of incumbents, dependence on dominant incumbents) or weak network (weak connectivity or complementarities among actors)
Institutions	Presence: institutions are absent Quality: stringent institutions that result in appropriability trap and favour incumbents, or weak institutions that hinder innovation (e.g. insufficiently supporting new technologies)
Infrastructure	Presence: infrastructure is absent Quality: infrastructure is inadequate or malfunctioning

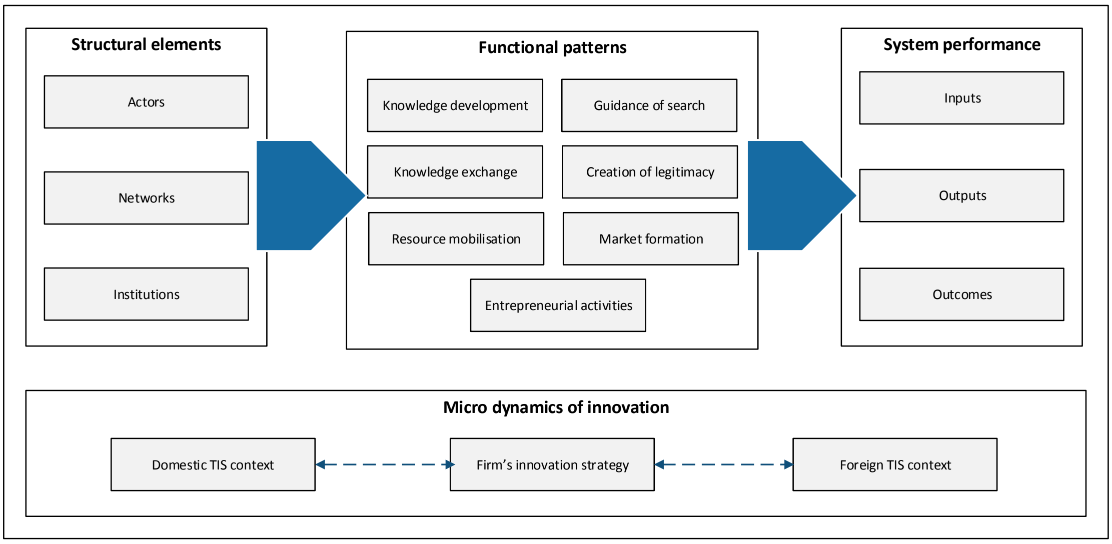
Source: Wieczorek and Hekkert (2012)

The important difference between the structure and functions is that the structure presents insight about which elements are active in the system, while the functions present insight about whether the elements are working towards the 'right' direction (Hekkert et al. 2011). For instance, a precondition of knowledge diffusion is the presence and interactions of actors. If the actors are absent or they lack the capability or competence to learn and utilise resources, they cannot even develop knowledge (one of the functions), or as a result of the differing objectives and assumptions of various actors, the interactions between them may be discouraged (Wieczorek and Hekkert 2012). That is to say, if a system function does not work well, it may be because certain structural elements are absent or weak.

Wieczorek and Hekkert (2012) conclude with four types of structural elements - actors, institutions, interactions and infrastructure. Then the systemic problems can be conceptualised as a) the presence or capabilities of actors; b) the presence or quality of institutions; c) the presence or quality of infrastructure; and d) the presence or quality of interactions. The structural analysis of a TIS is to map its elements and evaluate their capability (or quality) to stimulate innovation.

This thesis is concerned with two questions- a) whether China has become a leading innovator in wind technology and b) what factors are responsible for China's successes or failures. After comparing the NIS, TIS and EIS frameworks, this thesis adopts the "coupled structure-functional analysis" as the analytical framework but includes two additional dimensions – a) performance evaluation of the TIS and b) dynamics of innovation in a firm (see diagram 3-2). Regarding the functional analysis, indicators for quantitatively assessing functionality will be presented in Chapter 7.

Diagram 3-2 The analytical framework for the thesis



N.B. The diagram does not present a definite list of analytical elements for each sub-component (e.g. actors and institutions) as the coverage may vary depending on the research questions. The relationships between components (e.g. structural elements and functional patterns) or between sub-components are simplified as unidirectional for the research purpose of this thesis, but they are bidirectional in the real world. For example, the structure and functions may co-evolve and interact with each other over time, but it is beyond the scope of this research.

The thesis will firstly conduct an international comparison in the wind turbine industry across China, Demark, Germany and the USA to specify China's comparative performance. Then it moves to describe the presence and capabilities (or qualities) of structural elements embedded in China's wind energy innovation system. The functional analysis is employed to assess the functionality of the system to understand which functions have performed well or bad. Finally, a micro-level analysis on a pioneering Chinese wind turbine manufacturer is carried out to unveil how the firm (a structural element) has taken advantage of national and international factors to enhance technological capability.

3.6 Summary

Innovation is critical to economic development and social change. A variety of terms such as incremental innovation, sustainable innovation and social innovation have emerged to describe the characteristics or importance of innovation. The thesis adopts the definition proposed by the OECD and Eurostat (2005) and exclusively focuses on product innovation, namely technological innovation in wind turbines.

The framework of national innovation system (NIS) proves a useful tool for explaining a country's technological change and competitiveness. Despite the usefulness of the NIS framework, it suffers some flaws (e.g. static, constrained to national borders). The TIS framework has to a large extent narrowed the gaps by proposing a list of functions to understand the dynamics of the system and by extending the system boundary at the global level. The recently developed EIS framework has concluded the key characteristics of energy technology innovation and incorporated fruitful elements from TIS studies. In particular, it describes the multi-dynamic stages of the energy technology innovation process.

After comparing the multiple IS approaches, the thesis employs the "structure-functional analysis" derived from the TIS framework (Wieczorek and Hekkert 2012) plus two additional dimensions (i.e. system performance evaluations and dynamics of innovation in a firm) to study the Chinese innovation system of wind energy. The quantitative and qualitative methods used to conduct the analyses is to be discussed in the next chapter.

Chapter 4 Methodology

Research questions dictate the types of research methods, and in turn, the methods affect the reliability of results corresponding to the research questions. How the questions are addressed via appropriate methods is central to enhancing the evidence base. The last chapter builds an analytical framework based on the investigation of the multiple IS approaches. In this chapter, the research methods used in the thesis to carry out the analyses will be discussed.

To begin with, section 4.1 explains the rationales for the proposed "mixed methods" approach. Section 4.2 discusses the usefulness and limitations of the adopted quantitative and qualitative methods, as well as how they will be applied in the thesis. Section 4.3 summarises the practices and rising issues when collecting administrative data from Chinese and English sources. Concluding remarks are presented in section 4.4.

4.1 Research design

As it is illustrated in Chapter 3, the thesis focuses on four analytical dimensions: a) structural elements, b) functional patterns, c) system performance and d) dynamics of firm's innovation. To appropriately complete these research tasks, a combination of research methods is needed.

There have been two major strands of research methods in social science, namely quantitative and qualitative methods. Quantitative research is informed by objectivist epistemology and seeks to develop universal laws by statistical analysis whereas qualitative research is based on constructivist epistemology and explores socially constructed dynamic reality through value-laden and context sensitive methods (Yilmaz 2013).

Both approaches have their strengths and weaknesses, and which approach should be adopted depends on several factors such as research question(s) and personal experience (Yilmaz 2013). Many qualitative studies use and require quantitative information (Mahoney and Goertz 2017). The common misunderstandings between quantitative and qualitative research are caused by perceived mischaracterizations of their assumptions, goals and practices (Mahoney and Goertz 2017).

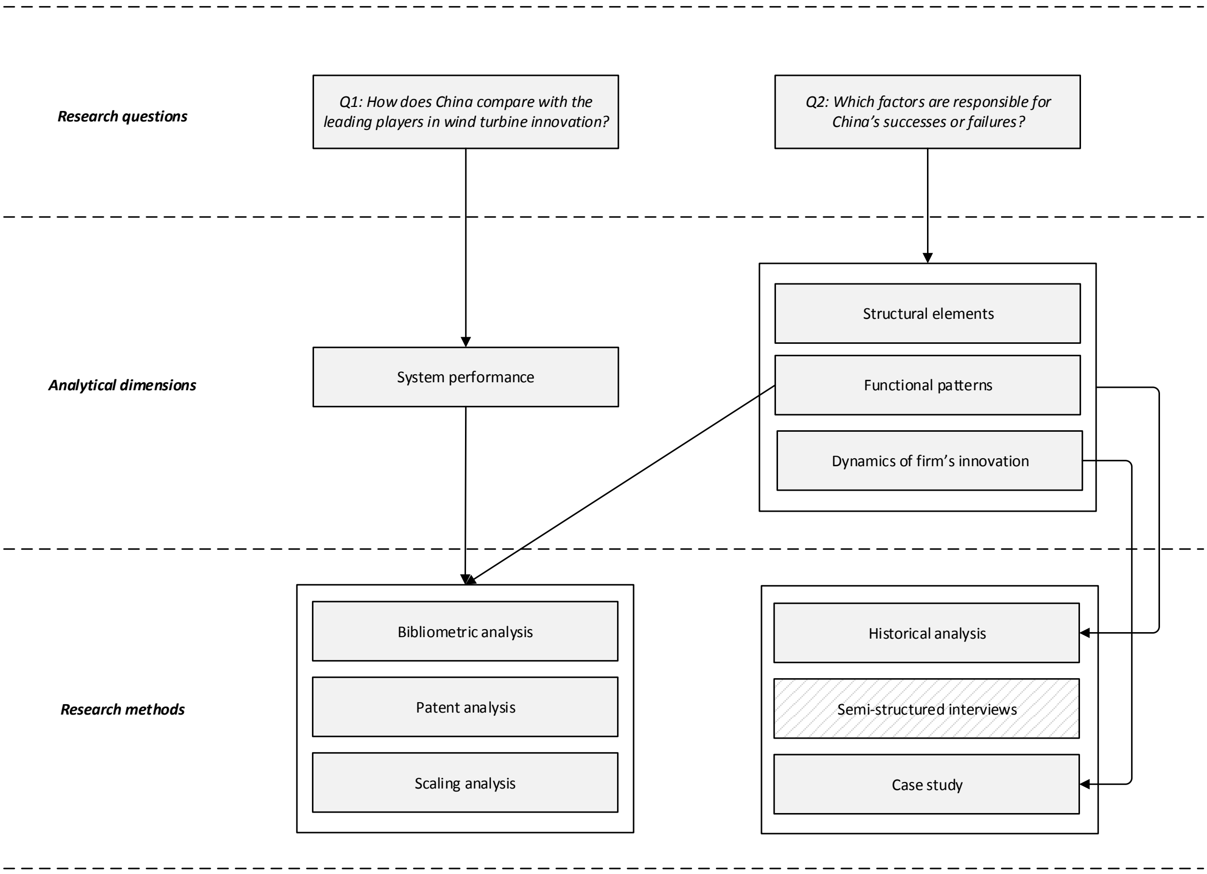
The past few decades have witnessed a surge in combining quantitative and qualitative research in a single study. Sommer Harrits (2011) argues that quantitative and qualitative (i.e. historical, comparative) methods can supplement each other to gain greater confidence. For example, quantitative analysis is valuable to identify patterns and correlations while qualitative analysis is essential to tracing causal mechanisms (Sommer Harrits 2011). The trend of combining quantitative and qualitative research has raised debate on the philosophical foundations (or worldviews) of research methods. In the book *Mixed Methodology: Combining Qualitative and Quantitative Approaches* (1998), Tashakkori and Teddlie proposed the so-called "mixed methods" (MM) which gained rapid acceptance in the following decades (Mertens et al. 2016).

Johnson, Onwuegbuzie, and Turner (2007) and Denscombe (2008) call the emergence of MM the third "methodological paradigm". The main features of MM are that: a) it partners with the philosophy of pragmatism (or practice-driven need), and b) relies on a combination of quantitative and qualitative methods according to one's research question(s) (Johnson, Onwuegbuzie, and Turner 2007, Denscombe 2008). The strength of this pragmatic approach is its emphasis on the connection between epistemological concerns about the knowledge produced and technical concerns about the methods used to generate that knowledge (Morgan 2007). Valerie Caracelli responded that "*a mixed method study is to provide a more elaborated understanding of the phenomenon of interest and to gain greater confidence in the conclusions*" (Johnson, Onwuegbuzie, and Turner 2007).

Mertens et al. (2016) suggest two core criteria for MM: a) use of more than one method, methodology, approach, theoretical or paradigmatic framework, and b) integration of results from different components. Creswell (2016) argues that the "use of more than one method" may suggest that the use of either multiple qualitative or multiple quantitative methods. If so, they should be called "multimethod" research rather than "mixed" research. Creswell (2016) argues that there is a distinction between "mixed methods" and "multimethod" approaches in which "mixed methods" includes both quantitative and qualitative research. The central premise of

MM is that the combining of quantitative and qualitative approaches provides a better understanding of research problems than either approach alone (Creswell 2016).

Diagram 4-1 Overview of research design and methods



N.B. The transcripts and quotes collected from semi-structured interviews were not used as evidence due to the lack of validity caused by restricted number of samples (see section 4.2.5).

This thesis adopts a mixed methods approach to addressing the proposed two questions (see diagram 4-1). There has been a variety of quantitative and qualitative methods in innovation studies. By considering the research questions and the maturity of the analytical tools, the thesis adopts bibliometric analysis, patent analysis, scaling analysis, historical analysis, semi-structured interviews and case study to produce quantitative and qualitative evidence. Each analytical dimension involves one or more concrete research methods. It is expected that the combining of these quantitative and qualitative methods can generate more reliable and comprehensive evidence.

4.2 Research methods

This section discusses the usefulness and limitations of the adopted research methods, as well as how they are used in this thesis. A key message is that each method can be used for different purposes and the appropriateness depends on how they can enable the investigators to answer the questions.

4.2.1 Bibliometric analysis

Bibliometric analysis is a statistical analysis of written documents, such as journal papers, books, reviews and conference proceedings, to characterise the impact, structure, networks and dynamism of scientific research. It has several advantages. First, time-series and cross-country data are available. A combination of bibliometric and patent data (see below) can demonstrate a firm or country's potential to foster technological innovation when the real number of product innovations is unavailable. Second, the quality and networks of research can be mapped out via citations and social-network analysis (Kajikawa and Takeda 2009). The ratio of highly cited publications shows research performance while co-authorships reflect knowledge exchange.

Despite its value, bibliometric analysis has a language bias that makes English speakers have a stronger presence (Leeuwen et al. 2001). Most bibliometric analyses extract data from English journals, excluding many non-English documents. Also, the searching queries used for extracting data vary considerably among analysts (Klitkou, Scordato, and Iversen 2010). The different searching practices have a direct impact on quantitative results. Broader searching may include irrelevant documents while a narrow or inaccurate focus may overlook important items. The quality of bibliometric analysis is highly related to one's personal experience.

In order to understand China's knowledge generation in wind turbines, bibliometric analysis is performed with the data extracted from the Science Citation Index-Expanded Database. A wind turbine consists of more than 8,000 components. It seems impossible to use them all to extract data. When performing the bibliometric analysis, this research refers to the category of the Cooperative Patent Classification (CPC) for wind turbine components (see box 4-1). These components represent the most sophisticated technologies and cover more than 70% of a wind turbine's manufacturing cost (EWEA 2009).

Box 4-1 Searching queries for bibliometric analysis

TI=(energ* OR electricity* OR power* OR blade* OR rotor* OR gearbox* OR generator* OR nacelle* OR tower* OR inverter* OR converter* OR transformer*) AND TS=(wind)

Language: English

Document type: article, proceedings paper, book chapter, review

Database: Science Citation Index-Expanded (SCIE), ISI Web of Science

Year: 1970-2015

4.2.2 Patent analysis

The growing relevance of technological competition has increased the importance of patents. Patent data provides insights into the processes and outputs of inventive activities, as well as the role of intellectual property rights (IPRs) in economic development, technology commercialization and technological forecasting (OECD 2009b). In particular, patent citations are useful to examine the connections between technologies, between science and technology, or between firms, industries, countries or regions (OECD 2009b).

A patent filed at a national (or regional) office is protected only within that jurisdiction. If the applicant wishes to protect the same invention in other countries or regions, then a separate patent application should be submitted to the designated patent office. The five largest patent offices in the world are the European Patent Office (EPO), US Patent and Trademark Office (USPTO), Japan Patent Office (JPO), China State Intellectual Property Office (SIPO) and Korea Patent Office (KPO). On average, it takes 3 to 5 years for a patent to be granted by the above authorities.

Patent analysis suffers from some drawbacks. First, not all inventions are patented - only 52% of product innovations are patented (OECD 2009b). Companies sometimes prefer to gain market dominance by other mechanisms such as secrecy and lead time (OECD 2009b). Second, national laws, administrative and patent examination procedures have a significant influence on patent applications, grants and citations (Cotropia, Lemley, and Sampat 2013). Third, timeliness (or truncation) in patent citations somewhat undermines the reliability of the associated results. Fourth, there exist differences in patenting behaviour among technologies and industries - some industries have a larger proportion of patents than others. Five, “home advantage effect” may benefit the institutions and individuals located in the same region as the patent office (Li et al. 2007, Criscuolo 2006, Dernis and Khan 2004). It is necessary for analysts to be aware of these pros and cons when conducting patent analysis.

This thesis is concerned with inventiveness, so simple counting works. Patent citations which may reflect the degree of its technological and commercial potential are not used as patent citations differ significantly across patent office due to the different disclosure obligations and examination procedures. For the USPTO, the number of references should be limited to 25, but there is no limitation when applying to JPO. The submission of references is optional at the EPO as examiners are responsible for constructing a list of references to the prior art to judge whether the invention is patentable. Thus, the references provided by the authorities may not be completely acknowledged by inventors, which makes citation analysis somewhat questionable. The timeliness of patent citations acts another reason for not using this measurement. In addition, patent applications rather than patent grants are considered as there exists a significant time lag between them. The latest data for patent applications available ended by 2011.

Patent counts from a single patent office show "home advantage" bias and ignore cumulative innovation efforts by catch-up countries. To fully assess a country’s potential to fostering novel technologies, the thesis includes a bundle of patent offices, namely the EPO, USPTO and SIPO. The data comes from the PATSTAT and PIAS. The former refers to the Worldwide Patent Statistical Database, jointly established by the EPO and USPTO, and the latter is the Patent Information Analysis System, a software developed by the SIPO and allows to extract the latest patent data in the Chinese market. The PATSTAT adopts the Cooperative Patent Classification (CPC) codes while the PIAS uses the International Patent Classification (IPC) codes. The CPC contains a wider range of sub-classifications of technologies, such as climate mitigation technology (Y02E). The searching codes used to extract data from the two databases are as follows.

Table 4-1 Searching codes for bibliometric and patent analysis

Types	Searching codes
PATSTAT	• blades or rotors (Y02E 10/721) • components or gearbox (Y02E 10/722) • control of turbines (Y02E 10/723) • generator or configuration (Y02E 10/725) • nacelles (Y02E 10/726) • offshore towers (Y02E 10/727) • onshore towers (Y02E 10/728) • power conversion electric or electronic aspects (Y02E 10/76)
PIAS	• wind motors (F03D)

4.2.3 Scaling analysis

The scaling analysis employed in this research is adapted from the meta-analysis of unit and industry level scaling dynamics of energy technologies (Wilson 2009). It was used to estimate the future technological scaling and market dynamics based on historical growth patterns. A logistic growth function (an S-shaped curve) was used to describe the growth pattern of a technology from initial adoption, rapid expansion to saturation. This research is not to project technology diffusion, so the logistic growth function will not be used. However, the idea of a meta-analysis of technology scaling inspires to measure technological progress in wind turbines.

The “scaling” refers to unit or industry capacity. It differs from the “economies of scale” used in economics (Wilson 2009). The latter characterises the decreasing cost of production as output increases while the former points to the increase in the size of a technological design or the whole industry. The “scaling” used in this research simply describes an energy technology that grows in capacity at unit or industry level (also known as “unit scaling” and “industry scaling”).

The unit capacity measured in MW can be taken as proxy for the stage of technological development of a manufacturer while industry capacity measured in GW captures the extent of technology diffusion. For many energy technologies, industry-level growth has been complemented by growth in the capacity of the technological unit (Wilson 2009). The global wind power industry has increased by nearly 60 times in two decades, from 7.6GW in 1997 to 435GW by 2015 (BP 2016) while the unit capacity of wind turbines has increased by 100 times over the last 30 years, from 75kW in the early 1980s to 7.5MW by 2011.

In addition to unit and industry level growth, the scaling analysis can be expanded to plant and system-level (Wilson 2009). The preferred metric is generating capacity denoted by MW. The unit capacity of wind turbines may grow from 8MW to 10MW, the capacity of a wind farm may grow from hundreds of MW to several GW, the wind power industry may scale up from 10GW to 100GW and the share of wind power in electricity system may rise from less than 5% to 50%. This research is mainly concerned with the unit and industry capacity.

4.2.4 Historical analysis

A TIS is not static but evolves over time regarding the core technologies, actors and their relationships. Historical analysis is useful to redefine the boundary of the TIS (Carlsson et al. 2002). Hekkert et al. (2007b) proposed the "history event analysis" (or process approach) to study the functions of a TIS, but it also applies to the structural analysis, namely investigating the presence, growth or decline of structural elements to explain how the existing structures come about, why the actors differ in their importance and why some actors strategically contribute to system build-up (Musiolik 2012).

This thesis does not apply historical event analysis in a strict way but attempts to "loosely" tell the story in a historical perspective. The analysis of functional patterns is to be completed via a set of quantitative and qualitative indicators supported by time-series data. There are many qualitative studies on the functions of TIS, but few have employed quantitative indicators for characterising the functionality. For the analysis of structural elements, a historical analysis is adopted to investigate their presence and capability (or quality) over time. A historical perspective is also embedded in the case study on a particular Chinese wind turbine maker to trace the firm's transformation from a technology imitator to a technology innovator.

Historical analysis requires plenty of data and archives. As such, desk-based research is conducted to search and review documents, collect time-series data and build files and datasets. Endnote has been helpful in managing many references, and Excel sheets are used to store and filter various types of data. A policy and measurement file for China's wind power industry is established by referring to the existing literature and the IEA and IRENA's database (IEA and IRENA 2016).

4.2.5 Semi-structured interviews

As a supplementary method to quantitative analysis, semi-structured interviews were carried out in China to collect opinions from Chinese experts. Two rounds of fieldwork were conducted to collect data that otherwise may not be obtained by desk-based research alone. The first took place in 6 – 23 October 2015 and the second occurred in 7 – 19 October 2016. The interviewees were from different backgrounds, e.g. universities, research institutes, industry associations and enterprises. Innovation is a collective achievement which requires efforts from both public and private sectors, so a diverse range of interviewees can enable better diagnosis of the problems and enrich the narratives.

The interviews were identified by scanning: a) the authors from journal papers; b) the members of the relevant industrial associations (e.g. Chinese Wind Energy Association); c) the R&D managers from company websites; and d) the policy makers from government websites. It was easier to contact with university academics as the papers contained their email addresses. It was extremely difficult to get in touch with the other interviews as their contact information was rarely published online. Baidu, Google and Linkedin were used to search the candidates' contact names and helped identify some information. As the China Wind Power Conference normally occurred in the third week of October, I exchanged business cards with the candidates and conference speakers when I was in Beijing, which helped secure a few other interviews. About 50 candidate interviews were identified and 21 of them accepted my interviews.

The semi-structured interviews comprised two parts: one was to invite interviewees to talk under the guidance of questions (25 minutes), and the other was to allow 20 minutes for interviewees to talk about other relevant issues that may not have been covered in the designed questionnaire. Approximately 40 questions (see Appendix B-1) were designed on the basis of the casual relations between structural elements and system functions.

It was impossible for one interviewee to answer all the questions in relation to the system functions, so each interviewee was asked to answer the ones that they were mostly familiar with. For example, university academics and institute researchers were invited to comment on the issues of Knowledge Development (F2) and Knowledge Networks (F3) whereas firm managers were requested to talk about Entrepreneurial Activities (F1), Resource Mobilisation (F6) and Market Formation (F5).

After analysing the interview transcripts, I found that only 8 of them were related to technological innovation with the remaining being either non-technological innovation but generic policy issues. However, the less relevant interviews did provide an excellent overview of China’s wind power industry and some interviewees provided very valuable references for the research. Some useful lessons were learnt from the conduct of semi-structured interviews.

It is more than important to focus on the questions during the interview. A list of questions may be referred to as guidance, but interviewee may not respond directly to them. The interviewees may be unfamiliar with the terms or did not read the questions sent to them before the interview. Another occasion is that the interviewer may be interrupted by the unexpected questions raised by the interviewee who thinks it a good opportunity to exchange ideas. This can happen easily when the both sides are eager to share opinions. When it is time to end the interview, many questions may be left unanswered.

A quiet and relaxing environment is crucial for interviews. A telephone interview can be very useful if it is not convenient to meet face to face. However, if the interviewee were outside the office when the interview occurred (e.g. in a park), he or she may find it difficult to concentrate on the questions and thus talk freely to his or her mind. The interview may also be terminated because of the interviewee’s prearranged meeting or unexpected visitors. It can be difficult to fix another interview, especially when it is to be done overseas.

The concerns of privacy may affect the conduct of interviews. In a wind power conference, I asked the panellists (chief managers of large Chinese wind turbine manufacturers) a question about the difficulties they encountered in technological innovation. No one was willing to answer the question at that moment, but “technological innovation” was planned as a special session of the conference the next year. This may reflect a cultural issue that interviewees may be unwilling to privately speak out what they are concerned with. Besides, the interviewee may change his or her mind and become unwilling to proceed when a recorder is found being used. It is necessary to be aware of these problems before the interview and try to avoid them.

4.2.6 Case study

Case studies provide a valuable research method and have increasingly used in social science (Yin 2013). It allows investigators to focus on a “case” and retain a holistic and real-world perspective such as organisational and managerial processes and the maturation of industries (Yin 2013). It is especially useful when the research intends to answer what, how and why questions, which is often called explanatory case study (Yin 2013). Case studies can be used as the sole method but also work as a part of larger mixed methods study (Yin 2013).

Innovation system studies have mainly focused on macro structures and institutions and overlooked the dynamics of innovation at the micro (or firm) level (see Chapter 3). As a structural element, firms are the central agents of a TIS that bring about novel technologies and deliver them in the market. With little knowledge about the firm’s innovation activities, it seems impossible to fully understand how the innovation system works. It is, therefore, necessary to unfold the innovation process that occurs at the firm level, in the wider context of the innovation system.

Goldwind is currently the largest and oldest Chinese wind turbine manufacturer. The firm’s innovation strategy and the associated innovation process can reveal the generic innovation patterns in China’s wind turbine industry and help understand the success or failure factors. In order to conduct a case study on Goldwind, about 270 Chinese journal papers, magazines and newspapers were downloaded from the China Academic Journals Database (CNKI) plus nine company annual reports (2007-2015) downloaded from the official information disclosure platform (www.cninfo.com.cn) designated by the Chinese Securities Regulatory Commission. After careful scanning, about 30 documents were identified as most relevant for writing an in-depth case study showing how Goldwind has transformed from an imitator to an innovator via technological learning and innovation.

4.3 Data collection

A range of data has been sourced from recognised databases, statistical reports and online datasets (see Appendix B-2). This section addresses practical issues that arose when collecting and analysing data: a) inconsistencies of data across databases; b) official statistics versus commercial datasets; c) the potentially limited size of data samples; and d) timeliness of data.

The numerical values of data may differ across databases. The historical values of data compiled by the IEA are substantially inconsistent with Bloomberg's datasets. For example, the IEA RD&D database shows that wind energy RD&D budget for Germany was 60 million USD in 2014 while Bloomberg recorded that Germany's R&D public expenditure (excluding demonstration) on wind energy was 72 million USD. Another example is that China's wind power capacity compiled by the BP and Global Wind Energy Council was slightly different from the Chinese Wind Energy Association. The Electronic Wind Performance Reporting System was an important reference when tracking the unit capacity of the US wind turbines to the 1980s. However, the data was inconsistent with that in the *Wind Technologies Market Report* written by Ryan Wiser and Mark Bolinger who sourced the data from the American Wind Energy Association. In these cases, the data published by the international organisations was used for cross-country comparisons while the data compiled by national authority was adopted when analysing a specific country.

Currently, two databases are available to extract wind RD&D data for studying wind technology innovation – the IEA RD&D Database (official statistics) and the Bloomberg Terminal (commercial datasets). Apart from the obvious differences in numerical values, the RD&D data in the IEA database is missing for some years while the Bloomberg Terminal only keeps data from 2004. Given that China's wind power industry boomed since only a decade ago and private

R&D represents a vital part in fostering technological invention, this thesis refers to the Bloomberg Terminal for RD&D data. However, Bloomberg does not explicitly provide their methods used in collecting the data. The transparency of data collection and compilation needs to be improved.

The measurement of unit capacity (the MW output capacity of a wind turbine) is a novel indicator for assessing the outputs of technological innovation. It is not difficult to make cross-company comparisons on unit capacity by collecting the data from individual companies, but it can be very challenging if a full list of data collected from all the country's companies is required. There can be many wind turbine manufacturers in a single country, and most importantly, this type of data may not be publicly accessible. In the Danish, German and US wind power markets, only one or a few wind turbine makers are big enough (regarding capacity supplied) that are comparable to Chinese firms. Hence, only the largest company (often most competitive) in each of these countries are included when collecting unit capacity data. The limited size of company samples may affect the accuracy of statistics in certain circumstances.

For bibliometric and patent analyses, timeliness is a big issue. It is easy to count the number of total publications up to the most recent year, but it is impossible to present a 100% accurate number reflecting the amount of highly cited publications as citations are dynamic. It may take several years for the value of a journal paper to be widely recognised. Likewise, it may take up to 24 months for the patent offices to disclose the patent information. Regarding R&D data, the IEA database just reported wind energy RD&D budget up to 2015 (only less than 60% of the IEA member states' data were available) while the Bloomberg Terminal already updated data to 2016 when this thesis was written up.

4.4 Summary

This chapter describes the research design and analytical methods for the thesis. To appropriately answer the proposed questions, a "mixed methods" consisting of six concrete methods is employed to generate both quantitative and qualitative evidence. These methods are bibliometric analysis, patent analysis, scaling analysis, historical analysis, semi-structured interviews and case study. Each of the analytical dimensions, namely structural elements, functional patterns and system performance, involves at least one of the six methods.

The usefulness and limitations of the adopted methods are discussed. The key point is that each method can be used in different contexts for different purposes, but the effectiveness relies on how well it enables investigators to answer the proposed questions. It is important for analysts to become fully aware of the pros and cons of the methods to avoid inappropriate use. How the various types of quantitative and qualitative methods are adapted to this thesis as well as the lessons learnt for using them (e.g. semi-structured interviews) are covered in this chapter.

The availability and quality of data are vital for scientific research. A range of Chinese and English sources are referred to when collecting and analysing data. There exist some problems in the current statistics of energy innovation data. The improvement of data infrastructure and data sharing across organisations may be a solution to tackling the problems. Commercial databases (e.g. Bloomberg Terminal) play a role in closing the data gaps that may not be filled by official data agencies, but the transparency of practices and methods in data collection by commercial entities needs to be improved.

Chapter 5 An indicator framework for measuring energy innovation systems

A major task of this thesis is to make quantitative evaluations of the performance of China's wind energy innovation system. Based on the IS approaches, particularly the stages of energy technology innovation process (see Chapter 3), this chapter aims to derive an adequate indicator framework consists of inputs, outputs and outcomes for achieving this purpose.

Section 5.1 identifies the need for quantitative metrics for energy innovation systems (EISs). Section 5.2 compares the key characteristics of some existing research on generic and energy-specific innovation indicators. Based on these, section 5.3 proposes an indicator framework for measuring the performance of EISs. Section 5.4 presents the conclusions.

5.1 The need for quantitative metrics

Driven by the mounting concerns about climate change, energy security, affordability and economic prosperity, energy technology innovation has been identified as a critical element in the transition to a sustainable energy system (IEA 2015, IPCC 2014). In reaction to these pressures, the world's major economies' energy RD&D budgets have experienced significant growth in a bid to stimulate greater innovation following decades' of decline and stagnation (Skea 2014). Innovation funding is expected to increase even further following the landmark Paris Agreement in 2015, which saw the launch of both *Mission Innovation*, an agreement between 20 countries to double their clean energy R&D over the five years and the *Breakthrough Energy Coalition*, a global group of 28 high net worth investors from 10 countries committed to expand their energy investment portfolios.

Given this recent and expected growth in energy RD&D spending, there is a growing need for scholars and policy-makers to have the necessary tools at their disposal to assess how effective innovation support has been in delivering advances in energy technology and the types of policy interventions that could accelerate innovation in the future. A vital step in this direction is to develop an indicator framework that enables us to measure the effectiveness of EISs.

Quantitative indicators have long been considered a valuable instrument to help understand, measure and explain the complexity of innovation and variations in innovation performance across countries, regions or sectors (Freeman and Soete 2009, OECD 2015a, OECD and Eurostat 2005).

The literature on energy innovation indicators is still in its infancy (see section 5.2). The IEA emphasises that "*Ongoing evaluation of innovation effort is needed to assess success, accumulate learning experience and determine how to best support specific technologies*" (IEA (2015), pp. 16). In a bid to advance the state-of-the-art on energy innovation metrics, this chapter aims to derive an indicator framework by drawing upon the IS approaches and lessons from a host of pioneering studies on (energy) innovation indicators. The indicator framework incorporates *input, output and outcome metrics* into the energy technology innovation chain, namely *research, development, demonstration, market formation and diffusion* (Wilson and Grubler 2014, Grubler, Aguayo, Gallagher, et al. 2012, Gallagher et al. 2012). It is offered as a conceptual and methodological contribution to quantitative evaluations on EISs.

5.2 Indicator frameworks in literature

There is a large body of literature on innovation metrics, but not many linking them to EISs. This section examines the characteristics of some pioneering studies on generic innovation indicators and the emerging research on energy innovation metrics to identify the gaps.

5.2.1 Key concepts and terms

The key concepts in this chapter include the energy innovation system (EIS), the energy technology innovation chain, the functions of technological innovation systems, the purpose of measurement, measurement structure, inputs, outputs and outcomes (see Table 5-1). Some of these concepts have been discussed thoroughly in Chapter 3, and this subsection focuses on the purpose and measurement structure of an indicator framework as well as the categorization of inputs, outputs and outcomes.

An innovation system can be measured for different purposes. Analysts can use indicators to describe how many inputs have been transformed into outputs and outcomes or to assess how well the system performs regarding the innovation processes (or functions). The former (system-level) is concerned with the historical progress (or effectiveness/efficiency) of the observed innovation system, often in a descriptive perspective; the latter (function level) zooms in the key activities that lead to the historical progress of the system, so it has diagnostic or explanatory power. It is important to make a clear distinction between the different purposes. Otherwise, the indicators may be mixed up without clearly-defined purposes.

An indicator framework consists of structural components (or analytical dimensions) which are the central aspects to be measured by indicators. For example, the *Innovation Union Scoreboard* (Hollanders, Es-Sadki, and Kanerva 2015) uses “enablers”, “firm activities” and “outputs” to characterise the processes and achievement of innovation systems. The *Global Innovation Index* (Dutta, Lanvin, and Wunsch-Vincent 2015) adopts “input” and “output” to measure innovation performance. The selection of structural components relates to the purpose of measurement.

There are quite a few categorizations of indicators, but in a historical perspective, the input, output and outcome indicators capture well the generic process of technological innovation. Inputs measure the financial and human resources that have been put into the innovation process. Outputs quantify the intermediate results of the innovation process, such as scientific publications, patent applications, manufacturing capability and scaling-up of unit capacity. Outcomes characterise the impact of a novel technology on the economy, including economic growth, job creations and CO_2 emissions reduction.

The existing indicator frameworks suffer from several drawbacks. First, they have been constrained to inputs (e.g. R&D expenditure) and failed to consider outputs and outcomes (Sagar and Holdren 2002). Second, the purpose of measurement has not been clearly defined, with many tapping a mixture of system and function-level indicators without clarifying the differences. Third, composite indexes are often used to benchmark countries, but the selection, weighting and aggregation of indicators vary considerably among researchers (Grupp and Schubert 2010). Fourth, many studies ignore cross-country variations in industrial mixes which impose considerable effects on the final scores (Galindo-Rueda 2013).

The next subsections will review a host of indicator frameworks around four central aspects: level of assessment, selection of indicators, interpreting methods and data sources.

5.2.2 Generic innovation indicator frameworks

Main Science and Technology Indicators

The OECD has been a pioneer in developing science, technology and innovation indicators. Drawing upon the NIS framework, the Oslo Manual (OECD and Eurostat 2005) and Frascati Manual (OECD 2015a), the OECD have generated a series of reports monitoring the changing landscape of innovation. The foremost ones are the *Main Science and Technology Indicators* (MSTI) (OECD 2015d), *Science, Technology and Industry Scoreboard* (OECD 2015e), and *Science, Technology and Industry Outlook* (OECD 2014).

The MSTI is concerned with system-level measurement (see Table 4-1), while the latter two dig deeper into the processes (or functions) of innovation systems (e.g. flows of knowledge and technology, collaborations on innovation). The MSTI has not explicitly categorised indicators, but the selected metrics can be classified into inputs (e.g. R&D expenditure), outputs (e.g. patent applications) and outcomes (e.g. international trade in R&D-intensive industries). The OECD interprets data with individual indicators, resisting ranking innovation performance via composite indexes as "*they do not adequately reflect the diversity and linkages of innovation actors and processes*" (OECD (2010), pp. 3). All the data is sourced from established databases such as the OECD Science, Technology and R&D Statistics, OECD Patent Statistics, and OECD-WTO Statistics on Trade in Value Added.

Innovation Union Scoreboard

The *Innovation Union Scoreboard* (Hollanders, Es-Sadki, and Kanerva 2015) is published by the European Commission for benchmarking the innovation performance of EU Member States. It focuses on system-level evaluations, but some function-level indicators (e.g. innovation linkages) are also included. The report presents a measurement structure that consists of enablers, firm activities and outputs. The enablers are to capture the drivers of innovation (e.g. financial resources); firm activities are to quantify firms' innovation efforts (e.g. entrepreneurship & linkages); the outputs are to characterise the impact of innovation (e.g. export and sales).

The groupings of some indicators may be controversial. Unlike many other studies that group scientific publications into 'outputs', the report classifies them as 'enablers', but co-authorships between public and private sectors are put into 'firm activities'. The research adopts a composite index with all indicators given the same weight (1/25 for each indicator). The use of a composite index may be because "*European Union urged its Commission to work together with the EU-15 countries to develop indicators and a methodology for the benchmarking of national research policies*" (Balzat (2003), pp. 13). The data stems from multiple sources, such as the Community Innovation Survey (CIS), Scopus and UN Comtrade Database.

Global Innovation Index

The *Global Innovation Index* (Dutta, Lanvin, and Wunsch-Vincent 2015) is co-published by Cornell University, INSEAD, and the World Intellectual Property Organization. It is concerned with system-level evaluations and relies on two sub-indices – the innovation input index and the innovation output index. The inputs quantify the elements that enable innovative activities, e.g. political stability and trade conditions. The outputs capture knowledge and technology productions in the manufacturing industry and creative goods or services, e.g. scientific publications, patents, new businesses and exports of high-technology products. Like the *Innovation Union Scoreboard*, some function-level indicators such as R&D collaboration between university and industry are included.

The research comprises three composite indexes and one ratio. The composite index is the simple average of pillar scores, while the ratio (innovation efficiency ratio) is the relative value of output index score to input index score. It depends on three types of data: a) official statistics (54 indicators), b) survey (10 indicators) and c) existing composite indexes (15 indicators). Some indicators are subjective and depend on personal perceptions. For example, the data for the indicator '*the intensity of local competition*' is collected by asking the question "*how intense is competition in the local markets in your country?*" (pp. 397).

5.2.3 Energy innovation indicator frameworks

Nordic Energy Technology Scoreboard

The *Nordic Energy Technology Scoreboard* (Klitkou, Scordato, and Iversen 2010) is produced by the Nordic Energy Research Institute, aiming to evaluate the innovation performance of low-carbon energy technologies at the system level. Five types of indicator are proposed: structural, input, throughput, output and policy indicators.

Structural indicators measure framework conditions, such as R&D intensity, industrial specialisation and energy mix. Input indicators measure the amount of resources invested by public RD&D budgets. Throughput indicators evaluate intermediate results of innovation process by scientific publications and patents. Output indicators capture energy technology exports. Policy indicators assess the stability and longevity of energy technology policies. The number of indicators adopted is relatively small (about 12). The indicators are interpreted by descriptive statistics with data sourced from Eurostat, OECD STAN Database, IEA RD&D Database, European Patent Office Database and UN Comtrade Database.

Indicators for Energy Innovation System

The report *Indicators for Energy Innovation Systems* (Borup et al. 2013) builds an indicator framework by incorporating inputs, throughputs and outputs into each of the system functions (Hekkert et al. 2007b). Input indicators measure public support for energy technology, such as public RD&D budgets, shares of different types of energy organisations, and public opinions about energy technologies. Throughput indicators measure the dynamics of innovation system indicated by scientific publications and EPO patents. Output indicators measure the resulting outcomes of the innovation system, characterised by electricity generation from renewable sources, energy technology exports, and employment.

It is noticed that a few indicators repeatedly appear across functions, and some functions cannot be easily measured by the proposed indicators. For example, R&D funding appears both in knowledge development (input) and resource mobilisation (input) functions. The knowledge exchange function is only covered by throughput indicators, whereas the legitimacy function is not characterised by any output indicators. This raises a question whether it is suitable to integrate the 'input-throughput-output' categorization into the system functions analysis.

Energy Innovation Scoreboard

The *Energy Innovation Scoreboard* (Kettner et al. 2014) serves as an input for the "IEA Expert Group on R&D Priority Setting and Evaluation Programme" to develop an energy innovation scoreboard that can benchmark countries' innovation capabilities in energy technologies. The scoreboard adapts the measurement structure of the *Innovation Union Scoreboard* (Hollanders and Es-Sadki 2013), focusing on four thematic groups – context, enablers, outputs and outcomes. In addition to the seven complementary (system-level) indicators to augment the indicator framework, another ten indicators are derived to conduct the assessment.

The intention of the scoreboard is to make evaluations on the performance of innovation systems, but it does not distinguish between system-level and function-level indicators. Moreover, some indicators are somewhat irrelevant for measuring system-level performance. For instance, the indicator '*share of small and medium-sized enterprises (SMEs) conducting in-house research*' is useful for investigating the diversity of actors and the role of SMEs in developing novel technologies, but it cannot measure the results of innovation activities, namely the outputs and outcomes. The data is sourced from almost the same channels as the above reports.

Core findings from other research

Sagar and Holdren (2002) suggest assessing "*the effectiveness of energy R&D efforts in terms of technical advances for a given expenditure (i.e. input–output relationships) … and the effectiveness of implementation and diffusion of new energy technologies (i.e., utilisation of the output) (pp. 468)*". Gallagher, Holdren, and Sagar (2006a) propose using input, output and outcome metrics to measure energy technology innovations: "*input metrics measure both tangible and intangible contributions to the innovation process… (pp. 210), output metrics measure the product of the innovation process resulting from the later stages of ETI… (pp. 211), [and] outcome metrics reflect the success of the deployment or diffusion of technologies generated in the innovation process and in the energy domain (pp. 213)*".

Wilson et al. (2012) propose input, output and outcome to evaluate the global ETIS, but the efficacy of indicators need to be justified. Some indicators such as (1) 'analysis & modelling', (2) 'technology roadmaps', '(3) UK/EU doctoral training centres', (4) 'learning rate' and (5) 'technology collaboration' (e.g. IEA implementing agreements, US-China Clean Energy Research Centre work plans) may not be adequate measures. For example, learning rate (percent cost reduction per doubling of cumulative output) can be affected by many factors like input prices, economies of scale and changes in market conditions besides 'learning by doing' (Gallagher 2014). The indicators (1), (2) and (5) may generate little impact if they have not been translated into actions, while indicator (3) may encounter international comparability issues as the organisations 'doctoral training centres' do not even exist in some countries.

Table 5-1 The key features of the selected indicator frameworks

Studies	Measurement structure	System or function-level evaluation	Selection of indicators	Data & Analysis
OECD (2015d)	n/a	system level	• R&D expenditure • R&D personnel • patent applications • technology balance of payments • international trade in R&D-intensive industries	official statistics & composite index
Hollanders, Es-Sadki,	• enablers • firm activities	mixture	• human resources • research system	official statistics &

and Kanerva (2015)	• outputs		• finance & support • firm investments • linkage & entrepreneurship • intellectual assets • innovators • economic effects	individual indicators
Dutta, Lanvin, and Wunsch-Vincent (2015)	• input • output	mixture	• institutions • human capital & research • infrastructure • market sophistication • business sophistication • knowledge & technology outputs • creative outputs	official statistics + surveys & composite index
Klitkou, Scordato, and Iversen (2010)	• structure • input • throughput • output • policy	system level	• industrial specialisation • human resources • energy mixes • resource endowment • public RD&D budgets • scientific publications • patents • technology export • longevity of policy	official statistics & individual indicators
Borup et al. (2013)	• input • throughput • output	function level	• entrepreneurial activities • knowledge development • knowledge exchange • guidance of the search • market formation • resources mobilisation • creation of legitimacy	official statistics + surveys & individual indicators
Kettner et al. (2014)	• context • enablers • outputs • outcomes	mixture	• GDP per capita • energy R&D intensity • patent applications & grants • energy efficiency • the share of renewable energy • CO_2 emissions reduction • technology export	official statistics & composite index
IEA (2012)	• input • output • performance	system level	• R&D expenditure • patents • demonstration projects • the growth of deployment rates • patents filed in the least two countries • technology export	official statistics & individual indicators
Wilson et al. (2012)	• input • output • outcome	mixture	• analysis & modelling • technology roadmaps • technology collaborations • portfolios & programmes • RD&D investments • niche market investments • market diffusion • learning rates • social returns on investment • mitigation potentials	official statistics & individual indicators

Source: The author.

In the *Energy Technology Perspectives 2012*, the IEA (2012) assesses ETIs from five perspectives with six distinctive indicators: a) public R&D investment (R&D expenditure), b) technology development (number of patents), c) technology demonstration (number of demonstration projects), d) technology deployment (growth of deployment rates); and e) technology diffusion (number of patents filed in the least two countries, and technology exports). However, these indicators only capture part of the innovation inputs and outputs. The IEA (2015) suggests using three types of indicators – input, output and performance indicators, but no specific indicators are identified in the report.

5.3 The proposed indicator framework

This section proposes an integrative indicator framework for measuring the effectiveness of EISs building on the approaches summarised in section 5.2. Section 5.3.1 explains the rationales for incorporating input, output and outcome metrics into the energy technology innovation chain. Section 5.2.2 justifies the strengths and weaknesses of the selected indicators. Section 5.2.3 discusses the issue of normalising indicators.

5.3.1 Structuring the indicator framework

It seems that most established studies are concerned with system-level evaluations, but often they employ a mixture of system and function-level indicators. This may be because innovation is so complex that it is wise to include as many indicators as possible to capture all the factors that potentially affect the success of innovation. However, it may blur the purposes for which measurement is being conducted. Is it to understand the historical progress of the system or the key functions that affect the progress? An indicator framework with a clearly-defined purpose is vital for indicator development.

Energy technology innovation is a multi-dynamic process (Grubler and Wilson 2014, Grubler, Aguayo, Gallagher, et al. 2012, Gallagher, Holdren, and Sagar 2006a). It covers the stages of Research (S1), Development (S2), Demonstration (S3), Market Formation (S4) and Diffusion (S5) A robust indicator framework should be able to characterise the technological progress across these stages which contribute to the generation, adoption and diffusion of economically useful knowledge (Lundvall 1992). This chapter focuses on the historical progress of EISs, namely how many inputs have been transformed into outputs and outcomes, so system-level indicators better suit.

An innovation system produces a range of tangible and intangible resources like scientific knowledge, artefacts, infrastructure, skilled labour and revenues. These resources comprise the inputs, outputs and outcomes of the innovation system. For example, R&D expenditure and personnel are the essential inputs to generate technical knowledge often in the forms of publications and patents (outputs). The codified knowledge and technology can be traded to earn revenues from royalty and license fees (outcomes), or become accredited by international organisations as standards or certificates (outcomes) if it proves of high value. After a set of single technologies are transformed into prototypes, they need to be demonstrated (inputs) to advertise their technological characteristics, especially when the end-user markets are fragmented or novel technologies cannot compete with the incumbents. The characteristics of the technology (e.g. unit capacity) and economies of scale (e.g. unit cost) (outputs) can be improved or achieved through cumulative R&D efforts. When the technology has become accepted by the market, it will diffuse within or across sectors and borders (outcomes).

Herein, the indicator framework for measuring the performance of EISs consists of inputs, outputs and outcomes, which covers the entire process of energy technology innovation. The purpose is to describe how many inputs have been transformed into outputs and outcomes. A list of indicators is proposed to achieve this purpose (see Table 5-2). It is not a definitive list of system-level indicators but illustrates the possibility of integrating suitable indicators into this conceptual framework.

5.3.2 Justifying the selected indicators

The selected indicators are less than perfect. Each indicator may have its own strengths and weaknesses (see Table 5-3). Some work does not use publications as an indicator as "*it contains no direct measures of the output of scientific and technological activities*" (OECD (2013a), pp. 3), but patents were adopted as a proxy for R&D output (OECD 2013a). Language bias (Leeuwen et al. 2001) and patent examination procedures (OECD 2009b) have a substantial impact on bibliometric and patent analyses. Declining to use the indicators because of their limitations or using them without being conscious of their constraints will hamper quantitative analyses of innovation systems or convey misleading information.

Table 5-2 An indicator for measuring the performance of energy innovation systems

Energy technology innovation chain	Research (S1)	Development (S2)	Demonstration (S3)	Market Formation (S4)	Diffusion (S5)
Input					
R&D expenditure ($)	←	→			
Demonstration expenditure ($)			↔		
Asset finance ($)				←	→
Subsidies ($)				←	→
R&D personnel (counts)	←	—	→		
State labs & testing centres ($)	←	—	—	→	
Output					
Scientific publications (counts)	←	—	→		
Patent applications (counts)	←	—	—	→	
Unit capacity (MW)			←	—	→
Unit cost ($/MW)			←	—	→
Manufacturing capacity (GW)				←	→
Installed capacity (GW)				←	→
Outcome					
Royalty and license fees ($)				←	→
Industrial added value ($)				←	→
Technology diffusion via trade (GW, $)				←	→
Job creations (counts)				←	→
Power generation (TWh)				←	→
CO_2 emissions reduction (tonnes)					↔

Note: The double ended arrows map out the timeframes of individual indicators across the energy technology innovation chain.

Table 5-3 Strengths and weaknesses of the selected indicators

	Indicators	Strengths	Weaknesses
Input	R&D expenditure ($)	• core input for technological innovation (OECD 2015a) • time-series data is available • cross-country comparison is possible • can be broken down by types and funding sources	• data is only available for certain economies • difficulty of estimating private R&D spending
	demonstration expenditure ($)	• core input for demonstrating novel energy technologies (Gallagher, Holdren, and Sagar 2006a) • time-series data is available • cross-country comparison is possible • can be broken down by funding sources	• data is only available for certain economies
	asset finance ($)	• core input for financing power projects (FS-UNEP Collaborating Centre/BNEF 2016) • time-series data is available • cross-country comparison is possible • can be broken down by funding sources	• data is only available for certain economies
	subsidies ($)	• core input for financing (renewable) power integration (see Couture and Gagnon (2010))	• data is unavailable for many economies • technology-specific data is unavailable
	R&D personnel (counts)	• core input for human power for developing cutting-edge technologies (OECD 2015a)	• data is unavailable for many economies • technology-specific data is unavailable • data on education levels of R&D personnel is unavailable
	state labs & testing centres ($)	• core input for organising R&D activities (e.g. Risø) • the number of labs and testing facilities can be identified	• financial data is unavailable • difficulty of estimating the number of technologies
Output	scientific publications (counts)	• core output of R&D activities (see Daim et al. (2006)) • time-series data is available • cross-country comparison is possible • research networks (quality) can be mapped out (measured) (see Kajikawa and Takeda (2009)) • can be broken down by components (e.g. generator, blade, gearbox)	• language bias (Leeuwen et al. 2001) • the boundary of the technological field is difficult to identify • searching queries vary among analysts (Klitkou, Scordato, and Iversen 2010)
	patent applications (counts)	• core output of R&D activities (Park and Park 2006) • time-series data is available • cross-country comparison is possible • research networks (quality) can be mapped out (measured) (OECD 2009b)	• the boundary of the technological field is difficult to identify (OECD 2009b) • not all innovations are patented

		• can be broken down by components	• citations and claims are determined by patent examination procedures and patenting strategy (OECD 2009b) • time lags between application and grant dates
	unit capacity (MW)	• core indicator for assessing technological characteristics (see Wilson (2012)) • time-series data is available • cross-country comparison is possible	• cannot reflect the quality and reliability of technologies
	unit cost ($/unit)	• core indicator for assessing economic advantages (see Verbruggen et al. (2010)) • time-series data is available • cross-country comparison is possible	• cannot reflect the quality and reliability of technologies
	manufacturing capability (GW)	• core indicator for measuring resources output • time-series data is available • cross-country/company comparison is possible	• cannot reflect the proportion of imported technologies in manufacturing
	electricity generation (TWh)	• core indicator for measuring resources output • time-series data is available • cross-country/company comparison is possible	• affected by land size, technical efficiency, plant designs and resources (see Lu et al. (2016) and Li et al. (2015))
Outcome	royalty and license fees ($)	• core indicator for assessing R&D outcome • core indicator for assessing the quality of technology	• technology-specific (e.g. wind and solar PV) data is unavailable
	int. standards or certificates (counts)	• core indicator for assessing R&D outcome • core indicator for assessing the quality of technology	• official statistics are unavailable • technology-specific data is unavailable
	industrial added value ($)	• core indicator for measuring resources outcome • time-series data is available • cross-country/company comparison is possible	• data is unavailable for certain countries • technology-specific data is unavailable
	technology diffusion via trade (GW, $)	• core indicator for measuring resources outcome and technological advantages (see Baldwin (2004)) • time-series data is available • cross-country/company comparison is possible	• affected by trade rules and input prices (e.g. WTO trade rules, labour cost)
	job creations (counts)	• core indicator for measuring resources outcome • time-series data is available • cross-country comparison is possible	• affected by labour endowment and cost
	CO_2 emission reductions (tonnes)	• core indicator for linking energy innovation to climate change mitigation (see Riahi, Grubler, and Nakicenovic (2007)) • core indicator for measuring resources outcome • time-series data is available • cross-country comparison is possible	• subjective to emission factors that are affected by a variety of technological and policy issues (see Zhou, Ang, and Han (2010))

The input indicators can be broken down by funding sources (i.e. public or private) to understand the contributions of various actors in financing energy technology innovation. The R&D expenditure can be split into basic research, applied research and experimental development. However, these types of data for a specific sector or technology seem unavailable.

The output indicators can also be interpreted in various ways. Apart from the number of publications, the quality can be indicated by a country's share of the world's top 10% most cited publications. Likewise, the quality of patents may be examined by citations, claims or patent families (e.g. triadic patent family) (OECD 2009b). Deficits exist in bibliometric and patent analyses, but these two quantitative methods are valuable to estimate the technological change of the innovation system (see Yeo et al. (2015), No, An, and Park (2015)).

Regarding the outcome indicators, they seem difficult to breakdown by types or components (e.g. generator, blade, gearbox). Otherwise, a firm or country's specific strengths or weaknesses in particular components can be identified by looking at revenues or payments for royalty and license fees for the patented technologies

Data constraints constrain indicator development. A pragmatic approach is to derive indicators that can indirectly capture the elements of technological innovation. For example, it is difficult to figure out how many product or process innovations have been generated in China's wind turbine industry, but it is possible to analyse the scaling-up of the unit capacity of wind turbines manufactured by Chinese enterprises. In other words, it is worth studying the existing indicators and statistics to identify which can be utilised to measure innovation indirectly (OECD 2013b, Sagar and Holdren 2002).

5.3.3 Normalisation of innovation indicators

Normalisation of indicators is an important part of indicator development. Normalising a nominator with an appropriate denominator can make information more susceptible to meaningful interpretation. Not many would care about how much electricity is consumed annually in a country, but if divided by the population, then it can assess the country's access to electricity. This is useful for evaluating living standards in electricity-poverty countries so that resources can be mobilised to improve it. However, analysts should be cautious when normalising innovation indicators. A simplistic normalisation may convey misleading information.

For example, suppose that country A invested $1 billion in energy R&D with 200 publications and 100 patents produced, whereas country B invested $200 million with 100 publications and 50 patents. It is fair to say that country A has been more productive than country B, but if the outputs were divided by inputs (e.g. R&D expenditure), country B would outperform country A. Other examples include R&D expenditure, publications or patents per capita. They are often used to reflect a country's research intensity (or research excellence), but the R&D resources, publications or patents are exclusively utilised or produced by R&D personnel rather than the entire population. This type of normalisation makes countries with large populations but relatively lower proportions of R&D personnel appear disadvantageously in innovation rankings.

Absolute values may rank large countries at a higher place as they tend to produce more outputs, but this may not always be true. If a country was not innovative at all, then no outputs and outcomes would be produced whether it was large or small. A hidden requisite for the assumption that large countries produce more is that large countries are innovative. What if they were not innovative? China was far more wealthy and populous than Britain even after the Industrial Revolution (1760 - 1840) (see Maddison (2001), pp. 241, pp. 261), but China failed to bring about any major innovations during that period. This evidences that large countries may not be more productive if they are not or are less innovative. Hence, cross-country comparisons with absolute numbers are acceptable in some circumstances.

An alternative method is to divide the outputs and outcomes by inputs stage by stage. Then, the normalised indicators can be scientific publications per R&D (counts/million $), patents per publications (%), manufacturing per patent (GW/patent), and export per manufacturing (billion $/GW). However, there are considerable time lags between R&D funding, publications, patents, commercialised innovation and technology diffusion. Popp (2016) shows that there exists a 2-10 years' time lag between R&D funding and publications, and 4-12 years' time lag between R&D funding and patents in the energy sector. The time lags between R&D funding, commercialised innovation and technology diffusion have yet to be confirmed by scientific research. This means that it is wrong to simply divide outputs by inputs for the same year even if it is carried out stage by stage.

Another issue is the use of an aggregated index. The USA has never been on the top in the Global Innovation Index (GII), but no-one will disagree that the country is strong in developing advanced technologies. Some countries or regions (e.g. Singapore and Hong Kong) whose industrial mixes are less complex hold a high position in the GII. This may be caused by the ignorance of cross-country variations in industrial mixes (e.g. proportion of R&D-intensive industries), use of personal perceptions (e.g. the opinion survey in GII) and subjective weighting of input and output indicators.

Given the above issues, this thesis will employ individual indicators rather than composite indexes or output/outcome-input ratios to describe the historical progress of China's wind energy innovation systems.

5.4 Summary

This chapter has proposed an integrative indicator framework based on recognised concepts. It differentiates the measurement purposes of system and function-level indicators, and justifies the strength and weaknesses of the selected indicators. The incorporation of the energy technology innovation chain enables the identification of historical progress across stages. The normalisation of innovation indicators is discussed and it appears that the misuse of normalisation may cause biased information. In some circumstances, absolute numbers based on time-series data can well describe the technological change of the innovation systems.

To be specific, the indicator framework distinguishes between system and function-level indicators. System-level indicators are concerned with how many inputs have been transformed into outputs and outcomes, while function-level indicators are more diagnostic as to why the observed system has achieved to that level. The mixed use of system and function-level indicators may obscure the of measurement purposes and undermine the reliability of quantitative results.

The indicator framework goes beyond inputs to emphasise outputs and outcomes. It covers the entire innovation chain and allows us to identify the strengths or weaknesses across stages. Conventional analyses have been constrained to R&D expenditure, bibliometric or patent analyses, but just examining a few input or output indicators may cause partial views of the EISs. Moreover, the strengths and weaknesses of the selected indicators have been justified. It suggests crystally presenting the cons and pros of the adopted indicators so that follower researchers can make continuous improvement.

The indicator framework experiments with some 'new' indicators, inspiring us to study existing indicators and statistics and from there work to identify which can be adapted for measuring the effectiveness of EISs. This is valuable when current statistics are not able to meet data requirements if the proposed indicators are completely new. The next chapter will apply the proposed metrics to the wind turbine industry across China, Denmark, Germany and the USA to identify China’s comparative position.

Chapter 6 Comparing China's wind energy innovation performance with other countries

Performance evaluation is a central part of innovation policy as it helps decision makers to identify the potential gaps so that changes can be made when required. Few studies have measured the performance of China's wind energy innovation system although the country has leapfrogged to become the world's largest user of wind technology. The existing literature has generated mixed opinions regarding whether China has grown as a leading innovator in wind technology. The inconsistent conclusions are partly caused by the lack of adequate metrics and data. This chapter intends to narrow this gap by applying the proposed indicator framework (see Chapter 5) to the wind turbine industry across China, Denmark, Germany and the USA.

The purposes are threefold. First, the cross-country comparisons via adequate indicators can help specify China's comparative performance and potential gaps to the leading countries. Second, this empirical study can be used to mobilise and test the efficacy of the proposed indicator framework. Third, by developing and applying the indicator framework, it expects to draw lessons for future research on the improvement of indicators and analytical methods. This chapter is, to some extent, an extension of Chapter 5. They are aimed to make a conceptual and methodological contribution to the literature on metrics for energy innovation systems.

This chapter comprises five sections. Section 6.1 explains the rationales for using the selected indicators and the associated methods for collecting and processing data. Sections 6.2 and 6.3 quantitatively measure the innovation performance of the four countries at national and firm levels. Section 6.4 discusses the implications of quantitative results. Section 6.6 presents the concluding remarks.

6.1 Methods and data

This section is to explain the reasons for choosing a selected list of indicators (see Table 6-1) and the methods used for collecting and processing the data for the indicators.

6.1.1 Indicator coverage

The proposed indicator framework consists of eighteen indicators. It is not a definitive list of indicators for measuring the performance of energy innovation systems (EISs). Given that the research on the metrics for EISs is still nascent, it is important to keep the range of the indicators flexible. A few new indicators may be required in empirical research, or some of the indicators may be less relevant and need to be omitted in certain circumstances. The indicator framework aims to apply to all energy technologies, but for certain energy technologies, the indicators need to be modified to better suit the context. For example, installed capacity is a good measurement for relatively mature technologies like wind and solar energy, but it does not fit well immature technologies such as wave and tidal. These newly-developed technologies are in experimental development or demonstration stage and have yet to be commercialised. In other words, the suitability of the indicators depends on the development stage of a technology.

Technology-specific characteristics also help verify the appropriateness of the indicators. Unit capacity is a useful indicator for measuring the technological sophistication of power generating sets (e.g. wind turbine), but it may not be the ideal indicator for other technologies like biomass. The levelised cost of electricity (LCOE) seems to work better here (see IRENA (2012)). The LCOE varies considerably across technologies, countries and projects, depending on the renewable energy sources, capital and operating costs and the efficiency of the technology (IRENA 2012). The numerical value of this indicator is affected by many external variables that do not directly respond to the performance of the technology per se. In any case, modifications of the indicators may be required according to the specific characteristics of the technology.

Table 6-1 The coverage of metrics for cross-country comparisons

Metrics	Nation-level	Firm-level	Data sources
Input			
R&D expenditure ($)	√	√	BNEF (2016)
demonstration expenditure ($)	×	×	
asset finance ($)	√	×	BNEF (2016)
subsidies ($)	×	×	
R&D personnel (counts)	×	×	
state labs & testing centres ($)	×	×	
Output			
scientific publications (counts)	√	×	WoS (2016)
patent applications (counts)	√	√	EPO (2016), SIPO (2016)
unit capacity (MW)	×	√	Company reports/websites
unit cost ($/unit)	×	×	
manufacturing capacity (GW)	√	√	BNEF (2016)
installed capacity (GW)	√	×	BP (2016)
Outcome			
royalty and license fees ($)	×	×	
industrial added value ($)	×	√	BNEF (2016)
technology diffusion via trade (GW, $)	√	√	United Nations (2016)
job creations (counts)	×	×	
power generation (TWh)	√	×	BP (2016)
CO_2 emissions reduction (tonnes)	√	×	IIASA (2015)

Source: The author.

Wind technology has become quite mature, and all the proposed indicators are in a good position to measure the historical progress of the technology. However, only some of them will be employed to the wind turbine industry across the countries, largely due to the lack of official statistics for the indicators. It is possible to collect and compile the required data on one's own efforts, but it will cost too much time from the limited length of a PhD study. Further details about the methods and data processing practices will be discussed in the next section. By considering the data constraint issues, this chapter adopts nine indicators for nation-level comparisons and six indicators for firm-level comparisons (see Table 6-1). Each type of the comparisons covers the inputs, outputs and outcomes of the innovation systems so that it can characterise the historical progress of each country or firm's innovation performance.

Country size may have an influence on the results as large countries tend to produce more innovations. To avoid relying only on the nationally aggregated data, this chapter investigates innovation performance at both national and firm levels. Nation-level comparisons describe the country's aggregate performance while firm-level assessment reflects the gaps across firms. A combination of the nation and firm-level comparisons can avoid partial assessments and produce more comprehensive findings.

However, some indicators that are used at the national level will not be considered at the firm level because of suitability problems. For example, scientific publications are not a suitable indicator for measuring a firm's innovation performance because firms are concerned with patents rather than producing journal articles or books. Wind power generation will not be counted for firm-level comparisons because it makes little sense to compare power generation across wind turbine producers or wind farm developers. This indicator is more appropriate to characterise the societal returns and environmental impact of the technology on the economy.

6.1.2 Methods

Descriptive statistics are adopted to measure wind energy innovation performance characterised by the growth or decline of innovation inputs, outputs and outcomes across the chain-linked stages. China, Denmark, Germany and the USA vary significantly in terms of wealth and population. A common approach to eliminating the effect of country size on empirical results has been to normalise indicators by GDP or population. This thesis does not normalise indicators by GDP nor population for the following reasons.

GDP and population are both aggregate figures. A country's GDP includes economic production from all sectors while population covers the R&D and non-R&D workforce in all technological fields. It seems problematic to normalise technology-specific (e.g. wind energy) indicators with GDP or population when countries are markedly different in sizes. For example, China's GDP in 2015 was about 11 trillion US dollars versus Denmark's 295 billion USD dollars (37 times less) (World Bank 2016a). Regarding population, it was 1.38 billion for China and 5.67 million for

Denmark (243 times smaller) (United Nations 2015). If the outputs and outcomes of the innovation systems were divided by the respective GDP or population, then large economies may always lag behind smaller ones.

This research is mainly concerned with China's role in the global energy system, so the adoption of absolute metrics is appropriate. However, if the narrower purpose had been to compare the effectiveness of innovation systems, then normalised indicators would have worked better. As it is highlighted above, country size may affect the reliability of indicators even if they are normalised. It seems best to adopt normalised indicators when countries are similar in terms of GDP or population.

Researchers may be sceptical about using absolute metrics as large countries are often more productive, but the hidden requisite for this assumption is that they are innovative. If a country were not innovative at all, then few outputs and outcomes would be produced whether it was large or small. China was more wealthy and populous than Britain even after the Industrial Revolution (1760 - 1840) (see (Maddison 2001), pp. 241, pp. 261) but failed to bring about major technological innovations during that period. This demonstrates that large countries would not be more productive than small countries even in absolute terms if they were not innovative.

When employing absolute indicators, nationally aggregated data may exaggerate the innovative capability of large countries. Therefore, this research makes both national and firm-level comparisons. It is expected that a combination of national and firm-level comparisons can produce a more comprehensive picture and gain greater confidence in the results. A leading manufacturer for each country (i.e. Goldwind for China, Vestas for Denmark, Siemens for Germany and GE for the USA) is selected for cross-country comparison at firm level. Despite these, a few indicators such as publications and patents are often affected by language bias or patenting propensity (see Sections 4.2.1 and 4.2.2). The limitations of non-normalised indicators, bibliometric and patent analyses and data constraints somehow undermine the reliability of quantitative results.

This thesis reveals China's relative performance to Denmark, Germany and the USA. These countries represent the pioneers in developing wind technology. By benchmarking China's performance with the world leaders, it is possible to identify whether China has become a leading innovator in wind turbine technology. Also, they are the largest users of wind technology and lead the world in wind turbines export. By comparing China's historical progress with them, it allows us to identify China's gaps across the energy technology innovation chain, namely Research (S1), Development (S2), Demonstration (S3), Market Formation (S4) and Diffusion (S5).

6.1.3 Data sources

The administrative data used in this paper are collected from a range of public and private sources. It is found that commercial databases (e.g. Bloomberg Terminal) play an important role in closing the data gaps that may not be filled by official agencies like the IEA, but the transparency of their methods in data collection and compilation needs to be improved. Despite the sheer efforts by the authors, some data is still unavailable from existing data repositories, which means only some of the proposed indicators will be applied (see Table 3). The uncovered indicators caused by data constraints may inspire future efforts to improve data infrastructure and statistics.

It is a difficult task to identify the data sources for the energy innovation indicators. Desk-based research is important for searching, reviewing and analysing the datasets from a range of sources. A large amount of literature and databases were scanned to achieve this purpose. In many cases, the raw data needed to be cross-checked to ensure reliability. As Chapter 5 has already justified the strengths and weaknesses of the indicators, this section will only explain the methods and practices adopted when collecting and adopting the data. The meanings of the indicators will be explained according to the specific context of the technology, i.e. wind turbine industry.

R&D expenditure

According to the Frascati Manual (OECD 2015b), "*research and experimental development (R&D) comprise creative and systematic work undertaken in order to increase the stock of knowledge and to devise new applications of available knowledge*". It covers basic research, applied research and experimental development (OECD 2015b). The wind energy R&D data is collected from the Bloomberg Terminal (BNEF 2016) and Goldwind's annual reports.

There are two concerns about this data. First, BNEF (2016) did not explicitly explain what the wind energy R&D expenditure covered. The wind energy sector includes a variety of actors from raw material providers and component suppliers to wind turbine producers and wind farm developers. It is possible that the R&D data compiled by BNEF (2016) may not be constrained to the wind turbine industry but covered the spending by other participants such as wind farm developers. Second, corporate R&D data compiled by BNEF (2016) was slightly different from the firm's (e.g. Goldwind) own reports. In this case, Bloomberg's data is used for cross-country comparisons, while the data published by the firm itself is used to conduct a case study on the firm's technological innovation (see Chapter 9).

Asset finance

The term "asset finance" is a core concept of the *Global Trends in Renewable Energy Investment* – an annually updated publication by the Frankfurt School – UNEP Collaborating Centre for Climate & Sustainable Energy Finance, the United Nations Environment Programme (UNEP) and Bloomberg New Energy Finance (BNEF). By consulting the author, it was confirmed that asset finance refers to "*all investment into renewable energy generation projects at utility scale, namely investment in electricity generation, heat, and combined heat & power with a capacity of more than 1MW and investments in biofuels with a capacity of more than one million litres per year… It does not include any investment related to RD&D or production of plant components*".

It is clear that asset finance corresponds to the capital invested in the construction of wind power projects. R&D activities are the core input for technological innovation, but a novel technology may not be widely adopted if the relevant infrastructure is missing. Asset finance indicates the adoption of the commercialised technology. It is crucial to facilitate the diffusion of novel energy technologies and pulls the demand for innovations. The data is collected from the Bloomberg Terminal (BNEF 2016).

Scientific publications

The data for scientific publications is extracted from the Science Citation Index-Expanded (SCIE) database. The searching queries used for extracting the data are the same as presented in section 4.2.1 (TI = (energ* OR electricity* OR power* OR blade* OR rotor* OR gearbox* OR generator* OR nacelle* OR tower* OR inverter* OR converter* OR transformer*) AND TS=(wind)). The data only covers eight major components of wind turbine technology. The document type is limited to journal articles, proceedings paper, book chapters and reviews written in English.

Patent applications

The data for patent applications is extracted from PATSTAT (Worldwide Patent Statistical Database) and PIAS (Patent Information Analysis System). The PATSTAT is jointly managed by the European Patent Office (EPO) and the US Patent and Trademark Office (USPTO). The PIAS is developed by the China State Intellectual Property Office (SIPO). The searching codes for retrieving the patent data are the same as presented in section 4.2.2.

The reason for retrieving patent data from two databases is that PATSTAT did not contain the latest data from the Chinese market. PIAS recorded the data up to the most recent quarter. Also, it is inadequate to exclude the patent filings to the SIPO which is one of the world's largest patent authorities and receives hundreds of applications from domestic and foreign companies every year in the field of wind turbine technology. There are three types of patents in China, namely invention, utility and design patents. Many scholars hold that the quality of invention-type patents rather than the latter two is comparable to those filed at the EPO or USPTO. Therefore, only invention-type patents applied to the SIPO are considered.

Unit capacity

The data for the maximum unit capacity of wind turbines over time is collected from company websites and the Danish Energy Agency (for Vestas) (DEA 2016). Each country may have many wind turbine producers. It is extremely difficult to collect all the firms' data and compare them at nation-level. For example, there are about 26 wind turbine manufacturers present in the Chinese market. The number may be much smaller in the other countries as the markets are relatively mature and have experienced restructuring. Only a few of the most competitive companies have survived. Although China has many manufacturers, most of them are not as competitive as their foreign counterparts regarding technological capability. It is plausible to compare the maximum unit capacity by focusing on the national champion of each country, namely Goldwind for China, Vestas for Denmark, Siemens for Germany and GE for the USA. The maximum unit capacity does not include prototypes nor those are still being demonstrated. Only the commercialised wind turbines or those having at least 20 units deployed are included.

Manufacturing capacity

The manufacturing capacity refers to the annual additions supplied by the country or firm. A country may have many wind turbine manufacturers. It is hard to compile all the firms' data. Only the largest companies in each country (excluding China) is included in the aggregations. The data is extracted from the Bloomberg Terminal (BNEF 2016). The method is that one firm (Vestas) is calculated for Denmark, two (Siemens and Enercon) for Germany and one (GE) for the USA. China's manufacturing capacity can be calculated by multiplying the new additions by the ratio of Chinese wind turbines (vs. joint ventures and foreign wind turbines as reported by CWEA (2016b)) plus the units exported to other countries.

Installed capacity

Installed capacity describes the annual additions by the country. It is different from the manufacturing capacity as some countries may have installed less than they manufactured. For example, Denmark installed only 154MW of wind power in 2015 while Vestas exported wind turbines equivalent to about 7.3GW. In this case, installed capacity cannot well reflect the penetration of the technology in a country because it is subject to the country's wind energy resource, land size and public acceptance towards the technology. This indicator is very useful when the analysis is conducted on a global scale. If it is used at the national level just like this chapter, it may need to be complemented by other indicators (e.g. export).

Industrial added value

Industrial added value is an economic term which quantifies the value added of an industry or the gross domestic product (GDP) by the industry. At the firm level, it refers to the revenue made by a firm in a given year. The official statistics have not recorded the value creations by the wind turbine industry. The revenues made by a few wind turbine producers are available from the Bloomberg Terminal (BNEF 2016). It is worth mentioning that the firm's revenue may come from several business units such as sales of wind turbines, royalty and license fees and earnings from operation and maintenance services. Even within the wind turbine business, it is subject to many other variables such as economies of scale, input cost and trade tariffs.

Technology diffusion via trade

International trade data for wind turbine related technologies is available from the United Nations Commodity Trade Database (United Nations 2016) and the Bloomberg Terminal (BNEF 2016). The former refers to wind power generating sets (HS Code: 850231), excluding those with spark-ignition or compression-ignition internal combustion piston engines (Foreign Trade 2017). It recorded the overall trade value of a country in US dollars. In comparison, BNEF (2016) captured some firm's export of wind turbines in capacity. It is difficult to say what exactly the "wind power generating sets" cover, but it is likely that it contains sales of turbine components. Given the differences, nation-level comparisons use the data compiled by United Nations (2016) while firm-level comparisons adopt BNEF (2016)'s data.

Power generation

The data for wind power generation can be obtained from multiple sources. This thesis collects the data from the BP Statistical Review of World Energy (BP 2016) as it is easily accessible and documents time-series data back to 1990. The amount of power generated from wind turbines reflects the economic impact of the technology, but it depends on several other factors such as installed capacity, technical efficiency and grid connection. Some countries may suffer from curtailment issues due to the lack of grid infrastructure and market regulations.

CO_2 emissions reduction

The data for CO_2 emissions reduction is calculated from IIASA (2015)'s GAINS Model which estimated the emission factors of air pollutants (e.g. CO_2, SO_2, NO_x, PM) from fossil fuel power plants across the world. The emission factors of CO_2 from fossil fuel power plants in the four countries are respectively 1,067g/kWh (China), 1,235g/kWh (Denmark), 725g/kWh (Germany) and 735g/kWh (USA) (IIASA 2015). The amount of CO_2 emissions reduction by the adoption of wind technology equals to the emission factor multiplied by wind power generation. This indicator reflects the environmental impact of wind technology.

6.2 Nation-level comparison

This section employs nine quantitative indicators to compare the performance of China's wind energy innovation system with Denmark, Germany and the USA. The purpose is to identify China's comparative position in inputs, outputs and outcomes at the national level.

6.2.1 Inputs

R&D expenditure and asset finance

China's wind energy R&D spending (260 million USD) has surpassed the USA (104 million USD) since 2010 and is approaching to Germany (278 million USD) (see Figure 6-1). Between 2005 and 2015, China invested 2.2 billion USD in wind energy R&D, with an average annual growth rate of 10.5%, representing the fastest growth rate among the countries (BNEF 2016).

The wind R&D growth has been along with the rise of asset finance (see Figure 6-1). In 2015, China spent 50 billion USD on wind power projects, compared to 12 billion USD by Germany and 14 billion USD by the USA (BNEF 2016). In total, 240 billion USD was invested by China between 2005 and 2015, with an average annual growth rate of 46.5% (BNEF 2016).

In summary, China's wind energy R&D expenditure and asset finance rocketed over the past decade. China now leads the other countries in these two aspects. It implies that China has put huge efforts in Research (S1), Development (S2), Market Formation (S4) and Diffusion (S5) to promote innovation and diffusion of wind technology.

6.2.2 Outputs

Scientific publications

China's R&D effort seems to be paying off regarding the production of scientific publications (see Figure 6-2). In 2015, China overtook the USA and became probably the world's largest producer of scientific publications in wind turbine technology. Between 2005 and 2015, the number of publications authored by Chinese scientists increased from less than 30 to 560, with an average annual growth rate of 36.8% (WoS 2016). Even if it is measured by the world's top 10% cited publications[6], China has emerged to play a somehow leading role to that of the USA. It indicates that China has somewhat leapfrogged other countries in scientific publications.

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[6] Publications may differ in quality - higher quality research tends to be more frequently cited. The total publications reveal the quantity of accumulated knowledge while the highly-cited publications (e.g. top 10%) demonstrates the quality of knowledge stocks. The data after 2013 can be very subject to citation changes because it normally takes years for a paper to be fairly cited.

Figure 6-1 R&D expenditure (a, left) and asset finance (b, right)

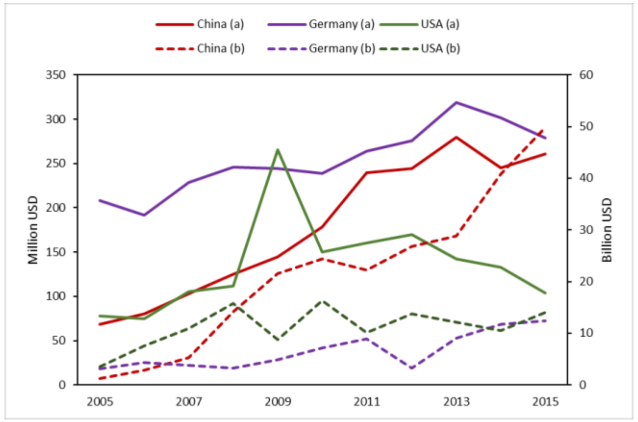


Figure 6-2 Total (a, left) and top 10% (b, right) SCI publications

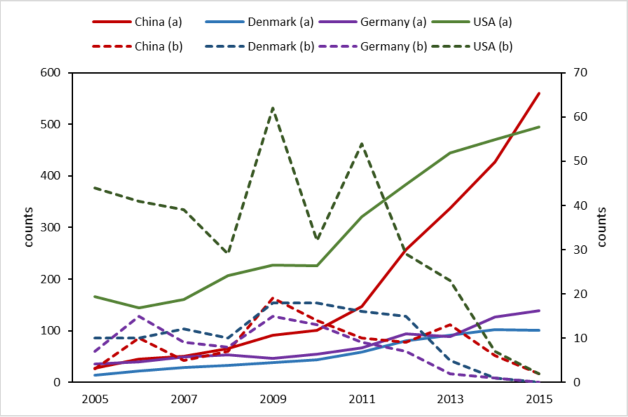


Figure 6-3 EPO (a), USPTO (b) and SIPO (c) patent filings

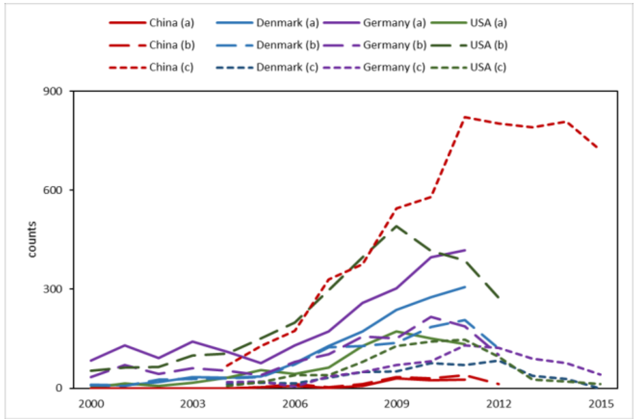


Figure 6-4 Manufacturing (a, left) and installed capacity (b, right)

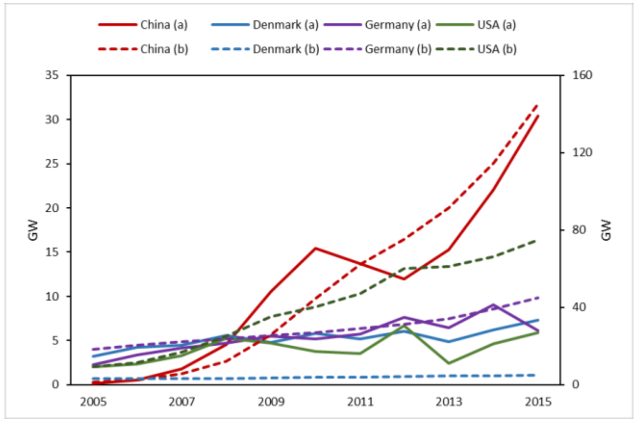


Figure 6-5 Export revenue of wind power equipment

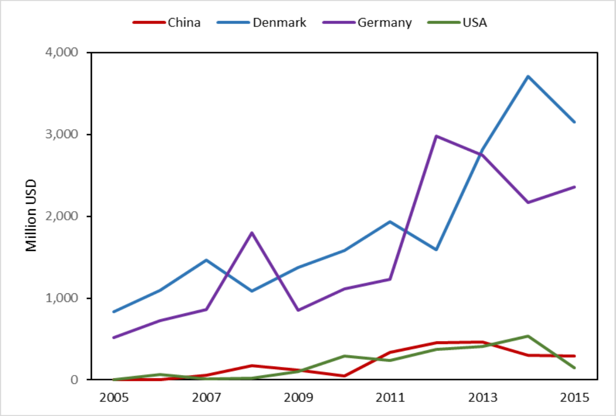
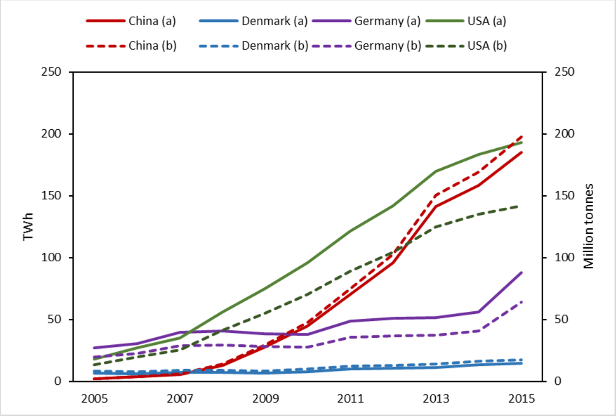


Figure 6-6 Wind power (a, left) and CO2 emissions reduction (b, right)



Note:

Figure 6-1:	a) Unless indicated, all monetary data in this chapter is calculated using exchange rates and converted into constant prices with 2015 as the base year; b) both public and private R&D is included; c) Source: BNEF (2016).
Figure 6-2:	Source: WoS (2016).
Figure 6-3:	a) Patent data after 2011 was unavailable from the PATSTAT; b) Source: EPO and USPTO (2016), SIPO (2016).
Figure 6-4:	a) Manufacturing capacity for each country is aggregated based on a few companies' data, i.e. Goldwind, United Power, Mingyang and Envision Energy for China, Vestas for Denmark, Siemens and Enercon for Germany, and GE for the USA; b) Source: BP (2016) and company annual reports.
Figure 6-5:	Source: United Nations (2016).
Figure 6-6:	a) CO_2 emissions reduction by utilising wind power was calculated by referring to the emission factors of fossil-fuel power plants estimated by IIASA's GAINS Model; b) Source: IIASA (2015) and BP (2016).

Patent applications

China performs well in scientific publications but lags significantly in patent filings at the EPO and USPTO (see Figure 6-3). In 2011, China only made 26 applications to the EPO and 40 to the USPTO, compared to 398 EPO filings and 188 USPTO filings by Germany (EPO and USPTO 2016). Before 2005, no Chinese residents had made patent applications to neither the EPO nor USPTO in the field of wind turbine technology (EPO and USPTO 2016). China's gap to the other countries in EPO and USPTO filings widened over the last decade.

When it comes to the patent filings to the SIPO, China far led the other countries. It made 820 SIPO filings in 2011, compared to 70 by Denmark, 130 by Germany and 148 by the USA (SIPO 2016). Between 2005 and 2011, China's SIPO filings increased by 540%, with an average annual growth rate of 40% (SIPO 2016). China caught up fast with the other countries in SIPO filings.

Manufacturing and installed capacities

Currently, half of the world's largest wind turbine manufacturers are Chinese firms (REN21 2016). These firms' manufacturing capacity in total equals to Vestas and GE combined (see Figure 6-4). The supply of wind turbines at reasonable prices enables China to deploy the technology at a massive scale. China's installed capacity of wind power increased from less than 1.3GW in 2005 to 145GW by 2015, with an average annual growth rate of 66% (BP 2016). China's cumulative capacity is three times more than Germany and two times the size of the USA.

In summary, China has caught up fast in scientific publications, manufacturing and installed capacities as well as patent filings at home and abroad authorities. These suggest that China has begun to harvest from its tremendous inputs in Research (S1), Development (S2), Market Formation (S4) and Diffusion (S5). However, China significantly lags the other countries in EPO and USPTO filings and the gap widened between 2005 and 2011.

6.2.3 Outcomes

Technology diffusion via trade

Denmark leads the other countries in wind power equipment export (see Figure 6-5). China and the USA have been rather small players in international trade of wind technology. In 2015, China exported wind power equipment worth 290 million USD, compared to 3.15 billion USD by Denmark and 2.4 billion USD by Germany (United Nations 2016). Chinese firms began to export wind turbines since 2007 (CWEA 2016b). Between 2007 and 2015, China's average annual growth rate of export of wind power generating sets is about 84%, compared to 14% by Denmark, 27% by Germany and 85% by the USA (United Nations 2016).

Power generation and CO_2 emissions reduction

China's wind power generation reached 185TWh in 2015, almost the same as the USA and equals to one-third of Germany's total electricity generation (BP 2016). Between 2005 and 2015, China's electricity generated from wind turbines increased by 62% on average, compared to 8% by Denmark, 14% by Germany and 28% by the USA (BP 2016). The adoption of wind power helped China reduce nearly 200 million tonnes of CO_2 emissions in 2015 that may have been emitted into the air from fossil-fuel power plants. The environmental impact of wind technology has been very obvious for large countries like China and the USA.

In summary, China leads the other countries in the amount of wind power generation and the associated impact on CO_2 emissions reduction. It demonstrates that China is benefiting from the outputs in Market Formation (S4) and Diffusion (S5).

6.2.4 Summary of nation-level comparison

China leads in six and lags in two of the eleven indicators (6:2), compared to 1:5 by Denmark, 2:2 by Germany and 3:3 by the USA (see Table 6-2). To be specific, China leads the other countries in R&D expenditure, SCI publications, SIPO filings, manufacturing capacity, installed capacity and CO_2 emissions reduction; but it falls behind in EPO and USPTO filings. It implies that China's relative weakness in inventive capability constrains its technological innovation. However, China's patent applications filed at the domestic authority show a contradictory result. One possible explanation for this is that the Chinese market demand is large enough to allow the Chinese firms to enjoy sustained growth by staying at home before they risk competing with the internationally leading firms in advanced markets where IPRs are essential.

Table 6-2 The inputs, outputs and outcomes across countries, 2015

Metrics	High ←			Low
Input				
R&D expenditure (million $)	🟪 278	🟥 206	🟩 104	
Asset finance (billion $)	🟥 50	🟩 14	🟪 12	
Output				
SCI publications (counts)	🟥 560	🟩 495	🟪 139	🟦 101
Top 10% SCI publications (counts)*	🟩 54	🟦 16	🟥 10	🟪 9
EPO filings (counts)*	🟪 418	🟦 307	🟩 133	🟥 26
USPTO filings (counts)*	🟩 388	🟦 207	🟪 188	🟥 40
SIPO filings (counts)*	🟥 821	🟩 147	🟪 130	🟦 71
Manufacturing capacity (GW)	🟥 30.4	🟦 7.3	🟪 6.1	🟩 5.9
Installed capacity (GW)	🟥 145	🟩 75	🟪 45	🟦 5
Outcome				
Technology diffusion via trade (million $)	🟦 3,150	🟪 2,358	🟥 291	🟩 149
Power generation (TWh)	🟩 193	🟥 185	🟪 88	🟦 14
CO_2 emissions reduction (million tonnes)	🟥 198	🟩 142	🟪 64	🟦 18

* The data is based on the year of 2011.	🟥 China	🟦 Denmark	🟪 Germany	🟩 USA

Source: The author.

Another observation is that Germany and the USA perform moderately well while Denmark which has often been considered as one of the most advanced countries in wind technology underperforms in the majority of the indicators. However, Denmark performs excellently in wind turbines export, followed by top 10% SCI publications, EPO and USPTO filings and manufacturing capacity. The relative underperformance of Denmark seems to suggest that large countries tend to be ranked higher at nation-level comparisons. To avoid the impact of country size on the results, section 6.3 will conduct firm-level comparisons.

The above summarised the results of horizontal comparisons between each country's inputs, outputs and outcomes in a given year. The following will reveal the vertical comparisons of each country's inputs, output and outcomes over time to identify the potential correlations. In order to draw implications from the historical patterns of the advanced countries, the summary of China's results will be presented at the end.

Denmark

Among the eleven indicators, SCI publications and export revenue have increased fastest, followed by manufacturing capacity and installed capacity (see Figure 6-8). All the variables have increased over time except RD&D (since 2010). Denmark's wind energy R&D expenditure by the public and private sectors is unavailable from the Bloomberg Terminal, so it is substituted by the IEA's RD&D budgets which may be lower or higher than the actual spendings. Denmark's wind energy innovation system has followed a relatively consistent pattern regarding the growth of inputs, outputs and outcome. The outcomes have increased more rapidly than the outputs.

Germany

Similar to Demark, Germany's SCI publications, power generation and export revenue have increased most between 2005 and 2015 (see Figure 6-9). All the indicators have increased except export revenue, asset finance and USPTO filings. SCI publications, manufacturing capacity and export revenue declined in recent years. Germany's wind energy innovation system had not strictly followed a consistent pattern between inputs, output and outcomes. The indicators have all increased since 2005, but the discrepancies and increasing patterns are quite different.

USA

Regarding the USA, SCI publications, power generation and installed capacity have risen most significantly. Before 2010, almost all the indicators had followed similar increasing patterns except for top 10% publications (see Figure 6-10). Since 2010, the SCI publications, power generation and installed capacity increased dramatically while R&D expenditure and asset finance declined slightly. The US wind energy innovation system had followed a consistent increasing pattern regarding the inputs, outputs and outcomes before 2010 but diverged between inputs, outputs and outcomes afterwards.

China

Among the eleven indicators, China has witnessed the largest increase in export revenue and SCI publications, followed by installed capacity and power generation (see Figure 6-7). It is interesting to find that China's wind energy innovation system has so far demonstrated the most obvious increasing pattern between the input, output and outcome indicators. The outputs and outcomes have grown more rapidly than the inputs since 2010. Before 2010, China had kept investing wind energy R&D at almost the same level while all the outputs and outcomes failed to increase in a similar speed. Like the USA, the Chinese data also suggests that the effects of cumulative R&D and asset financing began to emerge in the country.

In summary, China's wind energy innovation system has been operating stably regarding the growth of inputs, outputs and outcomes, and is moving towards the right direction. The issue lies in the country's deficit in EPO and USPTO filings. In comparison, the innovation systems of Denmark, Germany and the USA have operated less stably - they have all slowed the growth of or even cut R&D expenditure. Germany and the USA have also reduced asset finance in recent years. Despite the stagnant growth or reduction of inputs by Denmark, Germany and the USA,

Figure 6-7 China: inputs, outputs and outcomes

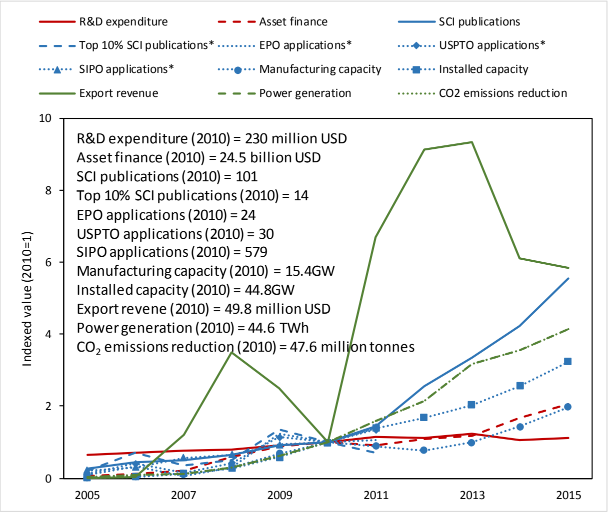


Figure 6-8 Denmark: inputs, outputs and outcomes

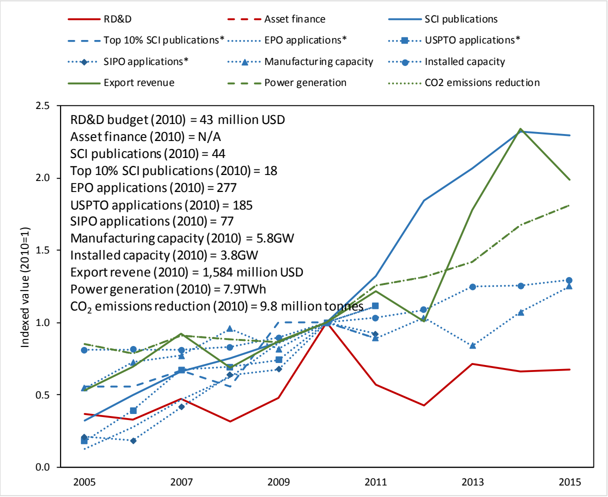


Figure 6-9 Germany: inputs, outputs and outcomes

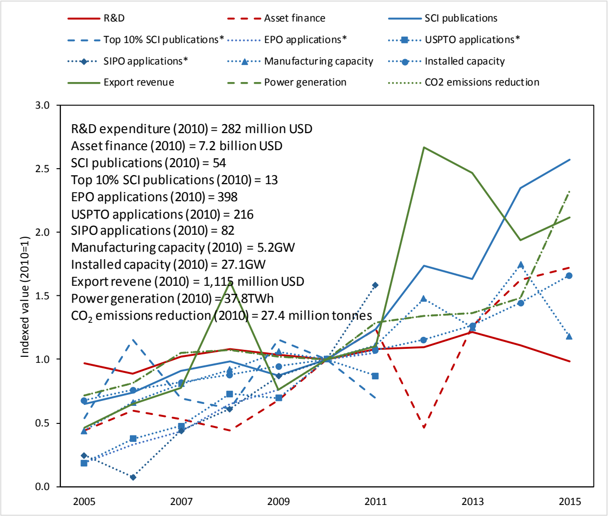
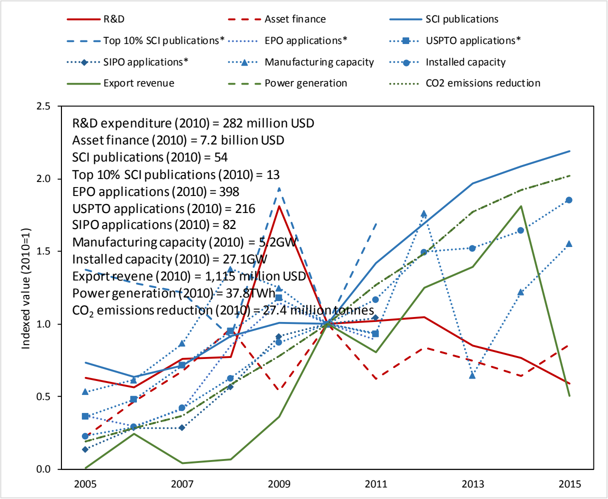


Figure 6-7 USA: inputs, outputs and outcomes



Note:

Figure 6-7:	a) The data for the top 10% SCI publications and SIPO filings after 2011 are omitted as they are subject to citation changes and patent examination procedure; b) CO2 emissions reduction overlaps with power generation in indexed values; c) these two notes apply to Figures 6-8, 6-9 and 6-10; d) Source: Multiple sources.
Figure 6-8:	a) RD&D budgets are used instead from the IEA's RD&D database; b) asset finance data is unavailable; c) Source: Multiple sources.
Figure 6-9:	Source: Multiple sources.
Figure 6-10:	Source: Multiple sources.

the systems' outputs and outcomes have continued to increase. In particular, they are all far ahead of China in EPO and USPTO filings. The continued increase of outputs and outcomes along with the stagnant growth or reduction of inputs indicates the importance of cumulative R&D investment. In other words, technological innovation requires continuous inputs of R&D, and the effect of prior R&D efforts and achievements matter much (see Laurens et al. (2016)).

6.3 Firm-level comparison

This section employs six quantitative indicators to make cross-company comparisons. The national champion of each country (i.e. Goldwind, Vestas, Siemens and GE) is chosen to identify the firms' comparative positions in inputs, outputs and outcomes.

6.3.1 Inputs

R&D expenditure

Vestas is a large R&D spender on wind turbine technology. The firm's R&D expenditure peaked at 328 million USD in 2012 and declined considerably since then (see Figure 6-11). It was overtaken by Goldwind which invested 250 million USD for R&D activities in 2015 (BNEF 2016). However, the cumulative R&D expenditure by Vestas between 2005 and 2015 hit 2.2 billion USD, far ahead of Goldwind's 0.9 billion USD (BNEF 2016). During the same period, Goldwind's R&D expenditure increased by 88% on average, compared to 13.6% by Vestas (BNEF 2016).

In summary, Goldwind is catching up fast in Research (S1) and Development (S2) and heading towards a top R&D spender. However, this has happened very recently. The cumulative R&D investment by Vestas over the past decade is two and a half times more than Goldwind.

6.3.2 Outputs

Patent applications

Just as China's relative weakness in patent applications at the national level, the performance at the firm level has appeared deficient too. As of 2011, Goldwind had registered only three patent applications to the EPO and USPTO, plus five by its German subsidiary Vensys (EPO and USPTO 2016). In comparison, Siemens filed about 180 patent applications to the EPO and 32 to the USPTO in 2011 (see Figure 6-12). Siemens, Vestas and GE lead significantly ahead of Goldwind.

Even in the Chinese market, Goldwind was not able to patent until 2010 (SIPO 2016). The firm merely made 8 patent applications to the SIPO, compared to 56 by Vestas, 58 by Siemens and 131 by GE (SIPO 2016). Before 2007, Vestas and Siemens had almost no patenting records at SIPO, but they had quickly built a strong patenting stock since then. The rapid increase may attribute to their prior inventions – they can modify their prior patents filed at the EPO or USPTO to meet the Chinese criteria so that the technologies can also be protected in the Chinese market. Goldwind has no prior inventions and must start from the very beginning. The recent data indicates a rapid growth of Goldwind's patent filings and a significant decline of the other firms, but this may be affected by the patent authority's examination procedure.

Unit capacity

There occurred a series of remarkable unit scaling in Europe and the USA between the early 1980s and 2005 when Vestas, Siemens and GW upgraded wind turbines from less than 1.0MW to 3.0MW (see Figure 6-13). Goldwind was not able to develop 1.5MW wind turbines (prototype) until 2003, thanks to a joint R&D project with Vensys. Since then, Goldwind scaled up turbine size to 3.0MW by 2015 when Vestas and Siemens successfully developed large offshore wind turbines that had a rated capacity of 6-8MW. Goldwind has developed 6.0MW prototypes, but they are yet to become commercialised and thus not included in the scaling analysis. There is still a large gap between Goldwind and the leading players in unit capacity.

Manufacturing capacity

Figure 6-8 R&D expenditure

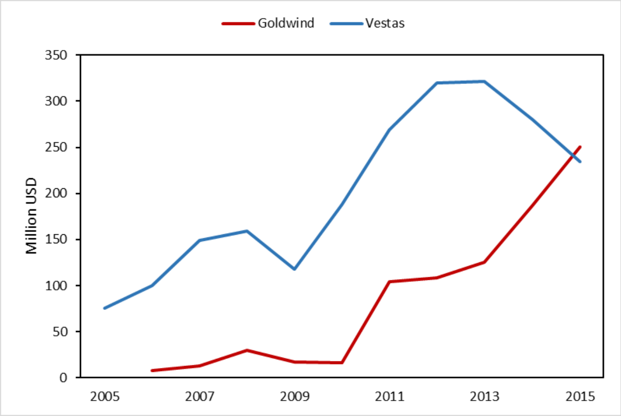


Figure 6-9 EPO (a), USPTO (b) and SIPO filings (c)

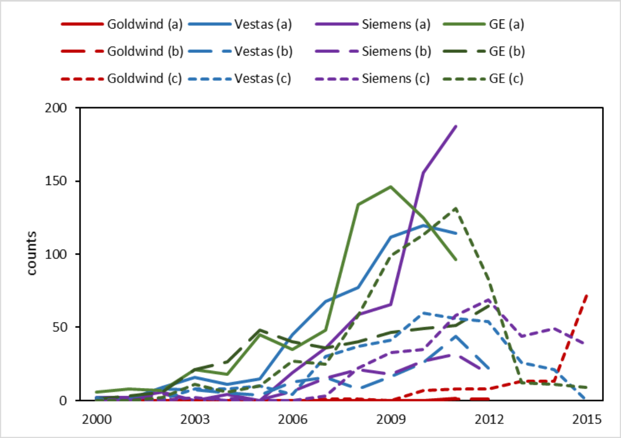


Figure 6-10 Maximum unit capacity

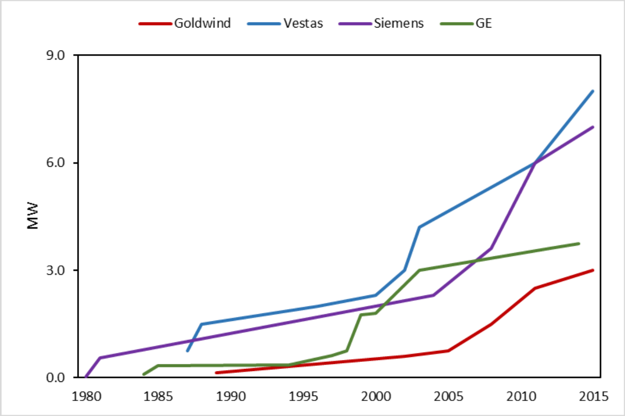


Figure 6-11 Manufacturing capacity

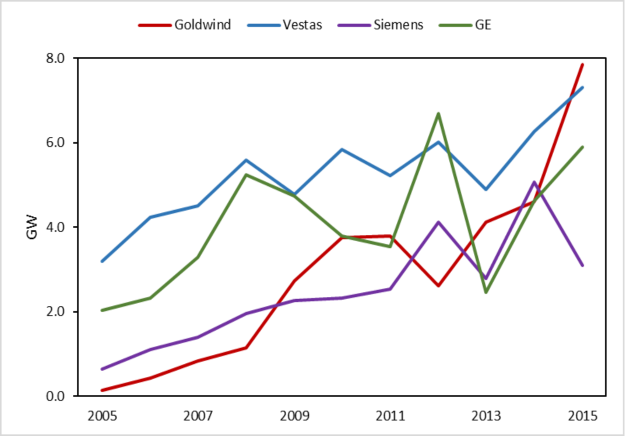


Figure 6-12 Revenue

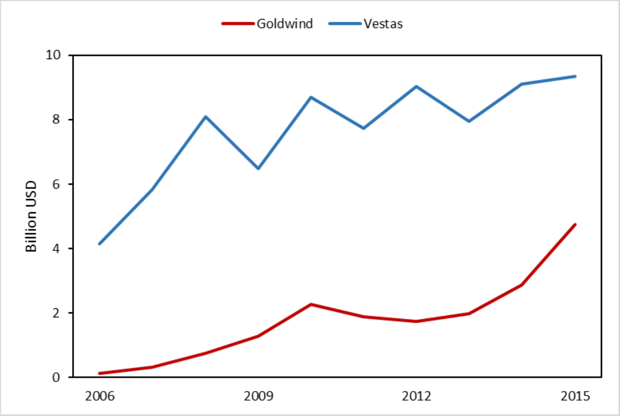
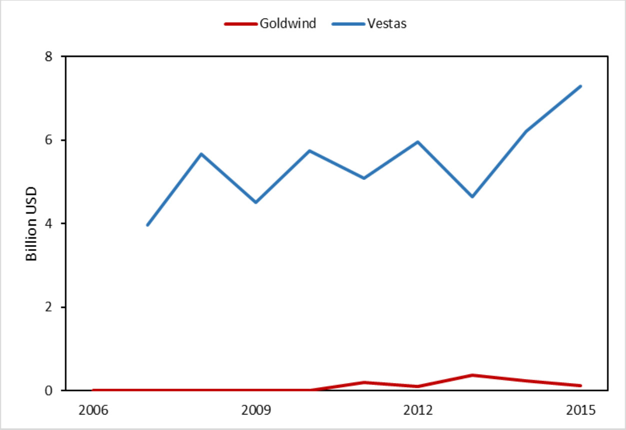


Figure 6-13 Export of wind turbines



Note:	
Figure 6-11:	a) R&D intensity refers to the ratio of R&D expenditure to total revenue; b) the data for Siemens and GE is unavailable; c) Source: BNEF (2016).
Figure 6-12:	Source: EPO and USPTO (2016), SIPO (2016).
Figure 6-13:	Source: Company websites.
Figure 6-14:	Source: BNEF (2016).
Figure 6-15:	Source: BNEF (2016).
Figure 6-16:	Source: BNEF (2016).

Driven by the fast-growing Chinese wind power market, Goldwind overtook Vestas and became the world's largest wind turbine producer in 2015 (see Figure 6-14). The firm delivered 7.8GW of wind turbines in 2015, compared to 7.3GW by Vestas, 3.1GW by Siemens and 5.9GW by GE (BNEF 2016). Between 2005 and 2015, the firm supplied 32GW of wind turbines to meet the booming Chinese market, with an average annual growth rate of 64% (BNEF 2016). Vestas and Siemens experienced gradual increases over that period while GE underwent ups and downs.

In summary, Goldwind has achieved remarkable progress in manufacturing relatively smaller wind turbines, which corresponds to Market Formation (S4) and Diffusion (S5); but the firm significantly lagged the other countries in the Development (S2), Demonstration (S3), Market Formation (S4) and Diffusion (S5) of large wind turbines.

6.3.3 Outcomes

Revenue and export

Goldwind leads in manufacturing capacity but far lags Vestas in revenue (see Figure 6-15). In 2015, Goldwind made 4.8 billion USD which was just half of Vestas' sales. This may be because Vestas turbines are priced higher than Goldwind's. On average, it costs about 1.28 million USD/MW for Vestas wind turbines, and 0.61 million USD/MW for Goldwind turbines[7] (BNEF 2016). It is interesting to find that lower prices have not worked as a competitive advantage for

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[7] Unit price is estimated based on the firm's revenue divided by the capacity it delivered in 2015.

Goldwind in the international market. Perhaps, the quality and reliability of turbines, as well as certification, are the other major concerns for wind farm developers (GWEC and IRENA 2012).

Regarding export performance, Vestas acts as a global trade leader, whereas Goldwind relies heavily on the domestic Chinese market. In 2015, Vestas exported about 7.2GW of wind turbines, compared to 115MW by Goldwind (BNEF 2016). Exports account for 96% of Vestas' delivered capacity while it is only 1.5% for Goldwind (BNEF 2016). Denmark's domestic demand for wind turbines is small while the Chinese market is huge. However, the export performance somewhat demonstrates the international competitiveness between Goldwind and Vestas.

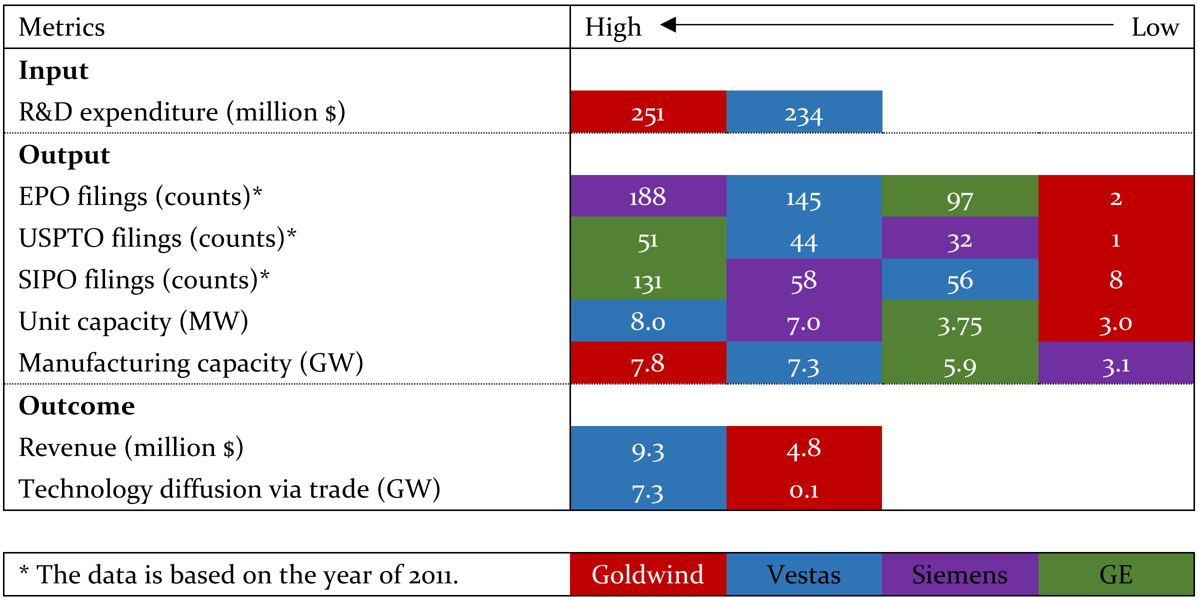
In summary, Goldwind largely falls behind Vestas in revenue and export. Besides, Vestas is strongly export-oriented while Goldwind is constrained to the domestic Chinese market. It suggests that Goldwind has achieved some success in certain aspects (e.g. manufacturing capacity) of Market Formation (S4) and Diffusion (S5) but underperformed in others.

6.3.4 Summary of firm-level comparison

Goldwind leads in two and lags in six of the eight indicators (2:6), compared to 3:1 by Vestas, 1:1 by Siemens and 2:0 by GE (see Table 6-3). To be specific, Goldwind leads the other companies in R&D expenditure and manufacturing capacity but falls behind in EPO, USPTO and SIPO filings, unit capacity, as well as revenue and export performance. The relative weakness in inventive capability constraints Chinese firms' technological innovation. The gap in patent filings between Goldwind and the other companies is very large. Although Goldwind delivered slightly more wind turbines than Vestas, the firm's revenue was just half of the latter's. When it comes to technology export, Goldwind's share was tiny compared to Vestas.

Vestas performs excellently, followed by GE and Siemens. The firm leads in almost all indicators except for the number of SIPO filings which was only two less than Siemens. Very different from the nation-level comparison, this firm-level comparison has shown that Denmark is perhaps the most advanced country in wind technology innovation. Denmark's success has to a large extent been demonstrated by Vestas' magnificent outputs and outcomes, particularly in unit capacity, revenue and export. It implies that firms in small countries can be ranked very high and that merely relying on nation-level comparisons may generate biased information.

Table 6-3 The inputs, outputs and outcomes across companies, 2015



Metrics	High ←			Low
Input				
R&D expenditure (million $)	🟥 251	🟦 234		
Output				
EPO filings (counts)*	🟪 188	🟦 145	🟩 97	🟥 2
USPTO filings (counts)*	🟩 51	🟦 44	🟪 32	🟥 1
SIPO filings (counts)*	🟩 131	🟪 58	🟦 56	🟥 8
Unit capacity (MW)	🟦 8.0	🟪 7.0	🟩 3.75	🟥 3.0
Manufacturing capacity (GW)	🟥 7.8	🟦 7.3	🟩 5.9	🟪 3.1
Outcome				
Revenue (million $)	🟦 9.3	🟥 4.8		
Technology diffusion via trade (GW)	🟦 7.3	🟥 0.1		

* The data is based on the year of 2011.	🟥 Goldwind	🟦 Vestas	🟪 Siemens	🟩 GE

Source: The author.

There are also consistent findings between nation and firm-level comparisons. First, advanced countries lead in R&D expenditure (Goldwind surpassed Vestas just in 2015), patent filings and export. Second, China leads in manufacturing capacity but lags significantly in patent filings and export. Third, China is catching up fast in R&D expenditure. A combination of the nation and firm-level comparisons can produce more convincing and comprehensive results.

The above makes horizontal comparisons between each firm's inputs, outputs and outcomes in a given year. The following will show the vertical comparisons of each firm's inputs, output and outcomes over time to identify the potential correlations. In order to draw implications from the internationally leading companies, Goldwind's results will be presented at the end.

Vestas

Among the eight indicators, Vestas has witnessed the fastest growth in unit capacity, followed by R&D expenditure, manufacturing capacity and export (see Figure 6-18). The indicators have experienced similar increasing patterns except for R&D spending which declined in recent two years. The patent filings show that Vestas seemed to have been more interested in applying to the EPO and SIPO than the USPTO. The inputs and outputs have increased more rapidly than the outcomes. This implies that Vestas is intensifying the efforts of pushing technology frontiers.

Siemens

Within the output indicators, Siemens has witnessed the fastest increase in unit capacity (see Figure 6-19). Between 2005 and 2011, the increasing patterns between the output indicators were quite similar, but the firm's manufacturing capacity went big ups and downs afterwards. The patent data shows that Siemens accelerated patenting in the US market. As the data for the inputs and outcomes are unavailable, it is unknown which part has grown most rapidly.

GE

Regarding GE, manufacturing capacity has risen most significantly. There was not a consistent increasing pattern among the output indicators (see Figure 6-20). Between 2005 and 2011, GE maintained similar patenting productions in the domestic market while intensified patent filings in Europe and China, particularly the former. The input and outcome data is unavailable, so it is difficult to know which type has increased fastest over that period.

Goldwind

Goldwind has accelerated R&D expenditure and SIPO filings the fastest (see Figure 6-17). The firm's export increased by 80 times between 2011 and 2013, but the peak value was just 400MW. The unit capacity has increased steadily along with the firm's revenue. By looking at the R&D expenditure and SIPO filings, it shows that Goldwind is intensifying technological efforts.

Figure 6-16 Goldwind: inputs, outputs and outcomes

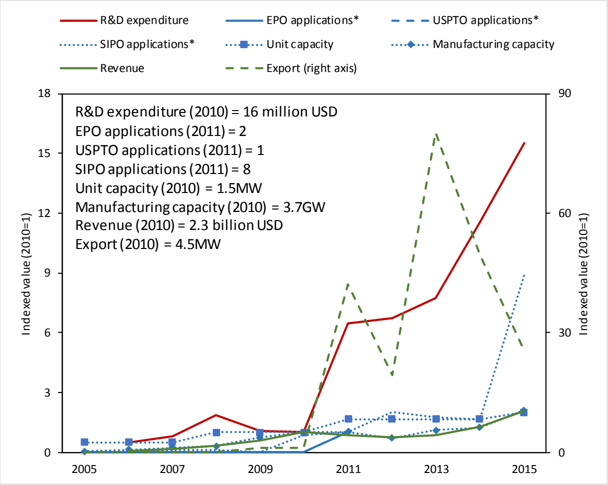


Figure 6-15 Siemens: inputs, outputs and outcomes

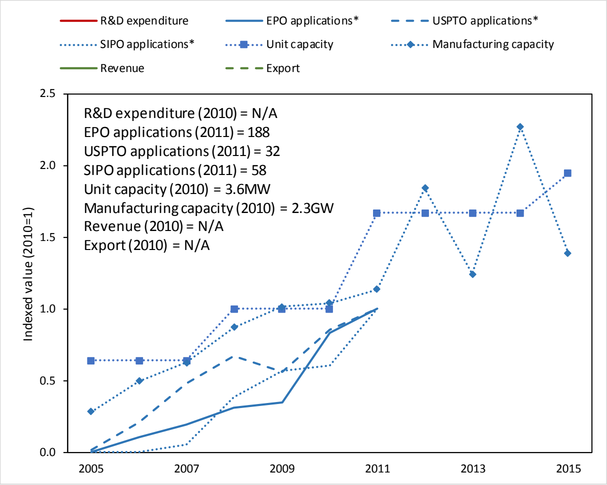


Figure 6-18 Vestas: inputs, outputs and outcomes

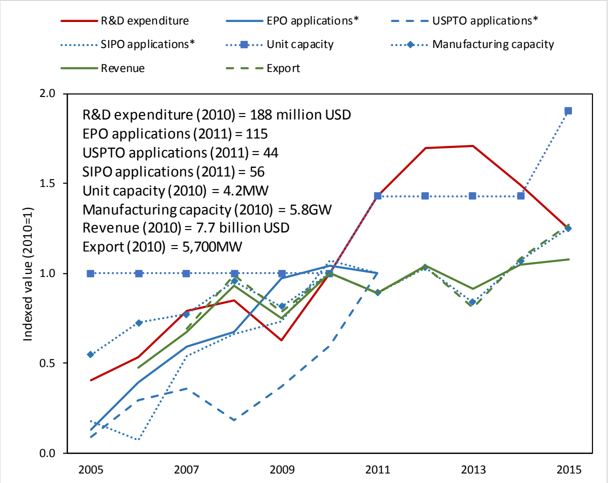
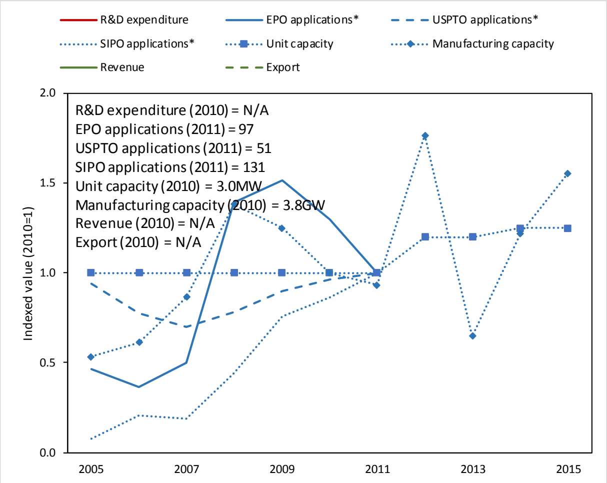


Figure 6-16 GE: inputs, outputs and outcomes



Note:

Figure 6-17: a) The data for the top 10% SCI publications and SIPO filings after 2011 are omitted as they are subject to citation changes and patent examination procedure; b) top 10% SCI publications and patent filings are indexed on the year of 2011; c) these two notes apply to Figures 6-18, 6-19 and 6-20; d) Source: Multiple sources.

Figure 6-18: Source: Multiple sources.

Figure 6-19: a) The data for R&D expenditure, revenue and export are unavailable; b) Source: Multiple sources.

Figure 6-20: a) The data for R&D expenditure, revenue and export are unavailable; b) Source: Multiple sources.

In summary, Goldwind is accelerating R&D inputs and begins to harvest the outputs in SIPO filings. The current issue lies in the firm's deficit in EPO and USPTO filings as well as revenue and export. There are large gaps between Goldwind and the world leaders in these areas. However, the EPO and USPTO filings not only depend on the firm's technological capability but also business strategy. Given that Goldwind's technological capability is yet to be improved to be fairly competitive in the international market and the domestic market demand is large, it is cost ineffective by applying for the EPO and USPTO patents. Vestas is a leader in wind technology and has intensified R&D investment and commercialised the cutting-edge 8.0MW wind turbine. The firm performs excellently in almost all areas, particularly unit capacity, revenue and export. In comparison, Siemens and GE perform moderately well and are speeding up patent filings in the Chinese market.

6.4 Reflections upon the results

This section intends to reflect upon the results of the nation and firm-level comparisons. It aims to address three issues: a) the factors responsible for China's innovation performance; b) the efficacy of the proposed indicator framework; c) the methodological issues in nation and firm level comparisons.

6.4.1 China's wind energy innovation performance

China has deployed wind energy at a large scale but may not have become a leading innovator in this technology. It is necessary to make a clear distinction between innovation and diffusion as the latter can be driven by adopting the technology through international technology transfer, while the former requires significant in-house R&D efforts. This chapter applies the proposed indicator in the wind turbine industry across China, Denmark, Germany and the USA. It shows that China has caught up fast in R&D investment, scientific publications, manufacturing capacity and installed capacity but significantly lags the world leaders in patent filings, unit capacity, revenue and export. The results evidence that China begins to lead in inputs and has leapfrogged the other countries in certain outputs and outcomes. The relative weakness in technical inventions represents China's biggest bottleneck.

By examining the input indicators, China has become the leader in R&D expenditure and asset finance. However, this has happened very recently. Germany and the USA have been big R&D investors for a much longer time than China. While Denmark's R&D data is unavailable, Vestas' R&D spending has been huge for the past decade and was just taken over by Goldwind in 2015 largely due to the firm's recent decline in R&D investment. By looking at the output indicators, China catches up fast in SCI publications but falls behind significantly in patent filings and unit capacity. In contrast, Denmark, Germany and the USA have been far ahead of China in technical inventions and large wind turbines. They continued to perform over China in these two core outputs although their R&D expenditures stayed stagnant or were cut. One factor for explaining this may be that Denmark, Germany and the USA are benefiting from their prior R&D efforts and achievements, namely the effect of cumulative R&D is working (see Laurens et al. (2016)).

China increased R&D spending since 2004, but it was not until 2011 when China overtook Denmark to be the top R&D investor. At the firm level, Goldwind did not intensify R&D activities until 2011 and slightly overtook Vestas in 2015. Hence, China's R&D investment at both the nation and firm-level took off very recently. It often takes years for the R&D funding to be converted into publications and patents. It seems impossible for China (originally a technology imitator) to have emerged as a technology leader in a short period. The rapid increase of SIPO filings between 2005 and 2010 by Denmark, Germany and the USA implies that they can quickly enhance patent portfolios in China based on their prior knowledge – effect of cumulative R&D.

The number of SIPO filings by all Chinese public and private sectors was 821 in 2011 (SIPO 2016). As of 2015, about 32 turbine manufacturers, 21 gearbox providers, 18 blade makers, and 17 control system developers were present in the Chinese market – they were all Chinese firms (Chinawindnews, 2016). If the public sector was excluded, then each of these firms shared about 9 patent applications on average, which was far less than Vestas (147), Siemens (130) and GE (71)'s performance. Goldwind, a pioneering Chinese manufacturer, made 8 SIPO filings in 2011. However, China's SCI publications have increased dramatically over the past decade and currently act as the world leader in this area. Obviously, the rapid growth of scientific research has not contributed to the similar increase of technical inventions. There exists a gap between academic research and industrial technology development. This may be another factor for China's innovation performance (see Chapter 8). The correlations between the input, output and outcome indicators have not been analysed but can be explored in future research.

6.4.2 The efficacy of the indicator framework

The existing literature has not arrived at a consensus as to whether China has become a leading innovator in wind energy. This may lie in three reasons: a) heavy reliance on qualitative data; b) bias amongst interviewees; and c) the lack of adequate metrics (see Chapter 5). It seems impossible to make an adequate assessment merely based on qualitative interviews as personal perceptions have an influential impact on interviewees' judgement. Some studies adopted quantitative indicators, but the indicators were often constrained to certain aspects rather than covered the entire process of energy technology innovation.

This chapter has mobilised and tested the efficacy of the proposed indicator framework by applying it to the wind turbine industry across China, Denmark, Germany and the USA. It shows that each country has its gaps across the innovation chain. It is important to identify the specific gaps to avoid the fragmented evidence by looking at the entire innovation process, namely Research, Development, Demonstration, Market Formation and Diffusion.

To be more specific, the indicator framework goes beyond inputs to emphasise outputs and outcomes. Conventional analyses have been limited to R&D, bibliometric or patent analyses, which may cause partial views concerning the performance of EISs. China has spent more wind energy R&D than the USA between 2005 and 2015, but this has not ensured China's superiority over the USA in EPO and USPTO filings and unit capacity. Just examining a few input or output indicators (e.g. R&D and SCI publications) will wrongly make China look more effective.

The indicator framework covers the entire innovation chain, allowing us to identify the country's strengths or weaknesses across stages. The USA has performed excellently in inventions but much less in unit capacity and technology export. This may imply that the USA has underperformed in transforming technological inventions into commercialised innovations or the inventions per se have little commercial value. This informs the need for the USA to pay closer attention to the commercialization of patented technologies.

6.4.3 Nation and firm-level comparisons

The nation and firm-level comparisons have shown a very different picture. At the national level, China leads in six of the eleven indicators while Denmark lags in five of the eleven indicators (see section 6.2.4). At the firm level, Goldwind (China) lags in six of the eight indicators while Vestas (Denmark) leads in almost all indicators except for SIPO filings (see section 6.3.4). The nation-level comparison demonstrates the aggregated figures of all firms while firm-level comparison shows the gaps across individual companies. The former method is significantly affected by a country's size, i.e. large countries tend to produce more. It may produce biased information by merely relying on nationally aggregated data.

The methodological issue of using rather aggregated data not only applies to a particular technology field but also a country's whole technology arena. Gupta and Wang (2016) assessed China's innovation capability by referring to the country's share of patent grants from the USPTO. The results were that China accounted for 2.2%, compared to Japan's 18.8%, Germany's 5.5% and Korea's 5.5%. However, a few of these countries' technological capabilities may be underestimated as a country may be exceptionally competitive in certain technological areas but not in all. Over-aggregated data may overlook innovation capabilities and patterns in specific technological fields, industries and sectors. Meta-data analysis, for example, at firm level can well complement the potential issues of the nation-level comparisons.

There are also consistent findings between the nation and firm-level comparisons. For example, they both show that China is catching up fast in R&D expenditure and installed capacity but lags in patent filings and export. This consistency helps grow confidence in the results. All in all, a combination of the nation and firm-level comparisons will avoid the effect of country size on the results and can produce more convincing and comprehensive results.

6.5 Summary

This chapter has applied the proposed indicator framework to the wind turbine industry across China, Denmark, Germany and the USA. The results are that: a) at the national level, China has caught up fast in R&D investment, asset finance, scientific publications, manufacturing capacity, installed capacity and strengthened invention capability at home, but significantly lags the leading countries in EPO and USPTO filings, the unit capacity of wind turbines, power generation, revenue and export; b) at the firm level, Goldwind has recently become a top R&D investor and built a large manufacturing capacity but significantly fallen behind in technical inventions, unit capacity of wind turbines, revenue and export.

They point to the fact that China has made considerable achievement in certain inputs and outputs, but there still exists a sharp innovation gap to the leading countries in others especially outcomes. The incorporation of input, output and outcome metrics into the energy technology innovation chain allows analysts to identify the specific gaps, which can be of great value for formulating the relevant innovation policies. The effect of cumulative R&D investment and knowledge exchange among actors may have affected China's innovation performance

It compares the differences between nation and firm-level comparisons, finding that merely relying on nationally aggregated figures may produce biased information. Meta-data analysis at the firm level can avoid the effect of country size on the results. Besides, the nation and firm-level comparisons can produce consistent results. The consistency increases the reliability of results. Therefore, a combination of the nation and firm-level comparisons can produce more a comprehensive picture and gain greater confidence in the results.

Chapter 7 Structural elements of China's wind energy innovation system

The cross-country comparisons show that China catches up fast in certain aspects but lags behind in many others (see Chapter 6). It is necessary to identify the factors that have been responsible for China's technological progress and problems. The analytical framework in Chapter 3 holds the assumption that the overall performance of an innovation system depends on the fulfilment of the system functions which relates to the presence and capability (or quality) of the structural elements. As such, this chapter intends to analyse the various types of structural elements embedded in China's wind turbine innovation system.

The core objectives of this chapter are to a) map out the major actors, networks and institutions of China's wind turbine innovation system, b) illustrate the presence and status quo of the structural elements, and c) summarise the key characteristics of the structural elements. To begin with, section 7.1 defines the analytical boundary of structural analysis. Sections 7.2 to 7.4 describe the presence (or status) of the structural elements in a retroactive manner. Based on these, section 7.5 concludes five features of the structural elements.

7.1 Setting the analytical boundary

Wieczorek and Hekkert (2012) summarised four types of structural elements – *actors, networks, institutions* and *infrastructure*. This research is concerned with wind turbine technology, so wind farm developers and grid operators are excluded in the structural analysis as they are not directly involved in developing the technology. Hence, the major *actors* include the regulators, universities, state labs, industrial firms, certification bodies and industrial associations which contribute to the development of the technology. The firms are divided into wind turbine manufacturers and component suppliers. It is extremely difficult to map out all the actors involved in the industry, so only the most representative ones are included in the analysis.

The *networks* among heterogeneous actors are very complex. They can be formal and informal connections, can occur between organisations or individuals, or between domestic or transnational linkages. This thesis will focus on three types of knowledge networks: a) university-industry interactions, b) wind turbine producer-wind farm developer connections, and c) international linkages of the industry. As Knowledge Networks (F3) is one of the system functions, it seems more appropriate to study it in the functional analysis (see Chapter 8). This chapter is to present a few concrete examples of the Knowledge Networks (F3) to show how the networks work, but the specific features will be explored in Chapter 8.

Institutions are sets of common habits, norms, routines, established practices, rules or laws that regulate the relations and interactions between individuals, groups, and organisations (Edquist 2005). They are the rules of the game. Institutional configuration influences innovative activities and can be changed by system builders (Malerba 2005). In this thesis, institutions refer to the laws, regulations and policies that influence the development of wind turbine technology. Institutions are closely related to the functions of Guidance of the Search (F4) and Creation of Legitimacy (F7). This chapter is to introduce the main points of some most influential law(s) and policies in China’s wind turbine industry while the functional patterns and problems of the institutions will be discussed in Chapter 8.

Infrastructure includes not only physical (e.g. buildings, telecommunication networks) but also financial (e.g. financial programmes) and knowledge infrastructure (e.g. R&D labs). However, infrastructure will not be examined separaely as it has many overlaps with the other analytical dimensions (i.e. actors, institutions). For example, the certification facilities for testing the reliability of wind turbines and the grid infrastructure that transmits wind electricity comprise the main infrastructure for wind power industry, but it seems more suitable to analyse the testing and certification facilities when studying the presence of testing and certification organisations which belong to the *Actors*. The thesis is concerned with wind turbine technology, so grid infrastructure is less relevant although the interactions between wind turbine producers and wind farm developers are one of the prime focuses.

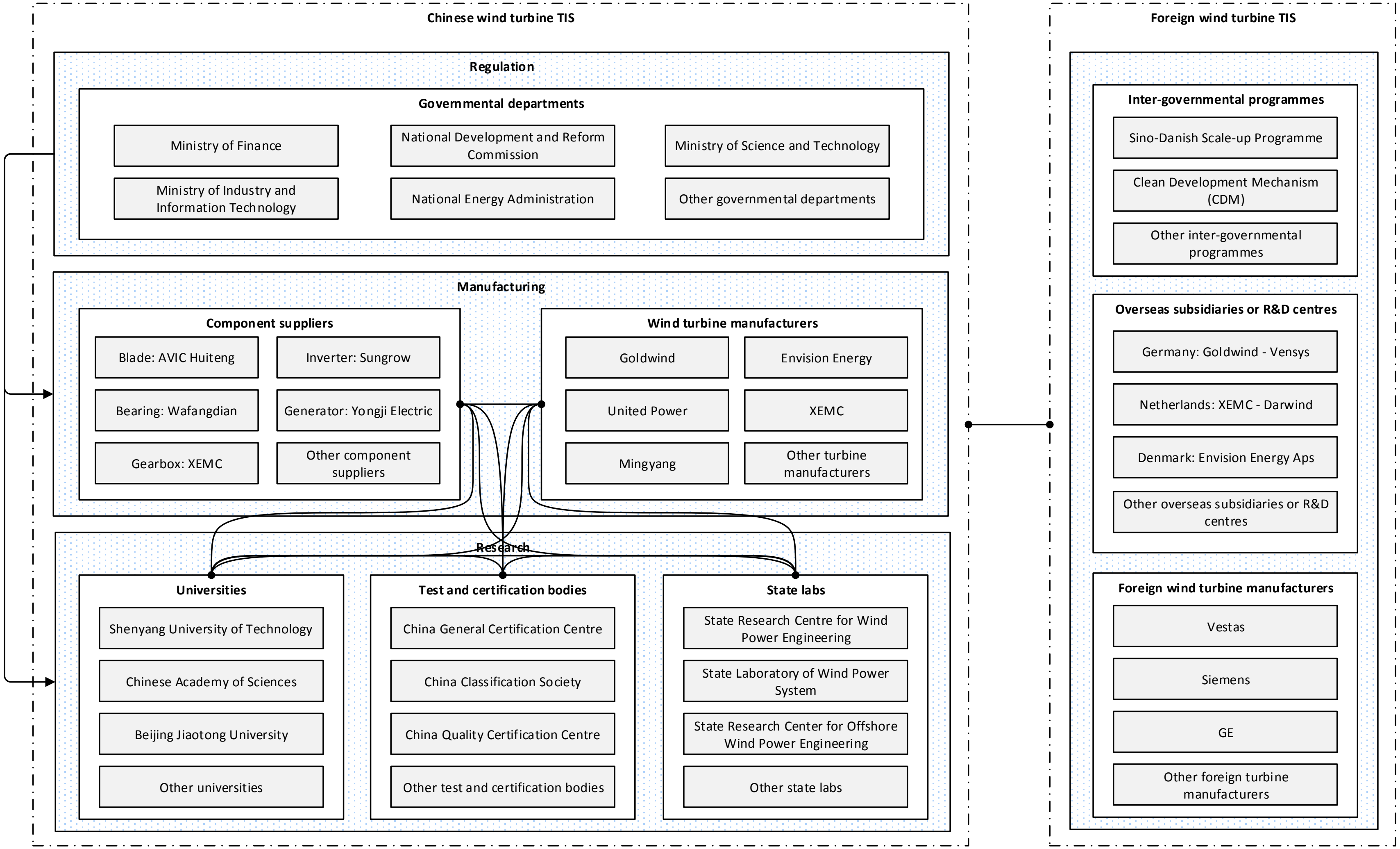
It is challenging to evaluate the capability (or quality) of the structural elements as a set of adequate indicators will be needed for meeting this purpose. Also, there is a wide range of heterogeneous actors, networks and institutions in the system and each type of structural element may require different indicators. For example, the indicators for evaluating the capability of government bodies and industrial firms can be very different. This thesis intends not to cover all the structural elements but examines a particular firm - Goldwind (see Chapters 5 and 9). This method allows me to conduct an in-depth analysis of the firms' technological innovation process. Understanding the emergence and evolution of structural elements is useful to understand the build-up of innovation systems of catch-up countries.

China started exploring wind turbine technology in the 1950s but had not integrated wind power into the electricity grid until 1986. Among many others, technological deficits and the lack of regulation represented the most significant factors hindering China's development of wind power (Dai et al. 2014). In other words, the innovation system for wind technology was not established. It is not easy to build an innovation system for developing countries, many essential elements of the system may be missing (Liu and White 2001), which inevitably obstructs the fulfilment of the system functions. As many actors in China's wind turbine industry have a short history, their capability may be highly related to the year of entrance.

Given the above reasons, the structural analysis will focus on three aspects: a) mapping out the major actors, networks and institutions; b) describing the emergence and status quo of the structural elements; c) summarising the key features of the different types of structural elements. It is hard to map out all the actors, networks and institutions. A pragmatic approach is to shed light on the major ones who can reflect the generic characteristics of the structural components of the system (see Diagram 7-1). The untouched elements may grow as the dominant ones in the future, but they are beyond our scope of analysis.

The data used in this chapter are mainly from Chinese references such as journal articles, company or government websites, magazines, newspapers, government documents and statistical reports. Desk-based research has been crucial to collecting these materials.

Diagram 7-1 The major actors and linkages of China's wind turbine innovation system



N.B. a) This note is for figure 7-1; b) the presence of actors is identified by the time when they issued the policies (government departments), established the research centres (universities), gained government approval (state labs), manufactured the products (firms), or provided the technical services (certification bodies and industrial associations), not by their establishment years; c) only a few examples of each type of the actors are shown.
Source: The author.

7.2 Actors

This section describes the presence and status quo of the major actors embedded in China's wind turbine innovation system (see Diagram 7-2). The actors include government departments, universities, research institutes, state labs, wind turbine makers, component suppliers, test and certification bodies, and industrial associations as displayed in Diagram 7-1.

7.2.1 Governmental departments

China's governance structure for wind energy has been fragmented and misaligned. This problem causes severe duplication and low efficiency of economic resources. For example, the National Energy Administration (NEA) is responsible for formulating and implementing energy policy, but some other departments like the Ministry of Science and Technology (MOST) have their specific impact. MOST takes charge of the approval, funding and regular assessment of major S&T programmes, including the state labs. Between 2004 and 2011, MOST backed about five state labs for advancing wind technology while the NEA approved another nine state engineering centres in 2009 and 2010.

"The manner in which [China's] energy sector is governed is one of the major factors which will determine the nature and rate of the [low-carbon] transition... Multiple centres of power, institution building and economic development prevail, and political and economic rivalry exists at and between all levels of government... The rigidities in the political system and the influence of

powerful actors constrain the ability and the willingness of the central government to undertake radical political or economic changes. ” -- Andrew-Speed (2012)

Table 7-1 Abbreviations for the major actors of the innovation system

Abbreviations	Full names
Government agencies	
MOST	Ministry of Science and Technology
NEA	National Energy Administration
MIIT	Ministry of Industry and Information Technology
NDRC	National Development and Reform Commission
CDB	China Development Bank
Universities	
CAS	Chinese Academy of Sciences
SUT	Shenyang University of Technology
SJTU	Shanghai Jiaotong University
BJTU	Beijing Jiaotong University
NCEPU	North China Electric Power University
State labs	
SRCWPE	State Research Centre for Wind Power Engineering
SRCOWPE	State Research Centre for Offshore Wind Power Engineering
SLWPEC	State Laboratory of Wind Power Equipment and Control
SLWPS	State Laboratory of Wind Power System
SLOWTT	State Laboratory of Offshore Wind Technology and Testing
SRCWPTCET	State Research Centre for Wind Power Transmission and Control Engineering Technology
Wind turbine producers	
Goldwind (GW)	Goldwind Science & Technology Co., Ltd.
Sinovel (SI)	Sinovel Wind Group Company
United Power (UP)	Guodian United Power Technology Co., Ltd.
Dongfang (DF)	Dongfang Electric Corporation
Mingyang (MY)	Ming Yang Wind Power Group Limited
Certification bodies	
CGC	China General Certification Centre
CCS	China Classification Society
CQC	China Quality Certification Centre
Industrial associations	
CWEA	Chinese Wind Energy Association
CWEEA	Chinese Wind Energy Equipment Association
NTCSWM	National Technical Committee for Standardization of Wind Machinery

Diagram 7-2 The presence of the major actors in China’s wind turbine innovation system

Actors	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Government agencies																															
MOST		●																													
NEA										●																					
MIIT																									●						
NDRC												●																			
CDB																						●									
Universities																															
CAS	●																														
SUT	●																														
SJTU																								●							
BJTU																						●									
NCEPU																							●								
State labs																															
SRCWPE																				●											
SRCOWPE																									●						
SLWPEC																										●					
SLWPS																										●					
SLOWTT																										●					
SRCWPTCET																											●				
Wind turbine producers																															
Goldwind												●																			
Sinovel																					●										
United Power																							●								
Dongfang																				●											
Mingyang																							●								
Component suppliers																															
AVIC Huiteng															●																
Wafangdian																							●								
NGC																				●											
Sungrow																								●							
Yongji																					●										
REnergy																								●							
Certification bodies																															
CGC																			●												
CCS																											●				
CQC																				●											
Industrial associations																															
CWEA	●																														
CWEEA					●																										
NTCSWM	●																														

National Development and Reform Commission

Established in 2010, the National Energy Committee (NEC) works as the top legislative power responsible for dealing with China's energy affairs. The Premier acts as the Director of NEC, the Director of NDRC works as the Director of NEC Office, and the General-Director of NEA is the Vice Director of NEC Office. NDRC is a trans-departmental organisation that oversees many other ministries. In the past, renewable energy did not have the chance to develop as coal and oil were prioritised. Now NDRC places more emphasis on climate change and renewable energy. It is responsible for: a) drafting strategies, plans and policies in response to climate change; b) taking the lead in international negotiations on climate change; c) facilitating sustainable development, e.g. energy and resources conservation, circular economy and clean production; and d) supervising NEA and formulating energy plans and policies (NDRC 2016).

National Energy Administration

NEA was established in 2008 but can be traced back to the then Ministry of Fuel Industry created in 1949. NEA takes responsibility of: a) formulating and implementing national energy strategies, programs and policies to promote energy sector reform; b) formulating industrial policies and standards for coal, oil, natural gas, electricity, new energy and renewable energy; c) facilitating and managing energy R&D projects; and d) (partly) regulating electricity industry and advising NDRC on electricity pricing (NEA 2016).

Ministry of Science and Technology

MOST leads in drafting national science and technology plans and policies, such as the *National Basic Research Programme* ('973 Plan'), *National High-tech R&D Programme* ('863 Plan') and *S&T Enabling Programme*. There were S&T policies for wind turbines in China between 1986 and 2000, but little technological progress was made in that period. The 7th (1986-1990) and 8th (1991-1995) S&T plans emphasised indigenous development of 150-300kW wind turbines (IEA and IRENA 2016). The *10th Five-Year Plan for New and Renewable Industry* (2001-2005) aimed to develop 600+kW turbines (IEA and IRENA 2016). However, China had already fallen behind the international leaders who were able to produce 2 MW+ turbines.

7.2.2 Universities and state labs

China's scientific research on wind turbine technology started quite late. It was not until 1984 that China's first ever academic conference on wind power took place (He and Shi 2010). Some research institutes and universities conducted R&D since 1975, but the capacity of wind turbines was then rather small (< 100kW) (He and Shi 2010). A number of Chinese universities and institutes now study wind technology, with the Shenyang University of Technology (SUT) and Chinese Academy of Sciences (CAS), and Beijing Jiaotong University (BJTU) being very active. However, like the state labs and national engineering centres (see Table 7-2), the universities and research institutes are so dispersed that no single one has stood out from the crowd, let alone compete against internationally-leading players.

Shenyang University of Technology

Established in 1983, the Wind Energy Institute at SUT is one of the earliest Chinese institutes engaged in wind turbine technology. It has undertaken state-funded projects on wind turbine technology since its establishment (Yao 2008). Between the early 1980s and 2000, the Institute achieved little technological growth. Many large wind turbines installed in China over that period were imported from overseas (Shi 1997). In 2000, SUT developed 200kW and 600kW wind turbines and in 2006 developed 1.0MW wind turbine (SUT 2016).

Even after the issuance of the landmark Renewable Energy Law (2005), Chinese firms had to license technology from foreign companies or create joint ventures to manufacture wind turbines. The quality of research institutes undermines China's wind power development, particularly the lack of state-level institutes that are public in nature and can serve the entire industry (Yao 2008). Wind technology entails a range of technological fields and scientific disciplines; it was difficult to facilitate technical experts with different backgrounds to focus on this comprehensive and transdisciplinary technology (Yao 2008).

Table 7-2 Research institutes for wind technology approved by MOST and NEA

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

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

Chinese Academy of Sciences

CAS has two institutes engaged in wind technology, namely the Institute of Electrical Engineering and the National R&D Centre of Wind Turbine Blade. The former began to undertake national research projects since 1978 (IEE 2016), primarily on the control system and inverter, while the latter was established in 2009 to conduct research on wind turbine blades. Under the Renewable Energy Partnership, the Institute for Electrical Engineering in dynamometer testing collaborates with the National Renewable Energy Laboratory in the USA (William Wallace 2012). MOST (2012) acknowledged that China lacked technological competencies in blade design and inverter. This may imply that the technological capability of these institutes cannot meet the demand. It seems that these two institutes have no collaborative research although they both belong to CAS.

Other Chinese universities that carry out research on wind turbines include Beijing Jiaotong University, Chongqing University, Shanghai Jiaotong University and Tsinghua University. Regarding the publications by Chinese researchers, it is slightly behind the USA (see Chapter 6). When looking at the average number of SCI publications per project, it is found that over 94% of funded projects have produced less than three journal papers, and only 4.5% of grants have promoted the publication of three to five papers per project (see Table 7-3). Currently, China does not have “presence” problems but suffers from “capability” problems.

Table 7-3 Cumulative SCI publications per research grant (1970-2015)

Publications per grant	Number of grants	% of 1754 grants
1 (Min)	1340	76.4
1<X≤3	314	17.9
3<X≤5	79	4.5
5<X≤7	13	0.7
7<X≤9	6	0.3
9<X≤11	0	0.0
11<X≤13	1	0.1
14 (Max)	1	0.1

N.B. As the datasets only covered English journals, language bias may exist.

Source: WoS (2016)

State Research Centre for Wind Power Engineering

The earliest Chinese state lab for researching wind turbine technology is the State Research Centre for Wind Power Engineering. It was established in 2004, hosted by Goldwind. According to the information disclosed by the National Engineering Research Center (NERC 2009), the lab indigenously developed 3.0MW wind turbines in 2009 based on three years' R&D activities. The research passed through a series of crucial stages, including project feasibility analysis, concept design, initial design, sophisticated design, initial production of components, unit assembly, testing, demonstration and connection to the grid (NERC 2009).

Little information has been published about the lab except that it collaborates with Tsinghua University, Beijing Jiaotong University, China Aerodynamics Research and Development Centre and Xinjiang University (The World of Inverters 2005). It was reported that the 1.5MW inverters co-developed by the lab and Beijing Jiaotong University realised mass production while 2.5MW and 3.0MW inverters were in experimentation (BJTU 2013).

State Laboratory of Wind Power System

The State Laboratory of Wind Power System was established in 2010, backed by MOST. It is based at Windey – one of the earliest Chinese wind turbine makers, with 67 researchers. The lab began to undertake state-funded projects since 2001, including the launch of a 7.0MW wind turbine R&D project (SLWPS 2016). It has been granted 11 invention patents and has actively participated in making national standards for wind turbine technology (Ye and Sun 2015). Windey is now able to develop 5.0MW wind turbines (prototype) with its own IPRs (Windey 2016). Despite these, the lab needs to improve in facilities sharing, talent training and industrial R&D for generic technologies (Ye and Sun 2015).

7.2.3 Wind turbine manufacturers

Few firms specialised in wind turbine technology before 2005, but currently, half the world's ten largest wind turbine makers are Chinese enterprises (REN21 2016). It is worth mentioning four Chinese companies which characterise the generic features of China's wind energy innovation - Goldwind, Windey, Sinovel and Envision Energy. The former two represent the earliest Chinese wind turbine manufacturers, but Windey has remained stagnant while Goldwind has emerged as the world's largest producer. Sinovel was once the largest Chinese wind turbine supplier but has slipped out of the world's top ten recently. Envision Energy is very young but has grown as a top manufacturer and wind farm software developer. More details about Goldwind's technological innovation are to be illustrated in Chapter 9.

XEMC Windpower

XEMC Windpower ranks as the 6th largest Chinese wind turbine producer (CWEA 2016b). In 2015, its revenue from selling wind turbines was about 5.3 billion RMB. The firm was established in 2006 as one of XEMC's subsidiaries specialising in wind turbine technology. XEMC is one of China's largest heavy equipment developers and manufacturers, and often seen as the cradle for China's mechanical and electrical products. The firm began to undertake state-funded projects on wind technology since the middle 1990s and has benefited from XEMC's technological advantages in mechanical and electrical engineering.

In 2007, the company developed 2.0MW turbines which were obviously larger than those of its Chinese peers. In 2009, it purchased the Dutch design company Darwind which owned 3.0-5.0MW turbine technologies (Yan 2009). The maximum unit capacity that XEMC Windpower can produce with its own IPRs is 5.0MW offshore wind turbine (prototype). The firm hosts the State Laboratory of Offshore Wind Technology and Testing and collaborates with Hunan University on the control system and system integration technologies.

Envision Energy

Envision Energy is the world's 8th largest wind turbine supplier (REN21 2016). It was established in 2007 by an overseas returnee who worked as an energy analyst for seven years in London's financial sector. The CEO has a sharp global perspective and dreams of creating a world-renowned company with Chinese wisdom like IBM and Microsoft (Slepniov et al. 2015). There are several features that make Envision Energy very different from other Chinese firms.

First, it adopts a global talent sourcing strategy to attract top performers across countries and industries (Ready, Hill, and Thomas 2014). They took search to Denmark for engineers with wind turbine innovation skills, to the USA for software architects and Japan for lean manufacturing managers (Ready, Hill, and Thomas 2014). Some of the senior personnel recruited from MNEs include Liou Shuh-Yuan previously working as Technological Leader at Ford and Senior Project Manager at GM, Anders V. Rebsdorf once worked as Departmental Manager at Dong Energy, and Tim Hertel the then Director of Technology at EDP Renewables.

Second, the firm has performed more creatively than its Chinese peers by absorbing insights from a range of disciplines and technological fields such as aerospace, defence, automobiles and IT (Zeng 2015). The design and manufacturer of wind turbines are highly interdisciplinary and technologically sophisticated and requires aspirations from a broad spectrum of knowledge fields. The company has built R&D centres in China, Denmark, Japan and the USA.

Third, the firm is not merely a wind turbine producer but also a software developer. Advanced management services are a big part of Envision Energy's business. The firm has developed the so-called "Greenwich Cloud Platform" and "Wind OS Management System" to improve wind farm efficiency and maximise yields. The software is adopted by world-renowned companies such as Pattern and E.ON, managing global renewable energy assets worth 50 GW. The global innovation networks of Envision Energy will be examined in section 7.4.2.

7.2.4 Component suppliers

Component suppliers have achieved considerable progress, particularly in the blade, generator and gearbox. Chinese blade producers make up the bulk of the Chinese market. As of 2010, the Chinese producer NGC accounted for 40% of the Chinese gearbox market and supplied more than 1,000 units to overseas firms like Vestas and GE (CWEA 2010). Regarding the generator, Yongji Electric far led other Chinese and foreign firms in the Chinese generator market. However, China relies on import for certain key components such as bearing, inverter and control system (CWEA 2010, Gosens and Lu 2013a). The blades are manufactured mainly based on foreign designs. Thus, the turbines often do not suit well to the Chinese local climate conditions.

Blade: AVIC Huiteng

As one of the key components of a wind turbine, blades account for about 20% of a turbine's cost (EWEA 2009). AVIC Huiteng, established in 2001, has grown to be the largest Chinese wind turbine blade producer. The company has a wide range of wind turbine blades for up to 5.0MW turbines. Its clients include the majority of Chinese wind turbine manufacturers such as Goldwind, Shanghai Electric Windpower and Windey. It also exports to about 15 countries, including the USA, Japan and South Africa. Currently, the world's largest wind turbine blade producer is LM Wind Power (Danish firm, acquired by GE in 2016) which has supplied one-third of global wind turbine blades.

AVIC Huiteng was originally an aviation propeller producer. The firm entered into the wind turbine blade field in 1999, mainly driven by the pursuit of receiving a state research grant for developing blades for 600kW wind turbines (Han 2013). In the beginning, AVIC Huiteng struggled to hit a technology license agreement with foreign companies but failed. It had to develop blade technology on its own (Han 2013). In 2009, it acquired a Dutch design company Composite Technology Centre, which contributes considerably to AVIC Huiteng’s blade R&D activities (Han 2013). Also, It benefits from AVIC’s (a Chinese state-owned aerospace and defence company) technological advantages in aerodynamics and composite materials.

Bearing: Wafangdian

Established in 1938, Wafangdian Bearing Group Corp. Ltd (ZWZ) is regarded as the cradle of China's bearing industry. ZWZ covers nine major categories of bearing products and exports equipment to over 80 countries, with more than 16,000 having its own IPRs (Wang 2011). The corporate has produced China's first industrial bearings, first plain bearings for railway waggons, and first bearings for large-scale tracking telescopes (Wang 2011).

In the field of wind technology, ZWZ has developed bearings for a range of wind turbines, including 1.5MW, 2.0MW, 3.0MW, 5.0MW and 6.0MW (Zhao 2013). Fan and He (2012) argued that Chinese firms can supply yaw bearing and pitch bearing technologies for wind turbines under 2.0MW. Prototypes for yaw bearing and pitch bearing for 5.0MW wind turbines have been developed, but spindle bearings which require more sophisticated technologies are under development (Fan and He 2012).

Gearbox: NGC

Nanjing High Accurate Drive Equipment Manufacturing Group Co., Ltd. (NGC) was founded in 1969. It was originally a machine repair factory and started manufacturing gearboxes since 1976. The firm produced wind turbine gearboxes since 2004 and built relationships with Goldwind and GE. The close cooperations with leading domestic and foreign companies helped improve NGC's quality management and product reliability (Zhao 2014). In 2015, about 7.8 billion RMB revenue was made from wind turbine gearboxes, increased by 35% compared to 2014.

Quality and reliability are the core values that NGC pursues. Few companies employ reliability checking outside the aerospace industry [and a few others], but NGC carries out overloading test to measure the reliability of gearboxes and understand the causes of the failures (Zhao 2014). The firm provides a range of wind turbine gearboxes from 750kW to 6.0MW. About 30% of its orders come from overseas, which is very rare in Chinese wind turbine industry.

Inverter: Sungrow

Sungrow was created in 1997 by a university academic who specialised in renewable energy technology. The firm initially produced solar PV inverters and developed China's first solar PV inverter in 2003. It has now expanded product portfolios to include wind power and other energy storage technologies and exported inverters to more than 50 countries, making it the world's largest supplier for solar PV inverters (4.6 billion RMB revenue in 2015). The firm's core competencies lie in the quality, reliability and lower cost (Sungrow 2016).

Sungrow employs nearly 1,500 workers, of which 40% are R&D personnel (Zhao 2012a). The firm has undertaken approximately 20 state-funded projects and made about 600 patent applications (including 80 invention-type patents) (China Brand 2015). The inverters have been certified by CE Intertek and DNV GL (China Brand 2015) and can meet the requirements of 1.5 – 6.0MW wind turbines (Zhao 2016). The firm has built close relationships with some leading Chinese universities for jointly training postdoctoral staff.

Generator: Yongji Electric

Yongji Electric was founded in 1969, affiliated to China CNR Corporation Limited (China CNR). In 2015, China CNR and China CSR merged into CRRC Corporation Limited (CRRC), making CRRC the world's largest railway rolling stock manufacturer. Yongji Electric has conducted research on wind turbine generators since 2000 and has taken national major S&T programmes since 2003. The firm produces generators for 2.0 - 5.0MW wind turbines. It secured a contract with Goldwind in 2014, worth 2.7 billion RMB - the biggest deal in China's wind power industry.

The lack of design technologies, qualified R&D personnel and R&D platform undermines Yongji Electric's technology development (Guo 2014). There is only 28 R&D personnel who mostly have an academic background in mechanical engineering, lacking the knowledge in aerodynamics and electromagnetics (Guo 2014). Their knowledge is insufficient to promote novel innovations that reflect the unique characteristics of wind turbine generators (Guo 2014).

Control system: REnergy Electric

REnergy Electric was established in 2008 as a specialist in control systems for wind turbines and solar PV. It has become China's largest control system supplier, with an annual revenue of about 1 billion RMB (Xia 2015). The firm developed China's first 1.5MW wind turbine control system with its own IPRs (Xia 2015). By the end of 2014, over 10,000 units of control systems supplied by REnergy Electric had been deployed (Xia 2015).

The firm spent 5% of its revenue on R&D activities and built an R&D team consisting of about 100 personnel (Xia 2015). REnergy Electric has filed about 170 patents (Xia 2015) and developed a range of wind turbine control systems suitable for China's local climate conditions (e.g. high-altitude plateau). The company developed China's smallest (physically) 3.0MW wind turbine control system in 2012 and had its control systems deployed in India where offshore and high-temperature requirements must be met (Xia 2015).

7.2.5 Test and certification bodies

Few Chinese wind technology certificates are accepted by European or American certification bodies. The lack of certification has somewhat undermined China's export of wind turbines. To facilitate technological progress and ensure wind turbine quality, the NEA issued the "*Notice on Regulating the Standardisation of Wind Power Equipment and Generators Quality*", requiring that all wind power equipment must be certified since July 2015 (NEA 2014). The emergence of Chinese test and certification bodies is improving the situation, but their technological capability has yet to be improved. Many Chinese certification entities collaborate with foreign counterparts to strengthen their technical services.

China General Certification Centre

The China General Certification Center (CGC) was founded in 2003 as the first certification body providing test and certification services for wind and solar energy technologies. The centre hosts 19 technical experts – 4 doctorate holders and 15 postgraduates (CGC 2016). CGC has developed certification guidelines for Chinese wind technologies by referring to international standards, including the International Electrotechnical Commission (IEC) 61400 design standards and Germanischer Lloyd's Guideline for the Certification of Wind Turbines (CGC 2016).

It has built collaborative relationships with the China Aerodynamics Research Center, Chinese Academy of Sciences, China Electric Power Research Institute, China Meteorological Administration, and North China Electric Power University. It also collaborates with Garrad Hassan, the National Wind Energy Technology Center at NREL, Risø DTU National Laboratory for Sustainable Energy, Germanischer Lloyd, and German Wind Energy Research Institute (DEWI). CGC signed an agreement with Intertek to carry out cooperative testing on wind turbines (Intertek 2014).

China Classification Society

The China Classification Society (CCS) was established in 1956 to provide technical standards and certification services for ships, offshore facilities, containers and other industrial products (CCS 2016). CCS recently adapted its technological advantages in marine engineering and wind turbine industry. About 100 professionals are employed to offer wind technology certification services. However, not many manufacturers have sought to obtain certification from CCS except

Chongqing Haizhuang and United Power. CCS signed an agreement in 2011 with United Power for strategic cooperations on testing and certification (MoT 2011). In 2013, CCS certified Chongqing Haizhaung's 5.0MW offshore wind turbines (not yet commercialised) (Chinanews 2013). United Power obtained certification from CCS in 2016 for its 2.0MW turbines.

China Quality Certification Centre

The China Quality Certification Centre (CQC) started wind turbine technology certification since 2014. CQC issued the first Chinese wind turbine certificate in 2007. It provides design and type certifications on wind turbines and components as well as offers technical services for wind farms construction and training courses for wind power management (CQC 2016). In 2015, CQC signed a cooperative agreement with DNV GL to ensure that: a) CQC accepts the certification accredited by DNV GL and b) CQC can issue type certificates to Chinese manufacturers by incorporating DNV GL's guidelines into Chinese quality requirements (Zhang 2015).

7.2.6 Industrial associations

Industrial associations have worked as the bridge between industry and government and organised a series of conferences to facilitate the exchange of knowledge and information. However, there are overlaps between the different associations regarding their activities.

Chinese Wind Energy Association

The Chinese Wind Energy Association (CWEA) was established in 1981 to play as the platform for academic exchange and technological cooperation with international counterparts, bridge the gap between governments and enterprises, and facilitate wind power development (CWEA 2016a). The association has about 120 members from enterprises and universities.

CWEA has been responsible for organising conferences, exhibitions, seminars and exchange activities. They invite technical experts from both domestic and foreign institutes to give lectures to industrial managers. They conduct policy research on wind power industry and provides policy recommendations to the government. The association edits a professional magazine Wind Energy (focusing on wind technology and policy issues) and has been working excellently on data collection and analysis of China's wind turbine industry.

Chinese Wind Energy Equipment Association

The Chinese Wind Energy Equipment Association (CWEEA) was established in 1989, consisting of about 400 companies or institutes engaged in R&D, equipment manufacturing, wind farms construction, professional training and consulting. Its main responsibilities include: a) tracking technology and market trends; b) making (or revising) technological standards and regulations; c) publishing product catalogue; d) facilitating R&D collaborations among member enterprises; e) promoting new products, new technologies, new processes and new materials; and f) making propositions for industrial restructuring and corporate asset restructuring (CWEEA 2016).

The CWEEA edits two professional magazines – Wind Power Industry, and Small and Medium-Sized Wind Power Equipment and Application. It organises nationwide conferences such as the National Large-Scale Wind Power Equipment Industry Annual Meeting, Small and Medium-Sized Wind Power Equipment Industry Annual Meeting, and National Wind Power Industry Symposium (CWEEA 2016). There exist some overlaps between CWEEA and CWEA in their activities, but CWEA represents China in cooperating with international organisations like the IEA and IRENA.

National Technical Committee for Standardization of Wind Machinery

The National Technical Committee for Standardization of Wind Machinery was established in 1985. It is responsible for the standardisation of wind power technology and acts as the contact body to liaise with the IEC/TC88 Wind Energy Generation Systems Technical Committee (NTCSWM 2016). The committee conducts technical standardisation work in line with the guidelines published by the IEC/TC88, makes proposals on behalf of China to the IEC/TC88's standardisation and participates in standardisation technical committee meetings.

The committee has undertaken some national major S&T programmes. It led the IEC 61400-5 Project on wind turbine blades and the Chinese S&T Enabling Programme "*Standardisation of*

Large Wind Turbines and Wind Power Technology Development Analysis" which won the 2014 China Machinery Industry Science and Technology Grand Award. The committee has made 61 national or industrial standards, including 26 for grid-connected wind turbines and 35 for off-grid wind turbines (Wang 2009). Among the 26 standards, 10 are adopted from the IEC. It plans to accelerate the adoption of IEC standards to ensure that China's wind technology standardisation proceeds in line with international standards (Wang 2009).

7.2.7 Summary of subsection

There are six main features about the actors. First, they surged around 2005 and have been in existence for only a short time (see Diagram 7-2). This may help explain that their capability is nascent and needs to be enhanced. Second, many producers have entered into wind turbine industry from neighbouring industries (e.g. mechanical and electrical engineering). The entrance of 'new players' or entrepreneurs has greatly improved China's manufacturing capacity. Third, 'learning by doing' exists prominently in both industry and government (e.g. technology licensing, wind concession programmes). China has developed wind power by using foreign technologies and adapting mature policies born in other countries to the Chinese market. Four, there has occurred two different innovation strategies among Chinese firms to achieve technological catch-up. The "older generation" (e.g. XEMC and Shanghai Electric) has followed the traditional path of technology licensing, joint R&D and indigenous innovation, whereas the "new generation" (e.g. Envision Energy) has taken advantage of talent sourcing strategy and global innovation networks. Five, the emergence and evolution of the actors have been influenced by international factors. Six, the misalignment between government departments and the lack of integrations of state labs cause fragmented policies and duplications.

7.3 Networks

The networks between university and industry, between producers and users, and between the domestic and foreign innovation systems represent the main channels for knowledge exchange in China’s wind turbine industry (see Diagram 7-3). This section focuses two types of networks – university-industry relations and transnational linkages to understand how Chinese manufacturers exchange knowledge and information via innovation networks. The producer-user connections will be discussed in Chapter 8 to identify the functional problems.

Each type of these two networks will be exemplified by one or two brief case studies – Mingyang and Shanghai Electric for university-industry relations and Envision Energy for transnational linkages. The functional pattern and problems of Knowledge Networks (F3) will be discussed in Chapter 8, and details about Goldwind’s innovation networks will be analysed in Chapter 9.

7.3.1 University-industry relations

Mingyang’s collaborations with universities

Ming Yang Wind Power Group Limited (Mingyang) is China’s largest private wind turbine manufacturer and the fifth largest overall. The firm was founded in 2006 when the Chinese market signalled a strong demand for megawatt-class wind turbines. However, China was not able to produce large wind turbines due to the lack of technologies. Mingyang felt that it could be an excellent opportunity to enter this promising industry given its technological competence in electronic and electric applications (Mingyang 2008).

Many Chinese firms started manufacturing wind turbines by licensing foreign technology or establishing joint ventures, but these practices proved problematic as the Chinese firms had no ownership of the IPRs, which makes it hard for them to lower the cost of wind turbines. Also, the licensed technologies were not well suited to Chinese local climate conditions. Given these constraints, Mingyang decided to build a wind turbine technological alliance with universities to make breakthroughs in the core technologies (Mingyang 2008).

Diagram 7-3 The formation of networks in China’s wind turbine innovation system

Networks	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Transnational linkages																															
GW-Vensys (Germany)																		●													
SI-Windtec(Austria)																						●									
UP-Aerodyn (Germany)																		●													
DF-ASMC (USA)																												●			
MY-Aerodyn (Germany)																										●					
EE (Denmark)*																								●							
WD-Repower (Germany)																								●							
XEMC-Darwind (Netherlands)																									●						
SE-Aerodyn (Germany)																									●						
HZ-Aerodyn (Germany)																										●					
University-industry relations																															
GW-BJTU																						●									
MY-Beihang																							●								
EE-Tsinghua																												●			
WD-ZJU																		●													
XEMC-HNU																							●								
SE-SJTU																										●					
HZ-CQU																														●	
Producer-user connections																															
Huadian-GW																															●
Guodian-UP																							●								
CGN-GW																										●					
Huaneng-MY																												●			
Datang-CWE																											●				
State Grid-Xuji																										●					

N.B. a) Transnational linkages only include the presence years of joint R&D except for Envision Energy who established an overseas R&D centre in Denmark; b) each actor may have formed networks with several others, but only one network is shown in the diagram; c) the dissolutions of networks are not considered; d) producer-user connections only reflect the networks in the forms of joint ventures, subsidiaries or strategic alliances, excluding normal business contracts.

Source: The author.

The company launched two research projects – one was about blade materials, and the other was concerned with gearbox and drive shaft. Beihang University (the former Beijing University of Aeronautics and Astronautics) was a knowledge producer in aerodynamics, aeronautical composite materials, gearbox and drive shaft. Mingyang decided to collaborate with Beihang University on these two projects (Mingyang 2008).

Wind turbine technology is complicated and costly, meaning that it requires strict testing to ensure the reliability and reduce maintenance cost. However, China had few qualified testing labs or facilities. Considering that the South China University of Technology had conducted considerable testing of wind turbines and components, Mingyang decided to build a collaborative platform with the university for testing large wind turbines (Mingyang 2008).

Efficient operations of wind farms are vital to maximise power outputs, reduce operation cost and guarantee grid stability. Chinese firms lacked the relevant technologies and equipment to achieve these targets. Tsinghua University and Beijing Jiaotong University had accumulated knowledge in electricity transmission technologies. Mingyang cooperated with them along with a wind farm developer to work on wind farm management technologies (Mingyang 2008).

Shanghai Electric's collaborations with universities

Shanghai Electric Wind Power Equipment Co., Ltd was established in 2006. Like many other Chinese firms, Shanghai Electric has grown technology by licensing and joint R&D (Shanghai Electric 2008). The company absorbed the licensed technology from Dewind's 1.25MW turbine and then carried out joint R&D with Aerodyn on 2.0MW turbines (Shanghai Electric 2008). Afterwards, Shanghai Electric purchased Aerodyn's design software which enabled the firm to design wind turbines indigenously (Shanghai Electric 2008). The successful commercialisation of 3.6MW turbines represents a typical example of how Shanghai Electric re-innovates based on licensed technologies.

In 2010, the firm established a technology strategic alliance with universities and institutes to facilitate innovation and industrialisation of wind turbine technologies. They include Shanghai Jiaotong University, Fudan University and Shanghai FRP Research Institute Co., Ltd., (Shanghai

Electric 2008). Take the 2.0MW R&D project as an example, Shanghai Electric led the project while Shanghai Investigation, Design and Research Institute and Shantou University took subtasks of the project. These institutes had their own technological advantages so they can complement each other. The complementarity greatly improved the efficiency and depth of R&D activities (Shanghai Electric 2008).

It has been reported that the success of this strategic alliance lies in three supportive factors – effective communications, complementary assets among them and demand-oriented R&D (Shanghai Electric 2008). It is crucially important to hold routine meetings and special sessions so that the different parties can collectively think of solutions to the problems they encountered while the complementarity allowed to inspire novel concepts and technologies (Shanghai Electric 2008). As the research was oriented towards the market demand, they were able to respond quickly to the market (Shanghai Electric 2008).

7.3.2 Transnational innovation networks

Envision Energy's transnational linkages

Envision Energy has built production and R&D facilities in China, Denmark, Japan and the USA. The company attracted talented engineers across countries and industries. By the end of 2012, Envision Energy employed about 500 people, of which 20% were non-Chinese nationals or those who had worked or studied overseas (Feng 2013). The proportion of R&D personnel comprises 60%, of which 75% are master or doctorate holders (Feng 2013).

In 2013, the firm developed 4.0MW offshore wind turbines which could react to local climate conditions. By integrating the knowledge of its innovation centres in Denmark and China, it developed wind turbines that could efficiently work in low-speed wind areas. It also employs molecular concepts and technology to design blades, which allows customising blades according to specific wind conditions so that power outputs can be maximised (Feng 2013).

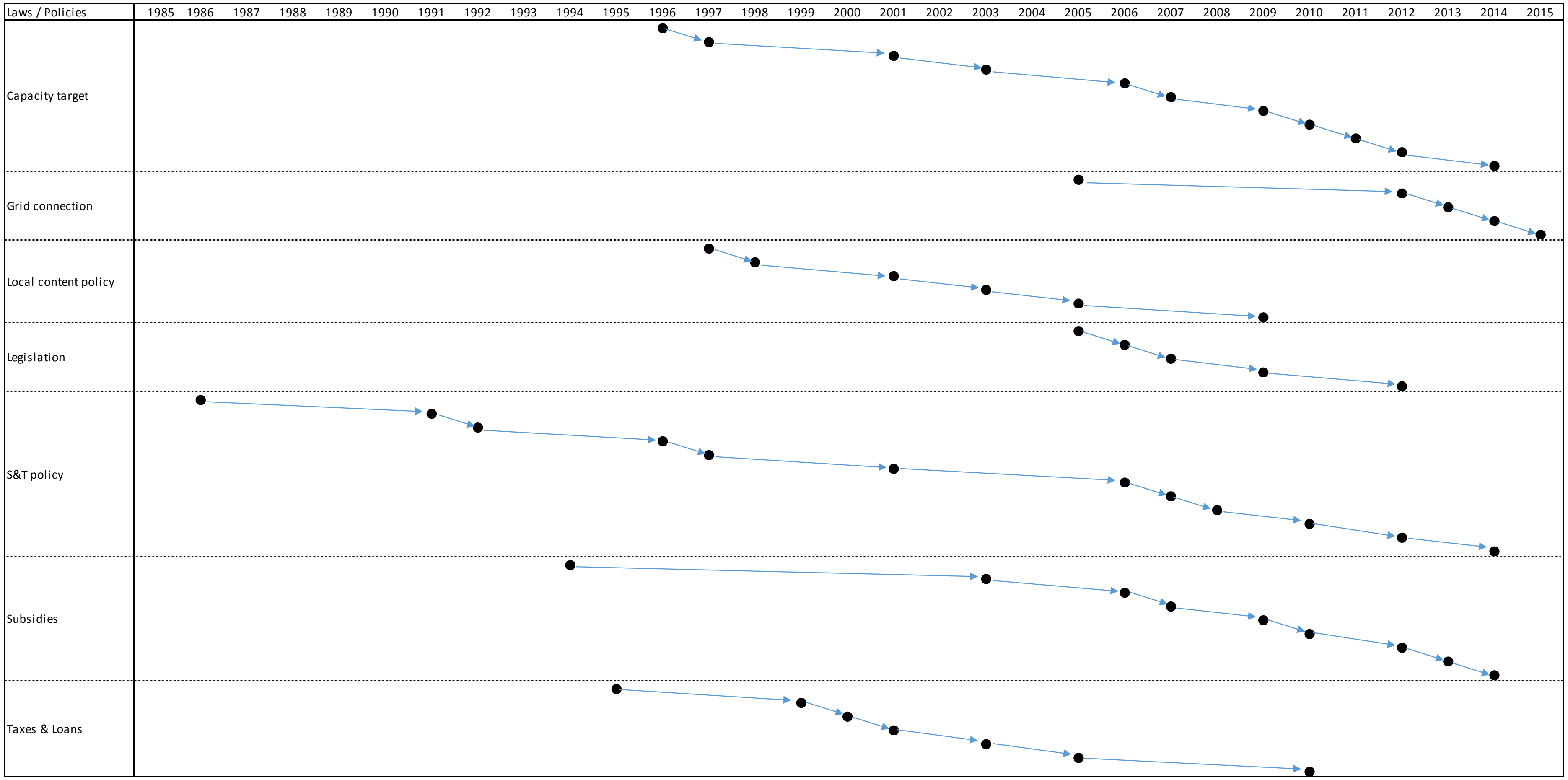
Envision Energy aims to become a world leader in the digital transformation of the energy sector and is building a global innovation network in energy digitalisation. In 2015, it invested in Vidder, a computer technology start-up which has the potential to change the rules of cyber security (Xie 2016). In 2016, the company acquired the Norwegian digital energy firm BazeField whose management system monitors turbines in real time to support operations and maintenance services. Envision Energy also invested in the world's largest electric vehicle charging network provider ChargePoint, and the world-leading energy digital company AutoGrid (Xie 2016).

7.3.3 Summary of subsection

In summary, there are four features of the formation of networks in China’s wind turbine industry. First, Chinese manufacturers proactively established knowledge networks with foreign counterparts via joint R&D after 2002 when a few of them had imitated foreign technologies for a while (see Diagram 7-3). In the past, they had been technology licensees and had little competencies to conduct joint research which intensively occurred between 2008 and 2010. Second, the university-industry collaborations were built almost the same time as joint R&D. This may imply that Chinese firms began to diversify technology transfers from merely relying on foreign firms to include domestic universities and institutes. Third, the examples of Mingyang and Shanghai Electric show that the spirit of Entrepreneurial Activities (F1) plays a role in encouraging to seek external knowledge. Four, the experience of Envision Energy implies that catch-up firms can leapfrog the early stages of networks (e.g. technology licensing and joint R&D) to build global innovation networks directly. The effectiveness of this type of leapfrog may vary across firms, but Envision Energy’s story demonstrates that a global innovation network can pool high-end R&D talents and accelerate technological innovations.

7.4 Institutions

Laws, regulations and policies have created a profound impact on China’s wind turbine innovation system, particularly the *Renewable Energy Law* (2005). There are a variety of policies that emphasise the scaling of industry and unit capacity, grid connection (or curtailment issues), Diagram 7-4 The emergence and continuity of laws and policies in China’s wind turbine innovation system



N.B. The same type of policy may be emphasised in more than one government document in a year. It is different from the frequency of policies in section 8.3.7.

Source: Compiled from IEA and IRENA (2016), Dai and Xue (2015), Surana and Anadon (2015b), Gosens and Lu (2013b) and government websites.

local content ratio of components, letitimacy, S&T development, subsidies, tax incentives and bank loans (see Diagram 7-4). This section describes the key features of some of the most influential policies to understand the institutional dynamics in China's wind turbine industry.

7.4.1 Renewable Energy Law

A critical reason for China's slow technological growth in the early years may be due to the lack of regulations and policies. In 2016, the 10th-anniversary conference of the *Renewable Energy Law* reached a consensus that the law issued in 2005 had played a fundamental role in facilitating China's renewable energy development, particularly wind power and solar PV (Zhu 2016). It laid basic rules on development targets, grid connection, price setting and special funds.

According to the law (NPC 2005), renewable energy is prioritised through government targets. Both state-owned and private enterprises are eligible to enter the renewable energy market. Special funds are provided to support R&D and commercialisation of renewable energy technologies (RETs). Universities are encouraged to offer academic courses on renewable energy, and standardisation authorities are required to make technology standards. Renewable energy projects can benefit from discounted government loans and tax incentive schemes. Renewable power can be sold at guaranteed prices to grid operators who can recover the associated costs through selling prices.

Despite the benefits, the law was criticised for several problems (Li 2007). Firstly, it proved extremely difficult for grid companies to fully purchase the power generated from wind turbines due to the prioritisation on coal power and the capacity of electricity grid. Secondly, wind power concession programmes had been mainly concerned with cost, which forced the stakeholders to compete on lower cost but it was sometimes impossible for them to profit from the projects.

The law was amended in 2009 to emphasise mandatory purchase, grid connection and subsidies (NPC 2009). The new regulation requires that energy administrative departments be responsible for making a target for the proportion of renewable energy power in total electricity generation. It binds grid operators to buy the whole renewable energy power and improve transmission systems to facilitate the integration of electricity from renewable sources. A special fund for renewable energy is established to balance the extra cost of integrating renewable energy power. Moreover, in the case of non-compliance with the imposed mandatory purchase policy, grid operators should compensate renewable electricity producers by an amount equal to twice the economic losses they have suffered. Nevertheless, wind power curtailment issue has not been solved as both the original and amended laws have primarily cared about installed capacity rather than power generation.

7.4.2 Public policies

Ride the Wind (1996)

The international wind power market has played an important role in pushing the Chinese government to develop wind energy sector. Between 1985 and 1995, Denmark, Germany and the USA achieved significant progress in wind turbine technology. Wind power developed quite slowly in China during that time. Throughout the 6th and 7th Five-Year Plan periods, China was only able to produce turbines less than 5kW. The 200kW wind turbine was not developed until the 8th Five-Year Plan and it was merely a prototype. It seemed impossible to achieve the proposed target of installing 1GW wind power by 2000 (SETC 1996b). It was too costly to import wind turbines from overseas given China's huge demand for wind power.

By taking into account these concerns, the former State Planning Committee (SPC) decided to implement the so-called "*Ride the Wind*" programme with the aim of enhancing China's technological capability of manufacturing large wind turbines via the process of importation, digestion, absorption and re-innovation (Zhou 1997). The government emphasised that the constructions of wind farms must go hand in hand with the localisation of wind turbine component. The purpose was to grow China's wind power industry with home-developed technologies.

"Trading market access for technology" has been a key feature of China's innovation strategy over the past decades. Wind turbine industry is not an exception. The "*Ride the Wind*" programme identified key steps (Zhou 1997): a) identify technological trajectory, i.e. the mainstream types of wind turbines; b) pick national champions to manufacture core components; c) organise firms and research institutes to undertake R&D projects (e.g. S&T Enabling Project); and d) establish joint ventures with foreign counterparts. In 2001, China's first patch (10 units) of 600kW wind turbines came off the production line from a joint venture, with 60% of components produced locally. It is fair to say that this programme initiated China's industrialisation efforts on wind technology.

Wind Power Concession Programme (2003)

The scaling-up of wind power industry in China can hardly be achieved without the supply of wind turbines at reasonable prices. By 2001, China's manufacturing and R&D capabilities in the wind turbine industry were relatively weak and the localisation of wind power equipment was still under development. In order to stimulate the wind power industry with lower upfront cost, NDRC launched the *Wind Power Concession Programme* (2003).

The government decided to commission companies based on their proposed prices per kWh of wind electricity and the share of components that can be produced locally. The bidders who proposed a lower price normally secured the contract. The bid price was guaranteed as a ffeed-in-tariff (FIT) for the first 30,000 full load hours, which significantly lowered down wind power price. In 2004, the government offered three more concession projects of 100-200MW in size. A total of eight Chinese and foreign companies participated in the bidding.

In 2005, the third concession projects were launched. This time the government particularly emphasised "localisation rate", namely at least 70% of components must be manufactured domestically while the weight of bidding price slipped to 40% in project evaluations (Jiang and Shi 2006). The local content requirement forced Chinese manufacturers to accelerate the pace of localisation and attracted foreign companies to build plants in China. Vestas opened a blade factory in China. By the end of 2005, China's installed wind power capacity reached 1.3GW, slightly higher than the government's proposed target (1.2GW).

There are several benefits of the concession programmes. First, it significantly reduced wind power price by introducing FIT. Second, it stimulated competition between Chinese and foreign firms and thus strengthened Chinese firms' motivation to innovate. Third, a fixed price contract was guaranteed between wind farm developers and utility companies. Four, the localisation rate policy forced Chinese firms to improve manufacturing capacity of core components. Nevertheless, the Chinese bidding companies competed against each other heavily on cost, undermining the quality and reliability of wind turbines.

Medium and Long-Term Development Plan for Renewable Energy (2007)

China's wind resources that are technologically and economically exploitable can enable the deployment of 1,000GW wind power (NDRC 2007). China had only installed 2.6GW wind power by 2006 (BP 2016). The major barriers were the lack of long-term and stable market demand and core technologies for megawatt-class wind turbines (NDRC 2007). In 2007, NDRC (2007) issued the *Medium and Long-Term Development Plan for Renewable Energy*, aiming that the percentage of renewable energy in total energy consumption will rise to 10% by 2010 and 15% by 2020. To be specific, wind power was expected to increase to 5GW by 2010 and 30GW by 2020.

One year after, the *11th Five Year Plan for Renewable Energy* adjusted the target and proposed a target of 10GW by 2010. It claimed that Chinese firms should be then able to produce 1.5MW+ turbines and develop 3.0MW+ offshore wind turbines. Meanwhile, the *Interim Measures for Administration of Special Funds for Wind Power Equipment Industry* (2008) was issued to provide R&D fund for 1.5MW+ turbines. According to the regulations, 600 RMB per kilowatt electricity would be offered for the firm's first 50 units of wind turbines, namely 45 million RMB for 50 sets of 1.5MW+ wind turbines. It was required that blades, gearboxes and generators must be produced by Chinese firms.

In the following years, the government issued other policies for regulating wind power price and promoting offshore wind power. The *12th Five Year Plan for Renewable Energy* set a target of developing 100GW wind power by 2010 and 200GW by 2020. This was a remarkable change in the original development target set in the *Medium and Long-Term Development Plan for*

Renewable Energy (2007), mainly caused by the sharp growth between 2008 and 2011. By the end of 2011, China's installed wind power capacity hit 62GW (BP 2016).

It has been clear that the *Renewable Energy Law* established the basic rules for developing wind power, and the *Medium and Long-Term Development Plan for Renewable Energy* (2007) outlines China's development agenda on renewable energy. The experiences from the *Wind Power Concession Programmes* (2003-2005) provided useful lessons for policymakers on wind power regulations. In particular, the alignment between technology-push and market-pull policies promoted China's rapid growth of wind power.

Special Plan for Wind Power Science and Technology Development (2012)

By the end of 2010, about 20 Chinese firms were able to produce megawatt-class wind turbines (MOST 2012). By means of technology licensing, joint R&D and indigenous innovation, Chinese manufacturers are capable of industrialising 1.5 – 3.0MW wind turbine technologies, of which 2.5 – 3.0MW wind turbines have been deployed at small scale (MOST 2012). Some firms already developed 3.6 – 5.0MW prototypes while 6.0MW+ turbines were under development (MOST 2012). Despite these, Chinese firms were not sufficiently capable of developing novel wind turbines and of developing design software with their own IPRs (MOST 2012).

Regarding wind turbine components, China is relatively weak in indigenous innovation and lacks the technology to improve intelligent processing and quality control (MOST 2012). The reliability of gearboxes and generators need to be improved; the indigenous design of wind turbine blade is at the primary stage; bearings and inverters for megawatt-class wind turbines are manufactured at a small scale, and control systems are in demonstration stage (MOST 2012). The testing and certification of wind turbines just started by referring to international practices and standards (MOST 2012). Wind resources survey and assessment are not sophisticated enough to support high-end designs of wind farms (MOST 2012).

Qi Liu, General Manager of Shanghai Electric Wind Power Equipment Co., Ltd. spoke at the China Wind Power Conference 2015 that "*there are still big challenges for Chinese wind turbine manufacturers to transform from price competition to quality competition, and ideally to* *technology competition and to be able to provide customised products and solutions*". A more critical issue may be that China lacks a strong public laboratory that develops and tests cutting-edge wind technologies. While over ten state labs have been established, they are so dispersed that it is hard to advance technology on the common ground. This problem has frequently been mentioned by the interviewees and the participants at the conference.

The *Special Plan for Wind Power Science and Technology Development* (MOST 2012) proposed a series of measures to solve these problems, such as enhancing basic and applied research, developing 7.0MW+ wind turbines, mastering the core component technologies of large wind turbines, and building national wind databases, R&D platforms and technological alliances. The plan identified the major problems China faced in wind technology innovation and proposed the associated solutions. However, whether the problems can be solved depend on the enforcement of those policy measures.

7.4.3 Summary of subsection

In summary, there are five features of China's wind power policies (see Diagram 7-4). First, China's wind power development is policy-driven. The government's targets for industry and unit capacity after 2006 had been highly related to the country's rapid growth of wind power. Second, the issuance of the *Renewable Energy Law (2005)* has acted as the watershed for China's institutional changes in wind power – all types of policies began to be emphasised more frequently after the law, along with the scaling of industry capacity. Third, the alignment between government policy and firms' activities is important to accelerate technological catch-up. The local content policy between 1997 and 2009 was in parallel with the firms' efforts to licence and imitate foreign technologies. Four, the role of S&T policy remained stable in the government's policy instrument between 1985 and 2005, but it was presented more recently when Chinese firms had embarked joint R&D and in-house innovation. Five, the policies on installed capacity and power generation were misaligned. The subsidies, tax incentives and preferential loans for wind power projects had gone hand in hand with the government's target for industry capacity, but the emphasis on grid connection appeared rather late when the curtailment issues had become very serious.

7.5 Summary

This chapter maps out the structural elements (i.e. actors, networks and institutions) of China's wind turbine innovation system, describes their presence and status quo and summarises their key features. In general, China has built the necessary elements of the innovation system, and the current challenge is to improve the capability or quality of individual elements.

The actors entered the industry rather late (around 2005) and the majority of the "new players" immigrated from neighbouring industries. The shorter history and limited experience affected their innovative capability. The Chinese government and firms benefited from international counterparts in technology and policy areas through "learning by using" and "learning by doing". However, the alignment between governmental departments was relatively poor, which often caused severe duplications and fragmented policies. The firms adopted two types of innovation strategy. The "older generation" (e.g. XEMC) followed the traditional pathway of technology licensing, joint R&D and indigenous innovation, whereas the "new generation" (e.g. Envision Energy) rapidly achieved technological leapfrog by tapping into the global innovation networks.

The networks were quite simple in the early years. The firms just licensed the technology from foreign partners. After they had enhanced technical skills based on technology imitation, they began to diversity knowledge networks to include joint R&D with foreign partners and meanwhile collaborated with domestic universities. Throughout the evolution of networks, the spirit of Entrepreneurial Activities (F1) motivated the firms' networking efforts. The experience from Envision Energy seemed to demonstrate that as China becomes increasingly integrated into the global networks of production and innovation, it is important to take advantage of the innovation sources distributed elsewhere as early as possible to accelerate innovation.

The institutional changes characterised by the *Renewable Energy Law* and a series of policies played a fundamental role in stimulating China's wind power development. The alignment between government policy and firm’s activities was crucial to facilitate technological catch-up. However, the misalignment in demand-pull policy (e.g. installed capacity and power generation) undermined the economic and social outcomes of wind technology. The policy focus recently was oriented towards technology-push and solving curtailment issues.

The structural analysis depends heavily on the availability of data and materials. The diagrams used to demonstrate the presence of the major actors, networks and institutions over time are drawn up by referring to a wide range of Chinese sources, including journal papers, government documents, websites, newspapers, magazines and statistical reports. The diagrams do not present a definite picture of the structural elements largely due to data constraints, but the method adopted to achieve the “mapping out” purpose may be valuable for future research.

The features observed from the structural analysis can partly explain China’s performance in wind turbine innovation (see Chapter 6). For example, the governance of the innovation system is fragmented. Universities, research institutes and state labs are disconnected and lack integration. The technological capabilities of wind turbine producers and component suppliers are yet to be improved. They still need to import the core components, software and facilities. The interactions between industry and university exist, but they have been far less than perfect despite the establishment of some technological alliances. These structural problems may inspire policymakers to formulate innovation policy.

The structural analysis helps understand the characteristics of the systemic elements and their problems. The next chapter will build on the structural analysis to examine how they contribute to fulfilling the system functions which affect the overall performance of the innovation system.

Chapter 8 Functional analysis of China's wind energy innovation system

The last chapter shows that China has established the necessary elements for an effective wind energy innovation system but suffers from their relatively weak capability or quality, which may affect the system's functioning. As a part of the structure-functional analysis, this chapter intends to identify the functional patterns and problems via quantitative and qualitative indicators.

Section 8.1 derives a set of indicators for measuring the functionality of the system. Section 8.2 proposes three hypotheses about the functional patterns and problems. Section 8.3 presents the results through quantitative and qualitative indicators. Section 8.4 discusses the results corresponding to the proposed hypotheses. Section 8.5 concludes the findings.

8.1 Indicators for measuring system functions

Chapter 5 has made a distinction between system and function-level indicators. The former is to understand the historical progress of technology development while the latter is to examine the fulfilment of the key functions that affect the progress. This section aims to draw upon the literature to derive a set of indicators for measuring system functions.

8.1.1 Historical events as indicators

The commonly-used approach to functional analysis has been the "historical event analysis" (see Hekkert et al. (2007b), Negro, Hekkert, and Smits (2007), Suurs (2009)). It is to "*presents a story line of how function X influences technology development and all the other functions*" (Hekkert et al. 2007b). The challenge is to collect detailed information about the events which may positively or negatively contribute to the functioning of the system. All events are allocated to the specific functions and plotted in figures with the frequency of the events as the Y axis. Theoretically, seven pictures will be produced to show the functional patterns of the system over time (see Negro, Hekkert, and Smits (2007), Suurs (2009)). In this way, the historical events serve as the indicators of system functions.

This approach relies heavily on the coverage of information, namely retrieving as many historical events as possible. The events are collected from journals, newspapers and websites or directly from LexisNexis – an electronic database for legal and public-records. However, it is very difficult to capture all the historical events manually. Even the Lexis-Nexis database may encounter coverage problems as its primary focus is on legal research. It is likely that this method may generate an incomplete picture of the events related to a technology development. Also, the real impact of the events (e.g. a firm's announcement on developing a novel technology) cannot be quantified by just looking at the plain texts.

An alternative method may be mining texts from social media (e.g. facebook, twitter) or company websites (see He, Zha, and Li (2013), Gök, Waterworth, and Shapira (2015)). It is quicker than manual collections, and more "user-friendly" than LexisNexis as programmers can code whatever topics they are interested. Again, this method suffers from coverage problems as many events recorded in books and magazines that have not been digitalised cannot be recognised. Even Google Ngram Viewer which enables searching for a single word or a phrase from over 15 million books has this problem. The scanned books by Google account for only 11% of all books ever published, let alone the deficits in optical character recognition (Michel et al. 2011).

8.1.2 Quantitative and qualitative indicators

Recently, researchers have derived quantitative indicators for measuring system functions (see Gosens and Lu (2013b), Borup et al. (2013), Vasseur, Kamp, and Negro (2013) and Markard and Truffer (2008)). Compared to the historical event analysis approach, indicators can be interpreted from the established statistical databases or the required data can be easily obtained and does not suffer from coverage problems too much. Borup et al. (2013) adapted a set of indicators to measure the functions of the Danish energy innovation system, but the incorporation of input, throughput and output indicators into the function analysis did not work very well (see Chapter 3). Gosens and Lu (2013b), Vasseur, Kamp, and Negro (2013) and Markard and Truffer (2008) suggested a set of indicators but did not test them in an empirical context.

Table 8-1 Indicators for measuring the functionality of energy innovation systems

Functions	Indicators
F1: Entrepreneurial Activities	• New entrants or entrepreneurs • Technology development strategy
F2: Knowledge Development	• (top 10%) SCI publications • Patent applications to EPO, USPTO or SIPO
F3: Knowledge Networks	• Public-private interactions • Producer-user connections
F4: Guidance of the Search	• Policy target for industry capacity • Policy target for unit capacity
F5: Market Formation	• Niche market policy for the technology • Market demand for the technology
F6: Resources Mobilisation	• R&D expenditure • Asset finance
F7: Creation of Legitimacy	• Presence of laws, regulations and policies

Source: Gosens and Lu (2013b), Borup et al. (2013), Vasseur, Kamp, and Negro (2013) and Markard and Truffer (2008)

By referring to the definitions of system functions and the existing work by Gosens and Lu (2013b), Vasseur, Kamp, and Negro (2013) and Markard and Truffer (2008), this section derives a set of quantitative and qualitative indicators for measuring system functions (see Table 8-1). The advantages of these indicators are that they capture the core meanings of the functions and the required data can be easily collected. The limitation is that the indicators can reflect only a partial view of the system functions, which is mainly caused by the range of indicators and the limitations of data availability. It acts as a positive response to the concern that indicators are needed to measure functionality (see Bergek et al. (2008), Hekkert et al. (2011)) and applies them to the Chinese wind turbine industry.

Arguably, certain indicators are almost the same as the system-level indicators, e.g. the indicators for Knowledge Development (F2) and Resource Mobilisation (F6). That is because some indicators have a generic feature and can be adapted in different contexts. It also occurs in the historical event analysis. An event may contribute to multiple system functions (Suurs 2009). For example, the establishment of industrial associations can be allocated to the functions of Knowledge Diffusion (F3), Guidance of the Search (F4) and Creation of Legitimacy (F7) (Suurs 2009). The appropriateness of indicators depends on the questions to be addressed.

8.2 Hypotheses

Chapter 7 analysed the structural arrangement of China's wind energy innovation system. This chapter will carry out the functional analysis and link it back to the structural elements and system performance. Three hypotheses are proposed:

Hypothesis 1: ***China's functional patterns are different from developed countries***.

System functions play a different role depending on the development phase of the technology (an S-shaped curve) (Hekkert et al. 2011). For example, in pre-development phase, Knowledge Development (F2) is crucial; for the development phase, Entrepreneurial Activities (F1) are the most important function (Hekkert et al. 2011). China is a latecomer in the global wind turbine industry and has built the innovation system via technology transfer, so its functional patterns may be different from the original developers. The motors of technological change can start from a certain number of functions that pull the other functions (Hekkert et al. 2007b). It is likely that China starts from Guidance of the Search (F4) and Creation of Legitimacy (F7) to Knowledge Development (F2) and Knowledge Networks (F3).

Hypothesis 2: ***The system performance depends on the fulfilment of the system functions.***

The fulfilment of the system functions either positively or negatively affects the overall performance of the system (Hekkert et al. 2007b). It is shown that China has made considerable progress in certain inputs and outputs but lags in many others especially outcomes. For example, China has caught up fast in scientific publications and manufacturing capacity but falls behind in patent filings and unit capacity of wind turbines. China's technological progress may be affected by the presence or weaknesses of the system functions or even the functional patterns, which will be tested via the indicators.

Hypothesis 3: ***The system's functionality relates to the capability of structural elements.***

The structural elements comprise the system's foundations upon which the functions are achieved (Wieczorek and Hekkert 2012). It is argued that the system's functionality is fulfilled through the presence and capability (or quality) of structural elements (Wieczorek and Hekkert 2012). Without the alteration of a structural element, the fulfilment of functions can hardly be achieved (Wieczorek and Hekkert 2012). Based on the structural analysis in Chapter 7, this chapter attempts to link functional problems back to structural elements. It may help verify that the relationships between structural elements and system functions also apply to a large transitioning economy and a technological catch-up country like China.

8.3 Results

This section applies the derived indicators to the Chinese wind turbine innovation system to identify the system's functional patterns and problems.

8.3.1 Entrepreneurial Activities (F1)

China is a latecomer in wind turbine technology. It was not until the early 1980s that a few public institutes started to research, develop and demonstrate wind turbines (Dai and Xue 2015). When advanced wind technology was available in the international market, Chinese domestic technologies were already outdated before they had the chance to become commercialised (Dai and Xue 2015). It was under this situation that Chinese government decided to accept donations and grants from Denmark and Germany to import their wind turbines (Shi 1997). More details about China's technology development efforts in the early years can be found in Chapter 9.

Before the 2000s, only a few Chinese firms were involved in wind turbine technology. A key feature about Chinese manufacturers is that they have entered the industry very recently (see section 7.2). As of 2015, about 32 turbine manufacturers, 21 gearbox providers, 18 blade makers, 17 control system developers, and 6 certification agencies are active in the Chinese market (Chinawindnews 2016). The emergence of new entrants or Entrepreneurial activities (F1) greatly enhanced China's manufacturing capacity. Chinese manufacturers adopted a variety of technology development strategies to enhance technological capability, including technology licensing, joint R&D, mergers and acquisitions (M&A), indigenous innovation, and the establishment of R&D centres in knowledge clusters (see Diagram 8-1).

How to read diagram 8-1?

The company names are abbreviated as follows:

Goldwind – GW
Envision Energy – EE
United Power -UP
Windey – WD
Dongfang -DF
XEMC Windpower – XEMC
Shanghai Electric – SE
Mingyang – MY
Haizhuang – HZ
Sinovel – SI

Please note that:

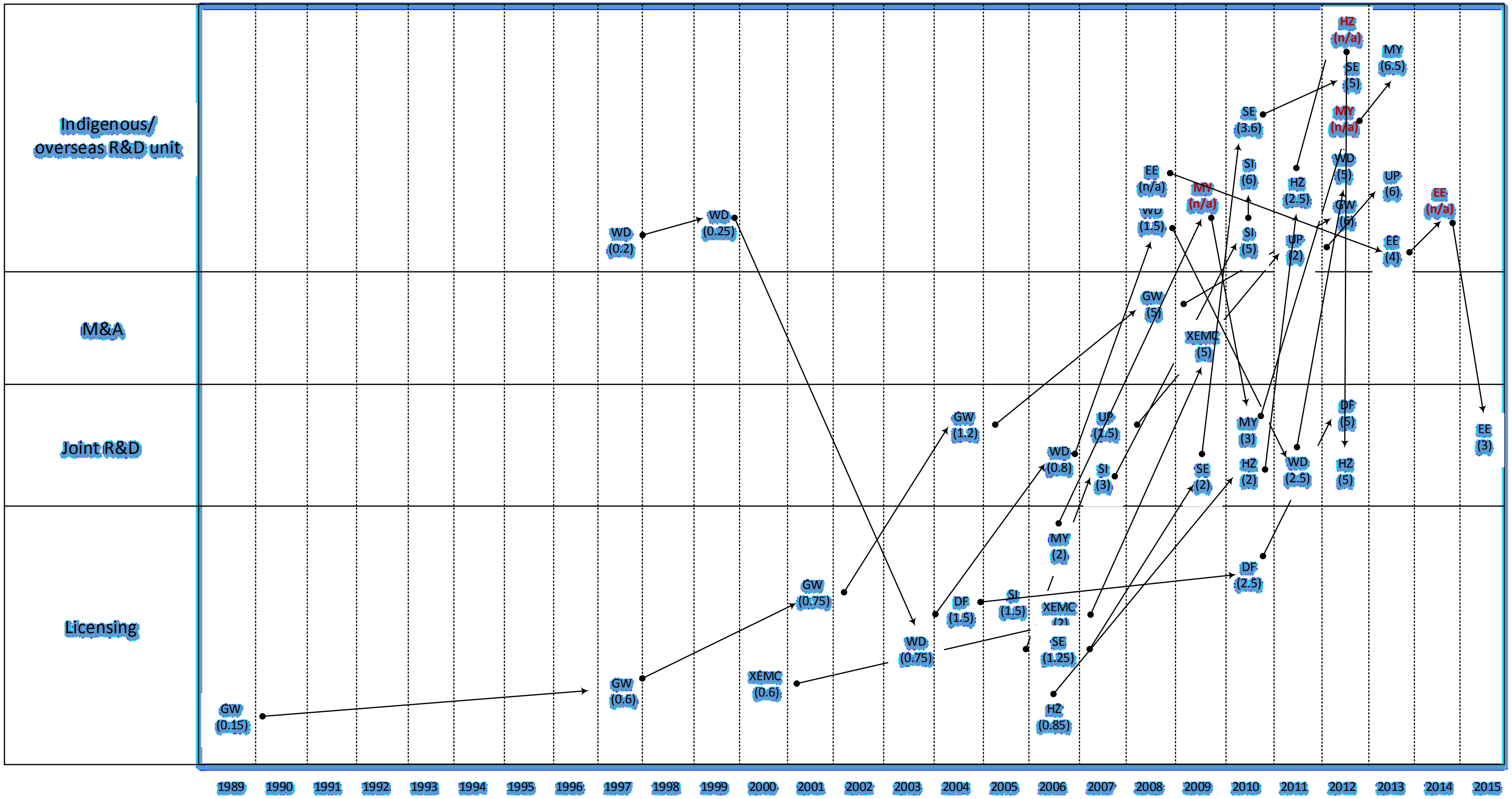
a) overseas R&D units are coloured in red;

b) only the maximum turbine sizes (in brackets) for each year are shown;

c) an upper position does not necessarily mean larger unit capacity.

The diagram is only used for illustrative purposes and cannot reflect the firm's complete innovation strategy.

Diagram 8-1 Innovation trajectories of the top ten Chinese wind turbine manufacturers



Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a) and Zhang et al. (2009)

The diagram shows the innovation trajectories of the top ten Chinese wind turbine producers. It characterises the generic features of Chinese firms' innovation strategy. Clearly, almost all Chinese firms have relied on technology licensing except Envision Energy and United Power. Most of the Chinese firms have substantially improved technological capability after technology licensing and joint R&D. After having developed the ability to produce wind turbines through licensing, they began to master the design capability by conducting joint R&D. Compared to independent R&D, technology collaboration with foreign counterparts allows them to acquire technology quicker and probably a less risky manner. Zhou et al. (2012) argued that Chinese firms trained technicians, improved technological capability and created more patents via joint R&D.

To be specific, Windey was capable of producing 250kW turbines in the late 1990s with own IPRs, but the firm licensed 750kW technology from REpower to obtain more sophisticated technical know-how. The company then conducted joint R&D with REpower on 800kW turbines before being able to design 1.5MW turbines. After having mastered 1.5MW technology, it carried out joint R&D with Garrad Hassan on 2.5MW technology. Windey now claims to be able to design 5.0MW turbines with advanced techniques.

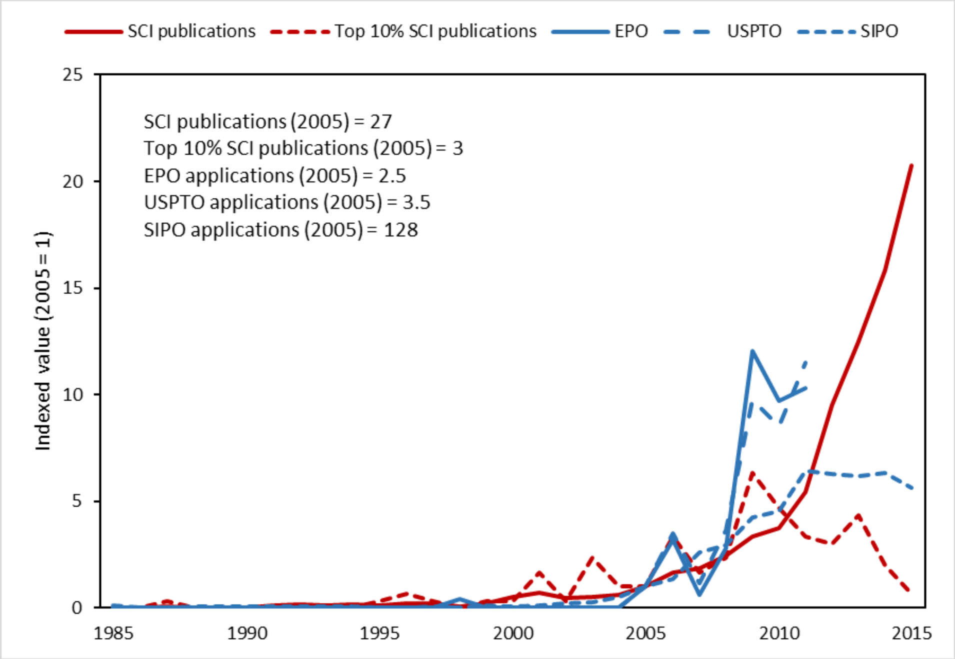
In recent years, a few Chinese manufacturers acquired foreign companies or established R&D units in innovation-intensive regions to access sophisticated technology. Goldwind purchased 70% of Vensys' shares to develop 3.0MW turbines. XEMC purchased Darwind for €10 million to acquire 3.0-5.0MW technologies (Yan 2009). Mingyang established an R&D centre in Demark to cooperate with Risø-DTU (Mingyang 2010) and then launched an R&D centre at North Carolina University in the USA (Quilter 2012). Envision Energy acquired its first research subsidiary in Denmark, allowing it to access the skilled R&D personnel and excellent test facilities (Slepniov et al. 2015). At present, almost all the top Chinese manufacturers except Envision Energy have developed 5.0MW+ prototypes.

The innovation trajectory has displayed a pathway of importation → absorption → digestion → re-innovation. During this process, the presence of Entrepreneurial Activities (F1) and the technology development strategies the entrants adopted undoubtedly facilitated China's technological progress. However, when compared to the world leaders, China still lags in developing leading wind turbines which have a larger unit capacity. China lacks the core technologies in intelligent manufacturing, quality control, and relies on foreign technologies for blade design, bearing systems, inverter and control systems (MOST 2012, Gosens and Lu 2013b).

8.3.2 Knowledge Development (F2)

China's ever first academic conference on wind turbine technology did not occur until the middle 1980s (He and Shi 2010). Although a few prototypes were developed during that period, they failed to become commercialised because they "lack science and technology theories" (Li et al. 2005). When China did develop small-scale wind turbines (< 300kW) in the 1990s, the accumulated knowledge had become out of date – foreign counterparts had already commercialised 1.0MW+ turbines. Chinese firms did not have the techniques and skills to upgrade the unit capacity to megawatt-scale. The deficits in Knowledge Development (F2) obstructed China's technological progress.

Figure 8-1 The dynamics of China's knowledge development in wind energy



Source: WoS (2016), EPO and USPTO (2016), SIPO (2016)

The build-up of knowledge stocks for developing countries may be underpinned by two sources – one is to absorb and digest cutting-edge knowledge developed elsewhere, and the other is to conduct in-house R&D relying on the domestic endowment. The first approach can be very challenging as the big technology gap between developing and developed countries may considerably offset the effect of absorptive capacity (Imbriani et al. 2014, Glass and Saggi 1998, Cohen and Levinthal 1990). Catch-up countries' imitation lag may be prolonged if the technological gap is large (Freeman 1987). Regarding the second approach, the firms in developing countries may face huge technological uncertainties and need to bear the high upfront cost of R&D and the long learning curves. Chinese firms' technology licensing from the foreign counterparts demonstrated that the second method did not work.

A closer look into Goldwind's technology innovation process reveals that Chinese firms combined the two approaches (refer to Chapter 9), namely licensing foreign technologies while conducting in-house R&D. The function of Knowledge Development (F2) surged around 2005. There was barely one publication authored by Chinese researcher(s) in 1985, but this figure increased to nearly 30 by 2005 and rocketed to 550 by 2015 (see Figure 8-1). A similar increase happened to the top 10% scientific publications, the patent applications to the EPO, USPTO and SIPO.

The growth of patent applications has been faster than scientific publications. It conveys the firms' strong willingness to "leapfrog" in inventive capability. When compared to the world leaders, China caught up rapidly in scientific publications but significantly lags behind in patent filings (see section 6.2). Scientific publications often stem from basic research normally carried out in universities or institutes while patent filings closely relate to applied and experimental research mostly conducted by firms. It implies that China suffers from an applied research deficit which may be caused by the lack of connections between basic and applied research, namely the interactions between university and industry (F3: Knowledge Networks).

China has established about seventeen state labs or engineering centres for developing wind turbine technology, but they have just appeared recently, and their technological capability is relatively weak (see section 7.2). All the labs are based in firms, which should have contributed to the firms' Knowledge Development (F2) in applied (and basic) research. However, the lack of qualified and high-end R&D personnel, the disconnections between the state labs, and the missing of a shared vision on developing generic technologies undermined the effectiveness of research.

8.3.3 Knowledge Networks (F3)

Innovation is a collective achievement that requires efforts from both public and private sectors. The Knowledge Networks (F3) among the various actors can be very complex. This section intends not to examine all the interactions that exist in China's wind turbine innovation system but focuses on three types of networks, namely the public-private interactions (or university-industry relationships), producer-user connections (or wind turbine maker-wind farm developer relationships) and international linkages of Chinese firms. The intra-relationships within the education and training system or between industrial firms will also be analysed.

University-industry relationship

Knowledge transfers from university to the industry through licensing agreements, joint ventures or start-ups represent a major source for commercialising scientific discoveries into industrial technologies. By tracking the histories of the top ten Chinese wind turbine manufacturers, no evidence has shown that they were originally joint ventures between a university and a firm or start-ups created by academics except Sungrow (an inverter producer). Thus, licensing agreements between universities and firms act as the main channel of transferring university research to industrial use, apart from the flows of students trained in universities to the industry.

Another type of connection between university and industry may exist when a state lab or national engineering centre is shared by a university and a firm. However, almost all the seventeen labs and centres for wind technology are exclusively owned by firms except the

Table 8-2 China’s “863 Plan” and “S&T Enabling Programme” for wind turbine technology (2011-2015)

Categories	Project participants		
S&T Enabling Programme	Universities / Institutes	Turbine producers	Component suppliers
	Project: *Design and Industrialization Technology for 7.0MW Wind Turbines and Key Components*		
	Huazhong University of Science and Technology; Nanjing University of Aeronautics and Astronautics; CAS Institute of Engineering Thermophysics	Windey; Dalian Huarui Heavy Industry Group	Corona; CSIC CQ Gearbox; ZWZ; Sinoma Wind Power Blade; Sungrow; Zhongfu Lianzhong Composites Group; NGC
	Project: *Design and Manufacturing Technology for Distributed Medium and Small-Sized Wind Turbines*		
	Inner Mongolia University of Technology	Inner Mongolia Huade New Technology	
	Project: Testing Technology and Facilities for Large-Scale Wind Turbines		
	CGC; CAS Institute of Electronic Engineering; China Electric Power Research Institute (State Grid)		
863 Plan	***Project***: *Design Technology for Large-Scale Offshore Wind Turbines*		
		Goldwind; United Power; Sinovel	
	Project: *Design and Manufacturing Technology for Front-End Speed Controlled Wind turbines*		
		Lanzhou Electric Corporation	
	Project: *Advanced Airfoils Design and Application for Wind Turbines*		
	China Aerodynamics Research and Development Center; CAS Institute of Engineering Thermophysics		
	Project: *Design and Manufacturing Technology for Wind Turbines Reacting to Low-Wind, High-Plateau and Low-Temperature Conditions*		
		Goldwind	

N.B. Wind turbine technology was not funded by “973 Plan” between 2011 and 2015, probably because the Plan is a basic research programme.

Source: MOST (2011a), MOST (2011b)

National Research Centre for Wind Power Blades based in CAS (see Chapter 7). Hence, this sub-type of Knowledge Network (F3) is missing. Alternatively, firms and universities may collectively undertake the state S&T programmes such as the "973 Plan", "863 Plan", "S&T Enabling Programme" and "Torch Programme". These R&D programmes work as China's major policy instrument for science and technology development and have stimulated some of the country's most ambitious and cutting-edge technologies, including the Tianhe supercomputers and the Shenzhou spacecraft (Springut, Schlaikjer, and Chen 2011).

The "973 Plan" is centred on basic research while the "863 Plan" mainly funds applied research, the "S&T Enabling Programme" aims to facilitate the R&D and industrialisation of generic technologies, and the "Torch Programme" is to demonstrate and commercialise high technologies. In the field of wind turbine technology, it appears that the "S&T Enabling Programme" encourages a variety of participants from universities, turbine manufacturers and sometimes component suppliers (see Table 8-2). In contrast, the "863 Plan" has been primarily participated in by turbine producers, excluding universities, public institutes and component suppliers. The China Aerodynamics Research and Development Center and the CAS Institute of Engineering Thermophysics which belong to the category of research institutes undertook a project on advanced airfoils, but industrial firms were excluded.

The features of Knowledge Networks (F3) in the "863 Plan" respond to the assumption from Knowledge Development (F2) that China is relatively weak in applied research probably due to the lack of interactions between university and industry. The CEO of a top Chinese wind turbine manufacturer responded in an interview that "*patents produced by universities are of low [commercial] value… [and] they can only undertake some of the sub-technology research but cannot complete the entire technology*". This argument may explain why Chinese universities are often missing in applied research like the "863 Plan" projects. On the other hand, Klagge, Liu, and Campos Silva (2012) argued that Chinese academics were more interested in publishing papers than establishing links between their research and industrial use. The weak connections between university and industry harmed Chinese firms' technology development.

Producer-user connection

The wind technology development histories from Europe and the USA demonstrate that producer-user interactions are crucial to technological innovation (see section 2.5). If the above analysis indicates ill-managed interactions between university and industry, then the formalised connections between wind turbine producers and wind farm developers may reveal over-strengthened networks (Gosens and Lu 2014, Walter and Stine 2005). For example, four of China's top ten wind farm developers have owned wholly or sizeable parts of some wind turbine producers' stocks (see Table 8-3). Three producers have formed a kind of strategic alliances with wind farm developers, with only three having no formalised connections with the developers.

The most representative example is the relationship between Longyuan and Guodian. Longyuan, a wind farm developer and a State-Owned Enterprise (SOE), was established in 1993 with a mission to develop renewable energy. Longyuan and United Power (a wind turbine manufacturer) became a subsidiary of Guodian (a utility group) respectively in 2002 and 2007. In 2014, 60% of Guodian's new installations were with United Power turbines. Gosens and Lu (2014) argued that the "close relationships" reduced competition on high-quality and high-power-output turbines, and thus undermined the producers' motivation to innovate. The formalised connection is a recent trend, but it is worthy for policymakers to pay attention to this issue before it worsens.

Table 8-3 The relationships between China's wind farm developers and turbine producers, 2014

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

Note: * the ratio of the producer's supply to the developer's installed capacity.

Source: CWEA (2015a)

International linkages

Chinese firms adopted a variety of strategies to develop wind turbine technology. Envision Energy has attempted to enhance competitiveness by implementing a talent sourcing strategy and establishing global innovation networks (see section 7.2.3). It indicates that in the era of R&D internationalisation, geographical borders do not necessarily mark the boundaries of innovation systems. International experience in technology and policy have had a significant impact on the Chinese wind turbine innovation system (see section 7.3.2).

Chinese firms not only locate R&D centres overseas but also establish joint ventures with foreign partners in China. For example, Shanghai Electric and Siemens set up two joint ventures in 2011 to supply equipment to the Chinese wind power market. One of the joint ventures is engaged in R&D and production of wind turbines while the other is responsible for sales, marketing and project management (Siemens 2011). Also, some foreign companies like Vestas, Siemens and GE have built manufacturing plants in China to serve the local or global supply network. In 2010, Vestas built an R&D unit in Beijing to focus on high-voltage engineering and software development.

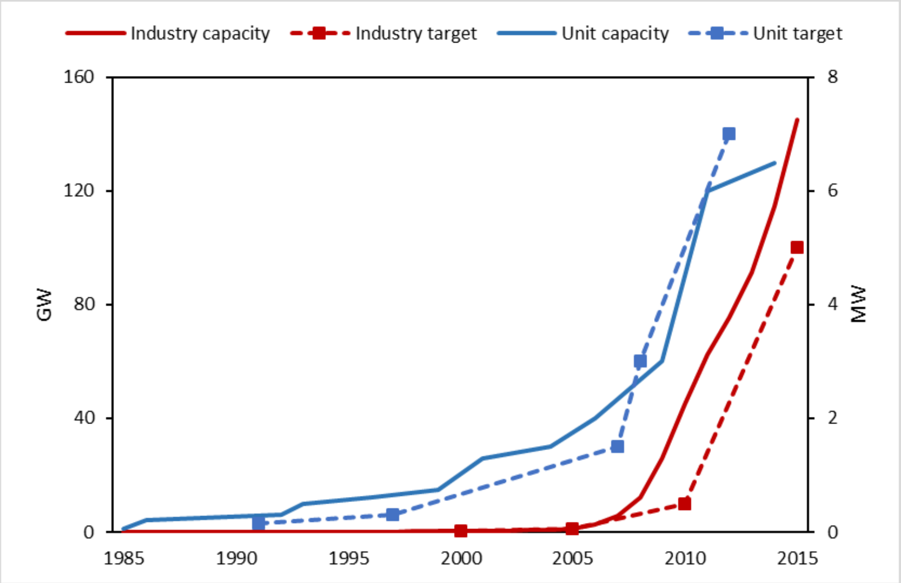
Apart from inter-firm linkages, China has also established inter-governmental cooperations with foreign countries. Two typical examples are the Sino-Danish Renewable Energy Development Programme and the Clean Development Mechanism (CDM). The Sino-Danish programme funds 12 technological innovation projects on renewable energy. In the field of wind technology, the project is jointly undertaken by the China Baoding Electricity Valley Renewable Energy Resource Detection Technology Co., Ltd and the Technical University of Denmark. The collaboration enhanced the technological capability and service quality of China's public testing platform for wind turbine blades (RED 2014). Regarding the CDM, China hosted about 1,460 CDM projects between 2005 and 2013, accounting for 65% of the world’s total registered CDM projects in wind energy (UNFCCC 2016).

The linkages between domestic and foreign innovation systems represent a key feature of China's wind turbine innovation system. The extent of the international linkages is unknown, but it is wise of developing countries to facilitate knowledge spillovers and information exchange in an increasingly globalised world.

8.3.4 Guidance of the Search (F4)

The core objectives of Guidance of the Search (F4) are to signal the need for the technology and accelerate the development of the market through policy instruments. As China's energy policy had for a long time been oriented towards fossil fuels particularly coal power plants for electricity generation, the government needed to scale up the wind power industry with very clear targets. The take-off and acceleration of China's wind turbine industry have depended on scaling at industry and unit levels. During this process, the government's guidance played an important role in motivating the firms to learn design and manufacturing technologies.

Figure 8-2 The Five-Year Plan targets for industry (left) and unit (right) capacity



N.B. Prototypes were included when mapping out the maximum unit capacity.

Source: Shi (2007), CWEA (2015b), CWEA (2016b), IEA and IRENA (2016) and company websites

The Chinese government has paid close attention to the sources of electricity generation since 1996 when the 9th *Five-Year Plan for New and Renewable Energy Development (1996-2000)* aimed to deploy 200MW of wind power by the end of the century. The purpose of developing renewable energy was, for the short-term, to meet the challenge that some rural and remote areas had limited or no access to electricity generated from conventional sources; and for the long-term, to optimise the energy mix and realize the coordination and sustainable development of the economy, energy and environment (SETC 1996a).

As of 1995, China had installed 200 units of small-scale wind turbines, equivalent to about 37MW (SETC 1996a). The maximum unit capacity of wind turbines deployed by then was 600kW, imported from Denmark (Shi 1997). Chinese firms developed prototypes of 200kW or above wind turbines, but they could not develop and manufacture larger ones. All the installed large wind turbines were imported from abroad, which lifted the power generation cost and made the maintenance of turbines extremely difficult (SETC 1996a). It seemed impossible to reach the government's target for deploying 200MW of wind power by 2000 if the country was not capable of producing large wind turbines with own (cheaper) technologies (SETC 1996a). The ninth five-year plan encouraged firms to license 500kW+ wind turbines from foreign counterparts and to accelerate the absorption and digestion of the technologies (SETC 1996a).

China installed about 350MW of wind power by the end of 2000 (BP 2016), exceeding the pre-set target. Chinese firms commercialised the 200-300kW prototypes developed during the eighth five-year plan, with 90% of the required components manufactured locally (SETC 2002). Moreover, the 600kW wind turbine technology licensed by Goldwind hit a localisation rate of 80% (refer to Chapter 9 for details). Despite this progress, the industry was constrained by technology deficits, the lack of technological and industrial standards and incentive policies (e.g. tax, pricing and financial policy) (SETC 2002). The *10th Five-Year Plan for New and Renewable Energy Development (2001-2005)* was issued to standardise technologies, enhance indigenous capability and improve market regulation (SETC 2002).

Table 8-4 The Five-Year Plans and policies for wind turbine R&D

Year	Policy documents	R&D targets/measures
1991	The 8th Five-Year Plan for Science and Technology	produce 150-300kW turbines
1996	The 9th Five-Year Plan for New and Renewable Energy	import 500kW+ turbines
1997	Ride the Wind	produce 300-600kW turbines
2001	The 10th Five-Year Plan for New and Renewable Energy	produce 600kW+ turbines
2007	Special Fund for the Industrialization of Wind Power Equipment	finance the first 50 units of 1.5MW+ turbines
2008	International Science and Technology Cooperation Programme for New and Renewable Energy	import cutting-edge technologies; support joint R&D; attract overseas scientists
2008	The 11th Five-Year Plan for Renewable Energy	produce 1.5MW+ turbines; develop 3.0MW+ turbines
2008	Interim Measures for Administration of Special Funds for the Wind Power Equipment Industry	implement the local content policy for blade, gearbox and generator
2009	Renewable Energy Law (Amendments)	establish a special fund for wind energy R&D
2012	The 12th Five-Year Plan: Special Plan for Wind Power Science and Technology Development	industrialise 3.0-5.0MW direct drive turbines; develop 7.0–10.0MW turbines and components

Source: Various years of the Chinese government’s policy documents.

The government initiated the wind power concession programme in 2003 to promote the construction of large-scale wind farms (see section 7.4.2). By the end of 2005, China had built more than 60 wind power plants, equivalent to 1.26GW compared to 1.2GW targeted in the tenth five-year plan (NDRC 2011). Thanks to technology licensing and in-house R&D, Chinese firms learnt the technical know-how to produce 600kW to 1.5MW wind turbines (NDRC 2011). Inspired by this achievement, the government in the *11th Five-Year Plan for Renewable Energy Development (2005-2010)* set an ambitious target for deploying 10GW wind power by 2010 (NDRC 2011).

After twenty years of “learning by using” and “learning by doing”, China became more experienced in guiding the development of the industry. This can be well demonstrated in the eleventh five-year plan where a variety of problems were identified, and the associated policy measures were precisely targeted. For example, it continued to emphasise the technological gap between domestic and foreign firms and proposed to build an industrial system for enhancing technological capability and scaling up industry capacity. The policy measures were quite similar to the notion of the technological innovation system in character. The government encouraged conducting joint R&D and indigenous innovation in the process of learning 1.5MW manufacturing technology and developing 3.0MW offshore turbines (NDRC 2011).

Wind turbine technology became increasingly mature during the first decade of the 21st century. As of 2010, the share of wind power in electricity generation reached 22% and 16% respectively in Denmark and Spain (NEA 2012). The unit capacity of wind turbines continued to scale up, and offshore wind gained unprecedented popularity: 2.0-3.0MW wind turbines became the mainstream products, 5.0MW+ prototypes were already demonstrated, 7.0-10.0MW projects were under research in Europe, and many countries began exploring offshore wind (NEA 2012).

Compared to the advanced countries, China lacked the core competencies particularly design capability (NEA 2012). Chinese firms need to import core components and materials albeit at a high cost. Given that Chinese firms were capable of producing 1.5-2.0MW turbines, the 3.0MW technologies were close to realising industrialisation, and 5.0-6.0MW prototypes had been developed, the government aimed to accelerate the R&D pace of 7.0-10.0MW wind turbines to catch up with the frontiers (MOST 2012). The term "wind technology innovation system" was firstly used in the *12th Five-Year Plan for Wind Power Development* (NEA 2012). The Ministry of Science and Technology (MOST) then published the *Special Plan for Wind Power Science and Technology Development (2011-2015)* which outlined a wide range of S&T policies to facilitate basic research, applied research, demonstration, and technology transfer and diffusion.

In summary, the Guidance of the Search (F4) signalled by the government through the five-year plans greatly motivated Chinese stakeholders to invest and develop wind turbine technology. The development targets for industry and unit scaling were well achieved under the guidance. At present, the government attempts to facilitate the building-up of a wind technology innovation system to close the technological gap between China and the leading countries.

8.3.5 Market Formation (F5)

A protected market is required to cultivate a novel technology when it cannot compete against incumbents in the existing regime. As a transitioning economy and a technology catch-up country, China faced two challenges when creating a favourable environment for wind power industry – the risk of technology lock-in caused by the established fossil fuels at home and the monopoly in wind turbine technology by foreign multinational enterprises (MNEs).

The government's policy stimulus can to a large extent remove the barriers to the growth of wind turbine industry, but the high cost of imported technologies, Chinese firms' technological gap to foreign MNEs, and the characteristics of technological appropriability mean that China needs to develop a home-based technological system. In this way, China can have the chance to lower down the cost and reduce reliance on foreign technologies.

The Chinese wind power market was rather small before the launch of the "*Ride the Wind*" programme in 1996 (see section 7.4.2). The programme was a typical example of China's industrial policy for stimulating technology development by localising imported technologies. It picked up some "national champions" to learn and modify the technologies transferred via trade. However, no significant technological breakthroughs were made until 2005 when Goldwind co-developed the 1.2MW direct-drive wind turbines with Vensys (see Chapter 9).

It is worth mentioning that Goldwind signed an R&D agreement with Vensys in 2002 when the *Wind Power Concession Programme* took place. The concession programme was particularly designed to boost the industry by creating a market demand. China's wind technology developed slowly between 1996 and 2002 without a promising market. The Market Formation (F5) promoted by the concession programme played a crucial role in encouraging Chinese firms to develop wind turbine technology and attracting foreign MNEs to locate their plants in China.

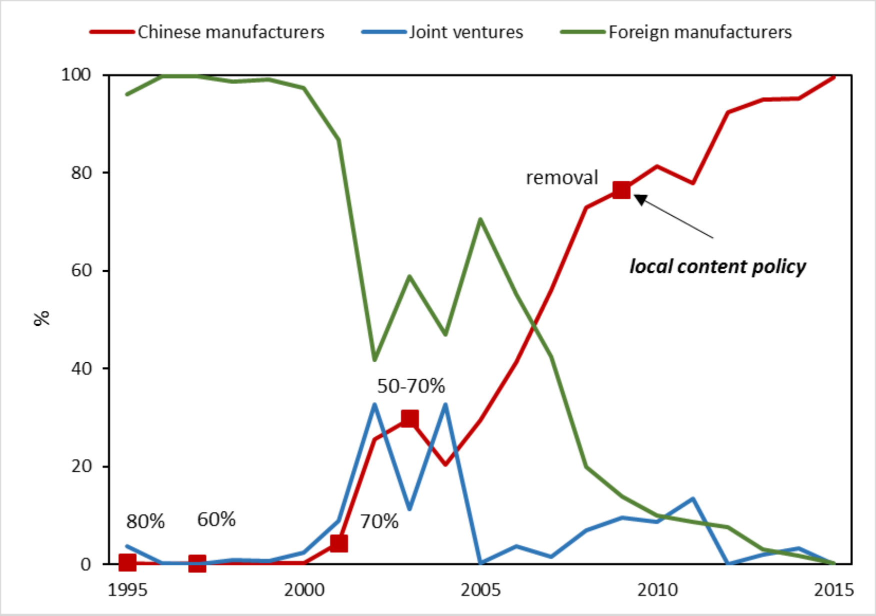
The issuance of the *Renewable Energy Law (2005)*, the *Medium and Long-Term Development Plan for Renewable Energy (2007)* and the *11th Five-Year Plan for Renewable Energy (2008)* conveyed very clear messages about the government's support for wind power. The *12th Five-Year Special Plan for Wind Power Science and Technology Development* (2012) claimed to support the building-up of seven gigawatt-scale wind farms in resource-intensive regions, reaching 105GW by 2015 (NDRC 2011). These plans were to stimulate technological development by the sustained market demand. In this sense, the Guidance of the Search (F4) has contributed to Market Formation (F5).

A 2.0MW wind turbine costs €0.9 million/MW to €1.2 million/MW (EWEA 2009). It would be too costly for China to rely on imports given its huge demand for wind power. The government imposed the so-called local content policy – a requirement that a proportion of wind turbine components must be manufactured in China (see figure 8-3). It forced Chinese firms to accelerate R&D speed and reduce over-reliance on foreign technologies.

A key part of China's industrial policy has been the emphasis on indigenous innovation capability - Chinese firms must be able to develop and produce the technologies with their own IPRs. The local content policy created a protected market for cutting down cost and facilitating knowledge spillovers. The empirical effect of knowledge spillovers from foreign MNEs to Chinese firms is yet to be understood, but the market share of Chinese wind turbines seemed to say that the local content policy achieved some success. Currently, 99% of China's annual additions is supplied by Chinese firms compared to less than 40% before 2005 (see Figure 8-3).

China has created a huge market for wind power (145GW). It is estimated that about 2,600GW onshore and 500GW offshore wind capacity is technically exploitable (IEA and ERI 2011). Wind power alone can meet the country's entire projected increase in electricity demand up to 2030 (Liu et al. 2013). The draft of the *13th Five-Year Plan for Wind Power (2016-2020)* aims to deploy 200GW by 2020, implying an annual addition of 10GW for the next five years. The function of Market Formation (F5) has operated well so far in China.

Figure 8-3 Local content policy and share of annual installations by Chinese firms



N.B. The ratios above the makers indicate the required proportions of locally produced components.

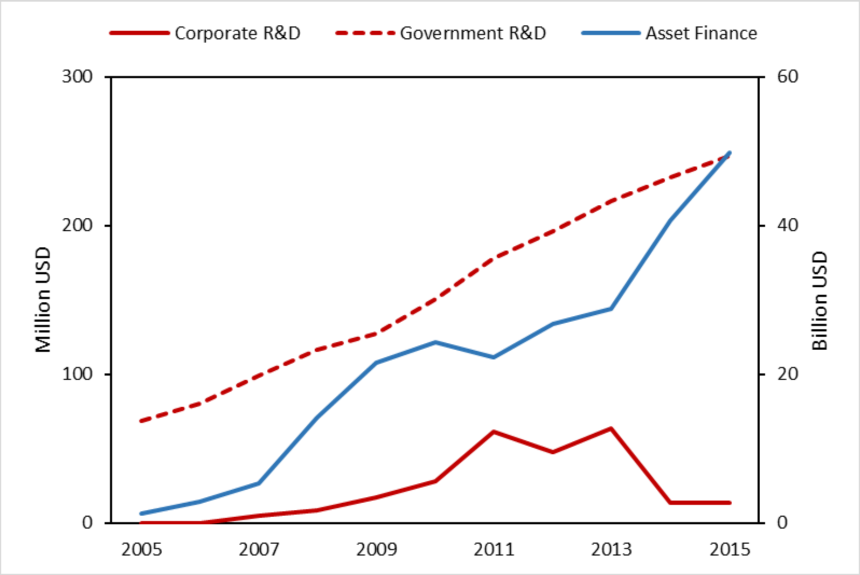
Source: Shi (2007), CWEA (2015b) and CWEA (2016b)

China had exported only 2GW wind turbines since 2007, with the USA as the main destination (CWEA 2015b). The firms' shorter operational records, the lack of certification of Chinese wind turbines and the trade protectionism in certain countries constrained their export performance (GWEC and IRENA 2012, Gosens and Lu 2014). Alternatively, they may venture into less developed countries where lower-quality turbines may be accepted. However, these countries often face financial difficulties, and Chinese firms need to burden themselves with high financial risks if they want to develop wind power there (Tan et al. 2013). The limited numbers of overseas orders reflect China's heavy reliance on the domestic market for Market Formation (F5).

8.3.6 Resource Mobilisation (F6)

Technological innovation needs capital. The major two types of economic resources that are directly related to wind turbine innovation are RD&D for developing and demonstrating novel wind turbine technologies and asset finance for building wind power projects. China has emerged as a leading investor in Resource Mobilisation (F6) for wind energy. It ranks second after Germany in R&D and first in asset finance (see section 6.2.1). Between 2005 and 2015, about 2.2 billion USD was invested to stimulate wind technology innovation, and 254 billion USD for financing wind farms construction (BNEF 2016).

Figure 8-4 China's R&D expenditure (left) and asset finance (right) for wind energy



N.B. Exchange rates and constant prices (2015 as the base year) are applied.

Source: BNEF (2016)

The government has played a prominent role in funding public and private sectors' R&D activities, providing funds for about 95% of wind R&D projects (BNEF 2016). The share of public R&D increased significantly over the recent five years whereas private R&D decreased sharply (see Figure 8-4). According to BNEF (2016), China's private wind R&D was 13.5 million USD in 2015. However, Goldwind reported that the firm invested 1.56 billion RMB (250 million USD) which was very close to Bloomberg's firm-level data on Goldwind (Goldwind 2016a). This implies that Bloomberg's data on China's corporate wind R&D which should be an aggregation of all Chinese firms' wind technology R&D was substantially underestimated. If Bloomberg's public wind R&D data was correct, China would be the world's largest wind R&D spender. Nonetheless, the annual Chinese public wind R&D investment between 2005 and 2015 recorded by Bloomberg was an upward straight line ($y = 14.473x + 71.2$, $R^2 = 0.9985$). It is likely that Bloomberg's data on China's public wind R&D had been roughly estimated.

Given these issues, analysts ought to be careful about Bloomberg's data on China's wind R&D investment. It may be inappropriate to produce Figure 8-4, but no other sources were available about this type of data. The IEA had only recorded the member states' public R&D budgets and suffered from missing data and timeliness problems (see section 4.3). The figures can only roughly estimate the patterns of China's wind R&D investment, but the data was obviously inaccurate. It is unknown whether this problem applies to other countries like Denmark, Germany and the USA. Moreover, if the R&D data was normalised using another indicator, for example, the relative value of patent filings to R&D budgets (or expenditure), then the statistical error of the normalised value might be enlarged. Further research is needed to justify the limitations and use of the existing energy R&D statistics.

Considering the challenges of empirically analysing the function of Resource Mobilisation (F6), this subsection turns to present some representative examples to draw up the mechanism of the Chinese government in financing wind energy R&D projects (see Table 8-5). It appears that China's public policies regarding Resource Mobilisation (F6) covered the different stages of energy technology innovation, from basic research to applied research, demonstration, market formation and diffusion. This function interacts with many other functions, particularly Entrepreneurial Activities (F1), Knowledge Development (F2), Knowledge Networks (F3) and Market Formation (F5). It demonstrates that one particular function influences others and positively or negatively affects the overall functioning of the innovation system.

Table 8-5 The mechanism of public resource mobilisation in China’s wind turbine industry

	Research	Development	Demonstration	Market Formation	Diffusion
Economic resources	Total R&D (2005-2015): 2.2 billion USD Share of public R&D (2015): 95%			Asset finance (2005-2015): 254 billion USD	
Government bodies for mobilising resources	MOST			NDRC; NEA; MIIT; MOF; CDB	
Innovation policies for mobilising resources	“973 Plan”; National Natural Science Fund	“863 Plan”; S&T Enabling Programme	Torch Programme	Interim Measures for Administration of Special Funds for the Wind Power Equipment Industry	Wind Power Concession Programme; Renewable Energy Premium
Resource recipients	*Universities/Institutes:* SUT; CAS; BJTU; SJTU	*State labs or engineering centres:* State Laboratory of (Offshore) Wind Power System	*Manufacturers:* Goldwind, Envision Energy, Mingyang, XEMC, AVIC Huiteng, Wafangdian, Sungrow	*Wind farm developers:* Huadian; Guodian; CGN; Huaneng; SPIC; China Resources; Datang; PowerChina; Three Gorges; State Grid	
Outputs/Outcomes	SCI publications (2015): 560	Patent applications (2011): EPO (26), USPTO (40), SIPO (821)	Prototypes (2015): CSIC produced 6.0MW generator rotor and 5.0MW offshore turbine	Cumulative capacity (2015): 145GW	Power generation (2015): 185TWh

N.B. a) Only a few examples are shown in the table; b) referring to Abbreviations for full names.

Source: The author.

MOST is the prime government body for funding universities and firms' R&D activities through the state major S&T programmes, including the "973 Plan", the National Natural Science Fund, the "863 Plan", the "S&T Enabling Programme" and the "Torch Programme". Other departments like the Ministry of Industry and Information Technology (MIIT) and China Development Bank (CDB) play a role in the later stage of energy technology innovation. CDB extended a credit line of $6 billion to Goldwind in 2010, and a second agreement in 2012 with another $5.3 billion (Xinhua News Agency 2012). Mingyang and Sinovel obtained $5 billion and $6.5 billion respectively from CDB for financing their overseas wind power projects (Yicai Global 2011, China Energy 2010).

Subsidies do not push wind turbine technology innovation but pull the market demand for advanced wind turbine technology. Between 2006 and 2014, about $18.3 billion was spent for subsiding wind power (Zhao, Guo, and Fu 2014)[8]. The subsidy rate for wind power is determined according to wind resources and wind farm construction conditions, and is categorised into four classes: 0.51 CNY/kWh, 0.54 CNY/kWh, 0.58 CNY/kWh and 0.61 CNY/kWh. Offshore wind enjoys a higher rate - 0.978 CNY/kWh for the Donghai Bridge Wind Power Project. Utilities and grid operators bearing the cost of feed-in-tariff will be compensated by the Renewable Energy Premium proposed in the *Renewable Energy Law* (NPC 2005, 2009).

8.3.7 Creation of Legitimacy (F7)

All the figures produced so far indicate that China's wind power industry took off after the *Renewable Energy Law* (2005) was issued. The law laid out the basic rules on development targets, grid connection, price setting and special R&D and industry funds. The legitimacy environment attracted many entrants to the industry, and through their technological efforts, China's manufacturing capacity increased tremendously. Before 2005, few Chinese firms were involved in wind turbine technology. After the law had been issued, the number of Chinese wind turbine manufacturers reached nearly 100 (Chinawindnews 2016). The law established the fundamental institutions and policy framework for renewable energy (Zhu 2016) and may have perhaps acted as the biggest driver for China's rapid growth in wind power.

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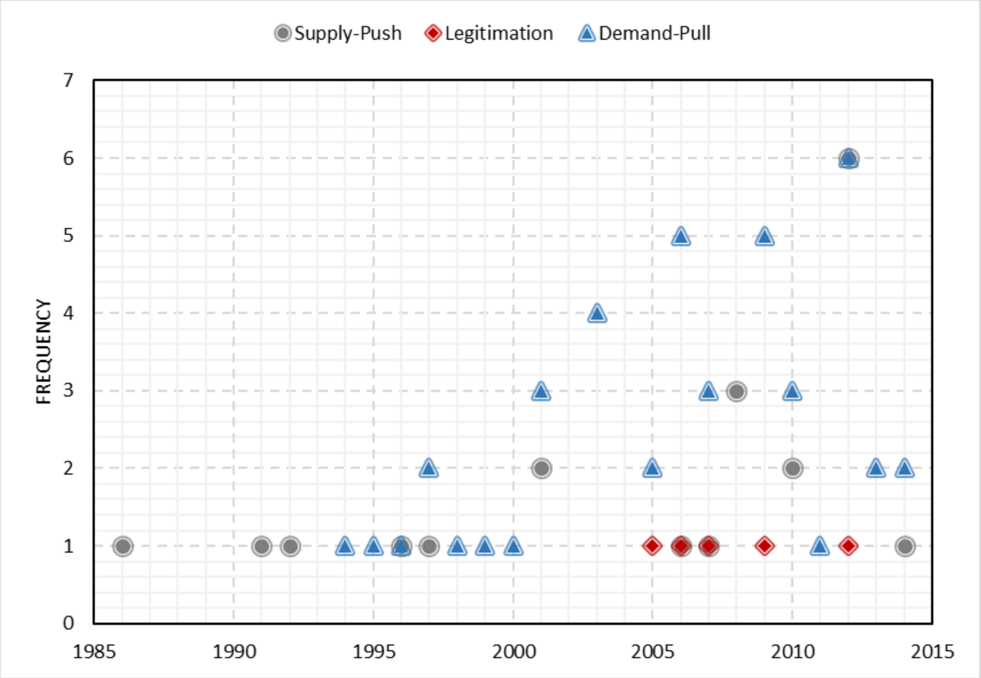
[8] The yearly data (2006-2011) was extrapolated (2012-2014) with a linear regression model ($y= -0.0054x + 0.2459$, $R^2=0.959$) derived from the datasets of Zhao et al. (2014).

Figure 8-5 Frequency of supply-push and demand-pull policies for wind power



N.B. Supply-push policy refers to S&T policy, unit capacity target, grid connection and local content policy; demand-pull policy includes industry capacity target, subsidies and tax incentives & bank loans; legitimation corresponds to the Renewable Energy Law and a few other legal regulations.
Source: IEA and IRENA (2016), Dai and Xue (2015), Surana and Anadon (2015b) and Gosens and Lu (2013b)

This subsection will not repeat what the law is about (refer to section 7.4.1 for details) but discusses its impact on the development of a series of supply-push and demand-pull policies (see Figure 8-5). These policies strengthened the legitimacy of wind power in China. The industry might not have grown so quickly without a match between the two types of policies. Pilot wind power projects in the early years had no influence on national energy consumption due to cheap coal (Dai and Xue 2015). The government began to implement bold demand-pull policies to create a promising market for wind power in 2003. The five-year plans since then set ambitious targets for industry and unit capacity (see Figure 8-2). Some of the most influential policies include the Wind Power Concession Programme (2003), the *11th Five-Year Plan for Renewable Energy*, the *12th Five Year Plan for Renewable Energy*, and the *Special Plan for Wind Power Science and Technology Development* (see section 7.4.2).

The goodwill for developing wind power can hardly be achieved without the supply of wind turbines at affordable prices. As such, the supply-push policy such as the local content policy embedded in the *Wind Power Concession Programme* and the state major S&T programmes was implemented to stimulate technological learning and innovation. Chinese wind turbine manufacturers adopted a variety of strategies to upgrade design and manufacturing technology. It shows that China's policy framework for wind power has become more sophisticated, owing to the increasing frequency of supply-push and demand-pull policies. It is challenging to collect all the historical events for characterising the system functions, but it becomes much easier to calculate the frequency of policy documents for a particular technology.

It is vital to coordinate supply-push and demand-pull policies. The inconsistency of these two types of policies represented a major cause of the early failures of wind energy innovation in the Netherlands and the USA (see section 2.5). The success of the Danish wind power industry attributes largely to the aligned policies in facilitating the supply and demand of wind turbine technology (see Lema et al. (2014)). The recent experience of China also demonstrates that the alignment between supply-push and demand-pull policies is of particular importance to achieving the fulfilment of the system functions.

8.4 Reflections upon the results

This section draws upon the above quantitative and qualitative analyses to address the proposed hypotheses. The collected evidence can well verify the assumptions.

8.4.1 Functional patterns of the system

The functional analysis indicates that the Creation of Legitimacy (F7), Guidance of the Search (F4), Resource Mobilisation (F6) and Market Formation (F5) have played a crucial role in activating China's potential to utilising and developing wind turbine technology. The functions of Entrepreneurial Activities (F1), Knowledge Development (F2) and Knowledge Networks (F3) have been vital in stimulating technological imitation and learning, but they have been undermined by the poor governance of the innovation system.

Compared to the countries where wind turbine technology originated (see section 2.5), China's Knowledge Development (F2) and Knowledge Networks (F3) are less developed. The other functions like Guidance of the Search (F4) and Market Formation (F5) worked much better. China had for a long time been a technology recipient rather than a technology originator. China rapidly diffused wind turbine technology by technology licensing and joint R&D rather than in-house innovation. In other words, the diffusion of foreign wind turbine technology in China happened earlier than the emergence of novel Chinese innovations.

The diffusion of wind turbine technology has been primarily driven by Creation of Legitimacy (F7), Guidance of the Search (F4), Resource Mobilisation (F6), whereas indigenous innovation can only occur when Entrepreneurial Activities (F1), Knowledge Development (F2) and Knowledge Networks (F3) start to operate. It corresponds to the hypothesis (1) that China's functional patterns are different from developed countries. China starts from Guidance of the Search (F4) and Creation of Legitimacy (F7) to Knowledge Development (F2) and Knowledge Networks (F3).

Catch-up countries can quickly diffuse a new technology with little pre-existing knowledge, but it does not mean that Knowledge Development (F2) and Knowledge Networks (F3) are unimportant. It is the huge demand for clean energy that stimulated China's massive deployment of wind power, but the lack of relevant knowledge led to a kind of technology acquisition-oriented entrepreneurship pursued by Chinese firms. As the industry develops, China must make great efforts in Knowledge Development (F2) and Knowledge Networks (F3) if it aims to develop a home-based innovation system to produce cheaper technologies.

8.4.2 Diagnosis of the system's functioning

China caught up fast in scientific publications, manufacturing capacity and installed capacity but has lagged in patent filings, the unit capacity of wind turbines and power generation (see Chapter 6). System performance is closely linked to the achievement of the corresponding functions. For example, scientific publications relate to a sub-type of Knowledge Development (F2) - basic research, manufacturing capacity to Entrepreneurial Activities (F1), installed capacity to Guidance of the Search (F4) and Market Formation (F5). Patent filings correspond to the lack of another sub-type of Knowledge Development (F2) - applied research and of Knowledge Networks (F3) between university and industry and power generation to Guidance of the Search (F4). It verifies the hypothesis (2) that China's system performance depends on the fulfilment of the system functions.

Knowledge Networks (F3) require particular attentions. The interactions between university and industry are weak. The government (F4: Guidance of the Search) has established many state labs and engineering centres owned by industrial firms, but almost no universities have participated in such policy initiatives. This situation also applies to the "863 Plan". Firms claim that patents produced by universities are of low commercial value, but this may be caused by the lack of university-industry interactions. Consequently, university academics seem to prefer publishing papers than converting their research findings to industrial use.

Another interaction that needs caution is the "close relationship" between wind farm developers and wind turbine producers. Knowledge Networks (F3) are important, but in certain circumstances, over-strengthened networks may undermine the actors' motivation to innovate. Formalised connections between producers and users may lead to an "internal market" (vs. competitive market) where the developers (SOEs) may choose just to accomplish the capacity target set by the government without caring much about the quality of turbines which potentially produce higher power output. The Chinese market has been criticised for competing on cost, which often results in lower quality and reliability of wind turbines.

The Knowledge Networks (F3) between domestic and foreign innovation systems represent a key feature of China's wind turbine industry. In fact, Chinese firms are not the only ones that use technology licensing, joint ventures, joint R&D or M&A to enhance technological competitiveness. Many foreign MNEs have become more competitive through these technology-seeking strategies. Gamesa was once a joint venture between Grupo Auxiliar Metalurgico SA (Gamesa's parent company) and Vestas till it bought 40% of Vestas' share in 2001. Danish manufacturer Bonus Energy built the world's first offshore wind farm in 1991 and was acquired by Siemens in 2004. Enron, which bought German manufacturer Tacke in 1997, was acquired by GE when it went bankrupt in 2002. More recent examples are that Mitsubishi Heavy Industries Ltd. (MHI) created a joint venture with Vestas (51% of share owned by MHI) in 2014, GE acquired Alstom Energy in 2015, and Siemens acquired Gamesa in 2016. It implies that global innovation networks are important for both developed and developing countries to accelerate technological innovation.

8.4.3 The relationship between structure and functionality

The functions of Creation of Legitimacy (F7), Guidance of the Search (F4), Resource Mobilisation (F6) and Market Formation (F5) seem to have performed best, followed by Entrepreneurial Activities (F1), Knowledge Development (F2) and Knowledge Networks (F3).

The government has played a vital role in the fulfilment of F7, F4, F6 and F5 through a top-down approach. The state's intervention in the economy is very influential. The government is passionate to boost an industry with strong state finance if it can potentially contribute to economic prosperity. Almost all the Chinese wind farm developers are SOEs or controlled by state capital (e.g. Goldwind). Eight out of the top ten Chinese wind turbine manufacturers are SOEs except for Envision Energy and Mingyang. Therefore, it is not difficult for the government to quickly achieve the specific functions through policy interventions. However, the interventions are not always positive. The issue of overcapacity of solar PV a few years ago represents a typical example of negative effects mainly caused by the local government's abuse of interventions (Wang, Luo, and Guo 2014).

The fulfilment of F1, F2 and F3 which are often unpredictable regarding the rate and direction of technological change has been hindered by the late presence and weak capability of structural elements, namely the turbine manufacturers, component suppliers, universities, research institutes and the establishment of state labs and engineering centres. Numerous literature has shown that technological innovation is a cumulative and continuous process, or "success precedes success". As a latecomer in wind turbine technology, Chinese universities and firms often suffer from the lack of high-end R&D personnel and sophisticated knowledge. Before 2005, almost no Chinese universities nor vocational schools offered academic and technical courses on wind turbine technology. Goldwind was forced to build a college (i.e. Goldwind College) to educate and train technical professionals on its own.

Looking back to sections 8.4.1 and 8.4.2, there exist close corelations between structural elements, functional patterns and system performance. The presence and capability (or quality) of structural elements build the foundation for the functional patterns which affect the overall performance of the innovation system. In a reversed order, the capability of structural elements may be strengthened or weakened because of system performance, which in turn enhances or impairs system functions. More broadly, the behaviour of one structural element influences others, the motor of technological change triggered by one function pulls the operations of other functions, and the innovation inputs affect the outputs and outcomes of the system. The relationships between structure, functions and performance as well as between the "internal components" of them are complex and multi-dynamic.

8.5 Summary

This chapter has addressed the frequency of historical events as indicators for measuring system functions, arguing that it suffers from data coverage problems and cannot quantify the impact of the historical events by looking at the plain texts. Instead, a set of quantitative and qualitative indicators have been derived based on the existing literature and applied to China's wind turbine innovation system. Three hypotheses about the relationships between structural elements, functional patterns and system performance are proposed and tested via the indicators.

The results show that there exists a close correlation between the presence and capability (quality) of structural elements, the functioning of the innovation system and the system's overall performance. To be specific, China's functional patterns are different from developed countries; the system performance owes to the fulfilment of the system functions; the system's functionality relates to the presence and capability (or quality) of structural elements. The functional patterns and problems are examined through in-depth analysis based on quantitative and qualitative data.

The Creation of Legitimacy (F7), Guidance of the Search (F4), Resource Mobilisation (F6) and Market Formation (F5) have been the most contributing functions responsible for China's wind turbine innovation. The functional patterns between China and advanced countries are different. Knowledge Development (F2) and Knowledge Networks (F3) functioned in the early stages of a technology development in advanced countries but were pulled by other functions in the Chinese context. The functional analysis demonstrates that fulfilment of system functions is vital for China to acquire, modify and diffuse wind turbine technology.

The analysis offers insights as to how to improve the governance of China's wind energy innovation system. For example, while China has become the largest wind technology producer and user, the country has not established a specific organisation that is responsible for guiding the development of the innovation system. Also, the coordination among governmental departments needs to be improved for ensuring alignment of public policies. In particular, closer attention should be paid to a few system functions such as Knowledge Development and Knowledge Networks.

The chapter sketches the patterns of the seven system functions, but detailed analysis of a specific function may produce insightful results that may be undiscovered. Also, the functional analysis cannot well illustrate the innovation process of a particular structural element (e.g. a firm). As such, the next chapter will zoom in on a pioneering Chinese wind turbine manufacturer (Goldwind) to understand the firm's evolution of technological learning and innovation.

Chapter 9 The dynamics of Goldwind's technological learning and innovation

The functionality of China's wind turbine innovation system has been affected by the presence and capability (or quality) of structural elements (see Chapter 8). Among the characterised system functions, Entrepreneurial Activities (F1) and Knowledge Networks (F3) played a major role in enhancing China's technological progress. entrepreneurs adopted a variety of innovation strategies to grow technological capability, but few studies have uncovered the dynamics of a firm's technological innovation, namely how the firm interacted with the system functions over time to produce technological innovation.

This chapter focuses on a pioneering Chinese wind turbine manufacturer (a structural element belonging to the *Actor*'s category) to shed light on its interactive relationships with the functions of *Entrepreneurial Activities (F1), Knowledge Networks (F3*) and *Resource Mobilisation (F6)*. It represents an in-depth analysis of a specific structural element fulfilling and reacting to the achievement of the specific system functions.

The case study has been conducted in a historical perspective, from Goldwind's technology imitation in the early years to indigenous innovation at present. The firm's interactions to the relevant functions were illustrated by examining the historical evolution of its technological innovation. The quantitative and qualitative materials were collected from original Chinese journal papers, magazines, newspapers and Goldwind's annual reports.

Section 9.2 describes Goldwind's technology imitation based on the 600kW and 750kW licensed technologies. Section 9.3 examines Goldwind's shift of technological trajectory and joint R&D with Vensys on megawatt-class turbines. Section 9.4 illustrates Goldwind's adaptive R&D strategy to enhance technology portfolios. The concluding remarks are presented in section 9.5.

9.1 Goldwind: a snapshot

The history of Goldwind (headquartered in Xinjiang and Beijing) can be traced back to 1988 when Xinjiang Wind Energy Corporation was established in order to develop wind farms (see Table 9-1). The firm shifted from a wind farm developer to a wind turbine producer in 1996 and represented one of the earliest Chinese companies with a particular focus on wind turbine technology. Goldwind employs over 6,500 workers, with a revenue of about 30 billion RMB in 2015. Currently, it is recorded as the world's largest wind turbine maker, accounting for 12.5% of the globe's additional capacity in 2015 REN21 (2016).

Table 9-1 The historical timeline of Goldwind, 1985-2015

Timeline	Historical events
1985	Xinjiang Wind Power Institute was established for assessing China's wind resources
1988	Xinjiang Wind Power Institute incubated Xinjiang Wind which was responsible for wind farms development
1996	Xinjiang Wind shifted from a wind farm developer to a wind turbine manufacturer and imported 450kW wind turbines from Germany
1997	Xinjiang New Wind was established to commercialise wind turbine technology; the firm licensed 600kW technology and undertook the state S&T programme on *Research, Development and Production of 600kW Wind Turbines*
2000	About 96% of 600kW turbine components could be made domestically in China
2001	Xinjiang New Wind was restructured into Goldwind which licensed 750kW technology from Jacobs and undertook the "863 Plan" on *Research, Development and Production of Megawatt-Class Wind Turbines*
2002	Goldwind shifted technological trajectory from gearbox to direct-drive technology and launched joint R&D project with Vensys on 1.2MW model
2007	Goldwind and Vensys co-developed 1.5MW direct-drive turbine
2008	Goldwind purchased 70% of Vensys' stock
2009	Goldwind developed 2.5MW and 3.0MW models and began to diversify product portfolios to meet different climate requirements
2014	Goldwind demonstrated 6.0MW offshore prototypes

Source: Goldwind (2016b); Goldwind annual reports (2007-2015)

Goldwind learned wind turbine technology from foreign counterparts. It was among the few Chinese firms that have paid close attention to the absorption and digestion of foreign wind turbine technologies. Like many Chinese producers, Goldwind followed the path of technology licensing->joint R&D->in-house R&D to achieve technological catch-up. The impacts of this strategy on innovation capability vary significantly across firms, but Goldwind has benefited from it. The firm is transitioning from a technology imitator to a competitive innovator.

Goldwind operates several subsidiaries in China and manages wind farms in Australia, the USA and Pakistan. In 2008, Goldwind purchased 70% of Vensys' share to gain ownership of its gearless technology. It actively collaborated with foreign counterparts when developing its milestone 1.2MW model. The global networks of innovation provide opportunities for MNEs in developing countries to integrate themselves into the global value chain and climb the innovation ladder. This is also true to Goldwind which experienced a slow technological imitation journey before it could conduct indigenous innovation.

9.2 Technology imitation: 1996 - 2001

Goldwind had little knowledge of wind turbine technology before shifting from a wind farm developer to a wind turbine producer. Goldwind overcame technical and financial difficulties to localise 600kW wind turbine technology successfully. This section describes the process of Goldwind's technological learning as a technology imitator in the early days.

9.2.1 Technological licensing: a hard choice

China started exploring wind turbine technology in 1958 and installed the country's first unit (30kW) in Changbai Mountains. Almost in the same period, a fisherman in Zhoushan City developed a 10kW wind turbine (Li et al. 2005). However, both designs failed to be commercialised because they "lack science and technology theories" (Li et al. 2005). In the late 1970s, Zhejiang Mechanical & Electrical Institute and Shanghai Electric Power Institute co-developed China's ever first industrial design of 18kW wind turbine (Li et al. 2005).

By the late 1980s, Vestas had already developed 1.5MW turbines while China was only able to develop 150kW units. In 1983, China imported three units of 55kW wind turbines from Vestas, with which China built the country's first wind farm in 1986. China's technological gap to the world leaders was large. It was not until 1984 when China's ever first academic conference on wind energy took place (He and Shi 2010). In a remote area like Xinjiang, only small off-grid turbines were used for generating electricity for local peasants and herdsmen. It was recorded that about 6,000 units of these turbines were installed by the middle 1980s (Goldwind 2016b).

The "economic reform and open-up policy" initiated in 1978 embraced foreign capital and technology. Chinese and foreign experts had more chances to communicate with each other. In 1985, the then Ministry of Water Resources and Hydropower and the Xinjiang Wind Power Delegation paid a visit to Western Europe to learn about the utilisation of wind power. The advanced wind power technology in Western Europe inspired the delegation about the development of wind power in China. In the same year, Xinjiang Wind Power Institute was established and began to collect wind resources data. In 1988, the Institute incubated the

Xinjiang Wind Energy Corporation (Xinjiang Wind) which was responsible for wind farm development.

"Trading market access for technology (Long 2005)" was a major innovation strategy in China. In 1989, Xinjiang Wind imported 13 units of 150kW wind turbines from Bonus via a Danish government grant of 3.2 million US dollars plus 6.7 million CNY raised at home (Ma 2016). With these turbines, China built the largest Asian wind farm - Dabancheng Wind Farm. The turbines did not generate electricity until one year later when Xinjiang Wind managed to connect them to the electricity grid (Ma 2016). The company lacked qualified technicians who understood the technical know-how of the imported turbines (Ma 2016).

Technological learning was much required. The firm paid close attention to absorbing and digesting foreign technology. Gang Wu, the then General Manager of the Dabancheng Wind Farm reminded that when they signed contracts with foreign counterparts, they required that "*Chinese technicians are obligated to receive technical training in Denmark, and Danish experts should give lectures in China*" (Ma 2016). "*We kept our minds open to communicate with foreign experts for learning technology*" (Ma 2016). Whatever it was a training course, academic conference or factory visit, company delegations used to request learning materials and bring them back for learning (Ma 2016).

In 1996, Germany implemented the so-called "Golden Plan" (*Huangjin Jihua*) – a preferential loan programme to developing countries. The programme encouraged China to experiment with wind technology, but the prerequisite was that China must import the equipment from Germany (Xia 2011). Even if it was not required by Germany, China had no choice but to import as the wind turbine market was monopolised by foreign companies. A wind turbine cost over 9,000 CNY/kW while engineering construction exceeded 10,000 CNY/kW. In general, about 70% of a wind farm's investment was used for purchasing wind turbines from overseas (Zhao 2012b).

With support from the then State Science and Technology Commission and the Ministry of Water Resources, Xinjiang Wind spent 3.8 million US dollars credited by Germany to import eight units of 450kW wind turbines from Tacke, Jacobs and AN Bonus (Jin 2008). Xinjiang Wind became able to learn advanced wind turbine technologies and train technicians. By comparing the performance of the different types of wind turbines, Xinjiang Wind found that they each had advantages and disadvantages. They learned that they could modify the turbines to maximise technical performance (Jin 2008). It was a bold idea as it meant that the company would shift from a wind farm developer to a wind turbine developer. Considering the extremely high cost of imported units, the firm finally decided to develop wind turbine technology.

China had almost no knowledge of wind turbine technology, or the accumulated knowledge was out of date and insufficient to bring about technological breakthroughs. To put it differently, the function of Knowledge Development (F2) was less developed. The lack of Knowledge Development (F2) forced Goldwind to license technology from foreign counterparts through Knowledge Networks (F3). After they had discovered the complementarity of the imported units that could potentially maximise technical performance, they decided to shift from a wind farm developer to a wind turbine producer (F1: Entrepreneurial Activities).

9.2.2 Technology imitation: 600kW and 750kW models

600kW model

When Xinjiang Wind entered the industry, no technical guidelines or standards concerning the manufacturing of wind turbines were available in China. The company needed to overcome a series of technological barriers in overall design, component R&D, assembly and testing (Wen 2005). It would take a considerate amount of time and capital to develop the technology with zero prior experience, so the firm decided to license from foreign companies in the hope of shortening the R&D lifecycle.

The company was confronted with financial difficulties. Coincidentally, the *9th Five-Year Plan for Key Science and Technology Programme (1996-2000)* tendered a research project on promoting the industrialisation of large wind turbines. Xinjiang Wind successfully secured the fund which was initially awarded to another research institute. The reason why Xinjiang Wind obtained the fund was that the firm planned not to carry out the research as an academic project purely but to establish a new company (Xinjiang New Wind Technology, Industry and Trade Limited Corporation) with a mission to commercialise the technology and gain profits.

Before the central government's decision for economic reform and open-up policy, Chinese society was afraid to talk about profit as it was seen as "capitalism". institutional changes created a favourable environment for Chinese entrepreneurs. In 1997, Xinjiang Wind Power Institute, Xinjiang Wind Energy Corporation (Xinjiang Wind) and Xinjiang New Wind Technology, Industry and Trade Limited Corporation (Xinjiang New Wind) collectively undertook a project on "*Research, Development and Production of 600kW Wind Turbines*" (Goldwind 2016b). In the same year, Xinjiang New Wind signed a licensing agreement with Jacobs for 600kW wind turbine technology (Jin 2008).

Xinjiang New Wind had been responsible for managing the Dabancheng Wind Farm for nearly ten years and accumulated some technical knowledge in wind power. It once conducted R&D on 100-300w turbines before licensing technology from Jacobs. However, what Xinjiang New Wind acquired from Jacobs was just heavy loads of design drawings (Zhao 2012b). The key issue was to convert the drawings into artefacts. A research group was created to develop 600kW wind turbine technology.

In the first place, Xinjiang New Wind organised R&D on the tower and then wheel hub, gearbox and blade. Xiangming Wang, the then Chief Engineer, recalled that "*foreign technical standards and requirements were quite strict, so we figured out the technical details step by step… what we were doing was to understand foreign technical requirements… it was vital to localise the technology via these minor accumulations*" (Zhao 2012b). By 2000, about 96% of turbine components could be made domestically (see Table 9-2).

Table 9-2 The localisation progress of 600kw wind turbine

Timeline	Localisation rate[9]	Major R&D tasks
Jul.1998	37%	tower, foundation, nacelle, assembly
Nov. 1998	54%	generator, wheel hub, the extended section
Jun. 1999	72%	gearbox, yaw bearing, yaw motor, yaw reducer
Aug. 1999	78%	electronic control system
Aug. 2000	96%	blade

Source: Wang (2005)

Technology guidance from Jacobs played an important role in the firm's technological learning. With financial support from the State Administration of Foreign Experts Affairs, Xinjiang New Wind paid German technical experts to provide feedback on their technological roadmaps and solutions, proof data and drawings, and review overall designs and component optimisation schemes (Wen 2005). German experts worked very hard and intensively when they stayed in China and even shared the latest technical information that was unavailable in the Chinese market. German experts also suggested that the firm concentrate on two core businesses - turbine design and sales, namely outsourcing component manufacturing to external suppliers, but focusing on technical standards, components assembly, and testing and marketing of wind

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[9] Localisation rate refers to the ratio of a wind turbine's components that can be made domestically. For example, 90% means that the domestic firms can provide 90% of the required components.

turbines (Wen 2005). This business model proved a big success for Goldwind in the following decades (see section 9.4.3).

Despite progress in technology development, the firm found trouble in manufacturing because of financial difficulties. It cost 4.5 million RMB to produce one unit (Jin 2008). The firm made every effort to encourage employees to become shareholders and actively applied for grant or loans from relevant entities. They finally raised 15 million RMB plus 20 million RMB bank loans and began to produce wind turbines (Jin 2008).

However, very few investors were optimistic about wind power. Xinjiang was generally seen as manufacturing low-end products rather than high technology like wind turbines. In a bidding conference in 2001, the firm secured a contract for delivering 600kW wind turbines. Compared to foreign turbines, the cost of Chinese ones was much lower. Later on, Xinjiang New Wind was selected by the State Planning Committee as a commissioned wind turbine supplier for the '*Ride the Wind*' programme (see section 7.4.2).

750kW model

The successful localisation of 600kW wind turbines was a milestone in the Chinese wind power history as it indicated that China was able to develop large wind turbines with its own IPRs for industrialisation purposes. The most important thing was that the research, development and production processes of 600kW wind turbines nurtured Chinese component suppliers and laid the foundation for future technology upgrading (Zhao 2012b). Goldwind commissioned more than ten external suppliers to produce components for the 600kW wind turbines (Zeng, Tian, and Gao 2001). It was a slow and painful learning process but built a supply chain for China's wind turbine industry and trained many technicians (Zhao 2011).

Thanks to the technological accumulation in developing 600kW wind turbines and economic returns from sales, Xinjiang New Wind planned to upgrade the unit capacity to 750kW. In 2001, the firm was restructured into a new company – Goldwind. When the 600kW wind turbines began to be deployed in China, Jacobs' 750kW model had become a very mature product. Again, Goldwind licensed the technology from Jacobs. There were no huge technical barriers shifting from 600kW to 750Kw. The 750kW turbine was built upon the optimisation of the 600kW model, so the localisation process had been much quicker.

In 2003, two units of 750kW prototypes were demonstrated in Dabancheng Wind Farm, with a localisation rate of 89% (Wang 2005). Comparing to the same types of imported units installed in the same wind farm, the newly-developed model proved to operate more stably with lower failure rate (Wang 2005). Until then, Goldwind became the first Chinese firm that could produce 750kW wind turbines. The 750kW model achieved a far better market performance than the 600kW turbines. By 2012, about 4,300 units of 750kW turbines were sold compared to 330 units of 600kW models (Zhao 2012b).

After Goldwind had entered the wind turbine industry, a few other system functions emerged such as Guidance of the Search (F4) and Resource Mobilisation (F6). The government provided funding for developing 600kW wind turbine technology. When Goldwind had learned the technology, it was commissioned to provide turbines for the "*Ride the Wind*" programme. In Goldwind's technological learning and imitation process, the government provided finance for paying foreign experts and supporting manufacturing activities. All in all, Goldwind's Entrepreneurial Activities (F1) in licensing foreign technologies and establishing R&D teams, and the Knowledge Networks (F3) between Goldwind's technicians and German experts played a fundamental role in ensuring the success of technological learning and imitation.

9.3 Joint R&D and acquisition: 2002 - 2008

The unit capacity of wind turbines increased dramatically over the 1990s. Vestas had commercialised 3.0MW by 2002; in contrast, Goldwind had difficulty upgrading the 750kW model to megawatt-class. This section illustrates why Goldwind decided to change technological trajectory, conduct joint R&D with Vensys and finally acquire the firm.

9.3.1 Joint R&D with Vensys

A huge technological gap existed between China and the world leaders even after Goldwind successfully localised the 750kW model. Vestas commercialised 3.0MW wind turbines by 2002 while Siemens developed a 2.5MW model and GE introduced a 1.8MW model. It became very clear that turbine size would grow in the following decades.

In 2001, Goldwind undertook the "863 Plan" project on "*Research, Development and Production of Megawatt-Class Wind Turbines*". Goldwind proposed a relatively new R&D strategy for this project - sourcing foreign talents and conducting joint R&D with foreign companies (Wen 2005).

Given that the firm had accumulated certain technical knowledge and the domestic supply chain for turbine components was coming into being, Goldwind aimed to develop megawatt-class wind turbines.

According to the strategy, foreign experts were paid to participate in each R&D stage, from concept design to initial, sophisticated and production designs. Goldwind referred to foreign expertise for technology guidance and proofing. Through joint R&D, Goldwind expected to master the design and manufacturing technologies for wind turbines and core components, have ownership of IPR, and accelerate indigenous innovation (Wen 2005).

It was very costly to hire foreign experts. For example, the monthly salary offered by Goldwind to an engineer with a PhD degree was several thousand RMB, but the daily payment for a foreign expert need be over ten thousand CNY (Wen 2005). The State Administration of Foreign Experts Affairs provided financial support to Goldwind.

In early 2002, Goldwind signed an agreement with Vensys to jointly develop megawatt-class wind turbines. Vensys was a small design company which had been researching direct-drive technology for nearly a decade and already developed a prototype (see Box 9-1). When Goldwind visited Vensys, they found that Vensys was a design company that only developed and transferred technology to manufacturers rather than produce by itself, which attracted interest from Goldwind.

After investigating the existing technologies worldwide, they planned to develop 1.2MW direct-drive wind turbines. During the R&D stage, Goldwind collaborated with foreign design companies, research institutes and manufacturers, such as Vensys, REpower, IDA Wind, Garrad Hassan, Risø, NREL and WEA. Foreign experts were paid to take part in technology evaluations and help solve technical problems (Wen 2005).

The first unit of a 1.2MW direct-drive prototype was demonstrated in 2005, with a localisation rate of 40%. The model gained certification from Germanischer Lloyd (GL) and was claimed to reach an internationally advanced level. Joint R&D quickly improved Goldwind's technological capability and trained a batch of qualified R&D personnel. The firm filed four patent applications, and by the end of 2004, about 22% of employees were R&D personnel, and 92% had a university degree (Wen 2005). In 2005, Goldwind created a subsidiary in Germany and recruited local engineers.

The concern about the technological gap as well as Goldwind's success on the technology imitation of the 600kW model inspired the firm to conduct joint R&D with foreign counterparts. It was again Entrepreneurial Activities (F1) that triggered this technology strategy. The function of Knowledge Networks (F3) became complex in joint R&D as Goldwind did not merely collaborate with one foreign firm but many other research institutes and manufacturers. Similar to the localisation of the 600kW technology, the government funded the joint R&D through the "863 Plan", i.e. Guidance of the Search (F4) and Resource Mobilisation (F6).

9.3.2 Shift in technological trajectory

Initially, Goldwind focused on wind turbine technology with a gearbox. As the "863 Plan" project proceeded, they felt that this technology may not be a good choice. They learnt that direct-drive technology could potentially reduce failure rate by 20% and increase power outputs by up to 5% (Zhao 2011). The risk was that a wind turbine with a gearbox had been the mainstream technology while direct-drive technology was only adopted by a few German companies.

It was a bold decision for Goldwind to shift from gearbox to direct-drive technology. Intense debates occurred in the firm on the two different technologies (Zhao 2011). The key point was that if Goldwind continued with the existing technology, it could quickly seize the market with substantial profits. The new technology would require huge upfront R&D investment, and what's more, Goldwind might lose its market to competitors when it was in transition.

Facing technology and market uncertainties, Goldwind eventually decided to adopt gearless technology. Although the new technology would cost a large amount of R&D spending, it was more cost-effective in the long-term. The cost of maintaining and replacing the gearbox over the designed lifecycle of a turbine (20 years) would be higher than the upfront R&D investment in gearless technology.

Another factor pushing Goldwind to shift to direct-drive technology was that the firm aimed to develop wind turbine technology indigenously. The executives realised that if the firm had no design capability and technologies for core components, it would have to import technologies that were often out-of-date in advanced markets. Moreover, the heavy reliance on foreign technologies would lock the firm into the technological trajectory forged by foreign MNEs. When the wind power market took off, many Chinese firms licensed the same technology from the same foreign company (Xia 2011). They had no design capability and core technologies and was forced to compete against the peers with the same licensed technologies.

Shifting to the direct-drive technology represented an opportunity for Goldwind to reduce reliance on the foreign mainstream technology (a wind turbine with a gearbox) and leapfrog to become a global leader in gearless technology if it proved successful. Given the many advantages, Goldwind gained approval from the government funding body for its shift to direct-drive technology. In 2003, Goldwind licensed gearless technology from Vensys before they carried out joint R&D a year later. A prototype of 1.2MW direct-drive wind turbine was demonstrated in 2005.

The spirit of Entrepreneurial Activities (F1) played a vital role in driving Goldwind to shift from the mainstream technology to direct-drive technology. The shift of technological trajectory in the "863 Plan" was accepted and supported by the government (F4: Guidance of the Search). Despite the huge technology and market uncertainties of the gearless technology, Goldwind decided to take the risk in the hope of reducing turbine cost without a gearbox and becoming a world leader in this novel technological field (F1: Entrepreneurial Activities).

9.3.3 Acquisition of Vensys

The *Renewable Energy Law (2005)* worked as the driving force for China's development of renewable energy like wind power. Thanks to the booming market, Goldwind's revenue enjoyed an annual growth of over 100% between 2005 and 2008. The technology licensing dilemma reminded Goldwind that due to the lack of core technologies, Chinese firms needed to pay huge license and royalty fees for every unit of turbines produced. In 2008, Goldwind purchased 70% of Vensys' stock to gain ownership of direct-drive technology (see Box 9-1).

Acquiring Vensys means that Goldwind would shift from another technological trajectory that might have had huge technological and market uncertainties. After considering the advantages of developing direct-drive technology, Goldwind decided to acquire Vensys. The acquisition has proved very successful. A few years later, Goldwind developed 3.0MW and 6.0MW prototypes. The company took measures to facilitate the integration of production facilities, technologies and brands between the two firms. Employees are encouraged to exchange thoughts so that they can understand each other well. Vensys now owns its factory and aims to serve the European market with a focus on high-end wind turbines.

The success of the acquisition owed to the strategic complementarity between the two firms (Du and Zhao 2014). From the perspective of Goldwind, the acquisition enabled the firm to enhance technological capability and ownership of gearless technology. Secondly, Goldwind's

R&D personnel would have the opportunity to be trained in an advanced design company. Thirdly, Vensys was located in Germany, so it helped prepare Goldwind to compete against the world leaders in the international market.

Box 9-1 Vensys

Vensys currently employs 223 staff and has invested in production facilities in Germany, China, Egypt, India and Brazil. It has built R&D platforms for developing 1.5MW, 2.5MW and 3.0MW wind turbines. As of 2014, about 12,200 units of Vensys licensed wind turbines were installed globally, including the North American, British and French markets, equivalent to 19.3GW. Its licensees include Goldwind (China), ReGen Powertech (India), IMPSA wind (Brazil) and Arab Organisation for Industrialization (Egypt).

The history of Vensys can be traced back to 1990 when the Forschungsgruppe Windenergie (a wind energy research group) was funded at the University of Applied Sciences, Saarbrücken, under the leadership of Prof Friedrich Klinger who conducted basic research and preliminary designs on generator concepts. Vensys was established in 2000 by members of the Forschungsgruppe Windenergie, with a focus on the development of gearless technology.

Between the establishment year of Vensys and 2005, Forschungsgruppe Windenergie was a close partner of Vensys in basic and applied research. In 2003, Vensys commissioned the Forschungsgruppe Windenergie to design a new turbine with 3.0MW rated power. They began to work more independently from each other since 2006. In 2008, Goldwind acquired 70% of Vensys' stock to have full ownership of the gearless technology IPRs.

Source: Vensys company websites

From Vensys' side, the benefits were obvious too (Du and Zhao 2014). To begin with, Vensys was strong in wind turbine design but had no factories. Goldwind's large manufacturing capability could help commercialise its cutting-edge technologies. Secondly, Vensys would be able to gain access to the Chinese market via Goldwind, which would enhance the presence and competency of direct-drive technology. Thirdly, Vensys' R&D activities required a large amount of capital which Goldwind could provide. Therefore, it was a win-win situation for both sides.

It was not easy to adapt Vensys' technology to the Chinese market. The technical solutions developed by Vensys were built upon the proven German manufacturing base that Goldwind found difficult to match. As such, Goldwind sent technicians to Germany to learn the relevant technologies and asked German engineers to work in China. This practice worked well – Goldwind's technological capability increased fast, and the localisation issues were adequately solved. In 2008, the 1.5MW direct-drive model came into mass production.

The acquisition enabled Goldwind to become more familiar with the global wind technology market. Goldwind has commercialised 3.0MW turbines, and six units of 6.0MW offshore wind turbines are demonstrated. Vensys built a factory with the financial support from Goldwind aiming to serve the European market with high-end wind turbines. The size of Vensys grew from 40 employees before the acquisition to 220 currently (Du and Zhao 2014). In 2011, Goldwind Windenergy GmbH (Goldwind's German subsidiary) endowed a professorship on wind energy at the University of Applied Sciences.

Technology licensing had led to Chinese firms' over-reliance on foreign technologies and locked-in the technological trajectory forged by foreign MNEs. They needed to pay for every unit of turbines produced and could not reduce the cost substantially without the ownership of IPR. As such, Goldwind acquired Vensys to gain full ownership of the direct-drive technology (F1: Entrepreneurial Activities). After the acquisition, Goldwind took measures to facilitate the knowledge exchange and integration between the Chinese and German firms (F3: Knowledge Networks). It also aimed to enhance the Knowledge Networks (F3) by Vensys' access to the European market and the endowment of a professorship on wind power in a German university.

9.4 Indigenous innovation: 2009 - present

Since the acquisition, Goldwind accelerated technological innovation and adapted its R&D strategy to market demands. It redefined its core businesses and tightened the control of components supply. This section presents how Goldwind achieved these targets.

9.4.1 Responses to the market demands

Market demand has played a vital role in stimulating China's wind technology innovation. Without the stable demand for wind power, Chinese firms may not be able to experiment with and accommodate newly-developed technologies. The global trend of wind technology development (e.g. larger unit capacity and offshore wind) has created a demonstration effect on China's wind technology trajectories. Chinese manufacturers have paid close attention to the changes of market demand when formulating R&D strategy.

The booming Chinese wind power market attracted plenty of new entrants into the industry. Most of them like Sinovel and Dongfang had been involved in producing heavy equipment or machinery but had little experience in wind turbine technology. In order to quickly gain profits, they licensed technology from foreign companies even when they had not been well prepared for manufacturing. "*Raising capital while planning business, securing contracts while building factories*" characterised the aggressive growth of Sinovel which surged from nothing in 2004 to China's top one wind turbine maker by 2008 (Xia 2011).

However, difficulties have emerged since 2010. Many firms suffered from cost competition along with quality incidents, lack of grid connection and power curtailment. Partly due to quality scandals, Sinovel slipped out of China's top five regarding annual new additions. The industry did not fully recover until 2014. The drastic market turbulence pushed Goldwind to consider its technology, quality, service and business model carefully (Goldwind 2012).

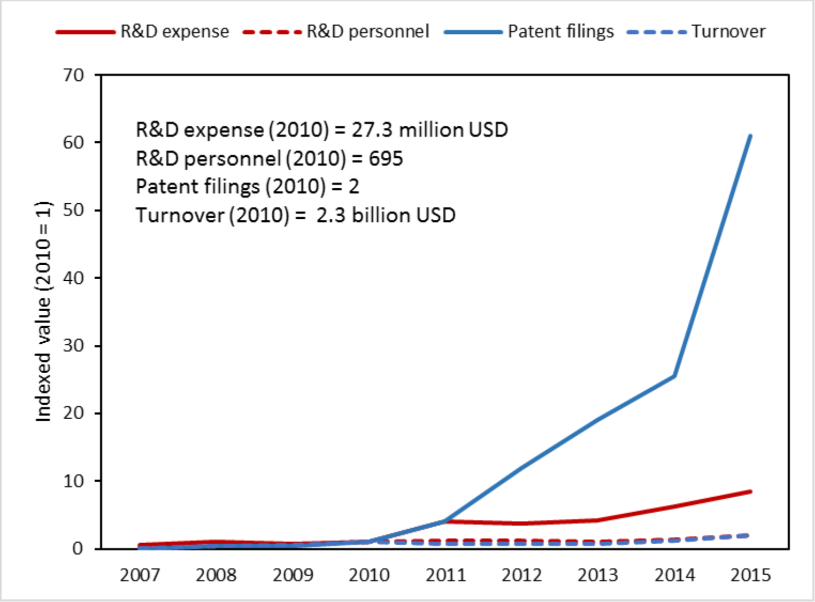
When Chinese wind farm developers were sensitive to turbine prices, Goldwind proposed that "*a wind turbine is designed to serve for 20 years, so wind farm developers should consider not only the upfront cost but more importantly turbine reliability and the producer's service capability*", said Danke Yu, the Chief Finance Officer of Goldwind (Yang 2009). Goldwind was more concerned about the lifecycle cost of a wind turbine rather than the upfront cost. This may be because Goldwind was originally a wind farm developer and very familiar with cost control. Goldwind considered becoming a systemic solution provider, expanding from R&D and manufacturing to include technical services and wind farm development (Goldwind 2010).

Goldwind was very sensitive to the changes of the market needs. To better satisfy the demand, Goldwind began diversifying product portfolios, enhancing technology quality and even developing wind farms to demonstrate its solutions to cost control. Entrepreneurial Activities (F1) again characterised Goldwind's technological innovation process after the acquisition.

9.4.2 Adaptive R&D strategy

Goldwind adopted an adaptive R&D strategy to develop a range of products that can meet the requirements. offshore wind appeared to develop as a promising future technology both at home and abroad. The *12th Five-Year Plan for Science and Technology (2011-2015)* emphasised unit size and offshore wind. Some Chinese firms already completed or planned to develop 6.0MW offshore prototypes by 2012. Another technical change was that there was an increasing demand for turbines that can adapt to specific climate conditions, such as low-wind, low/high temperature, high-plateau and sand-proofing. Goldwind adjusted its R&D strategy in response to these changes.

Figure 9-1 The growth of Goldwind's R&D inputs and outputs



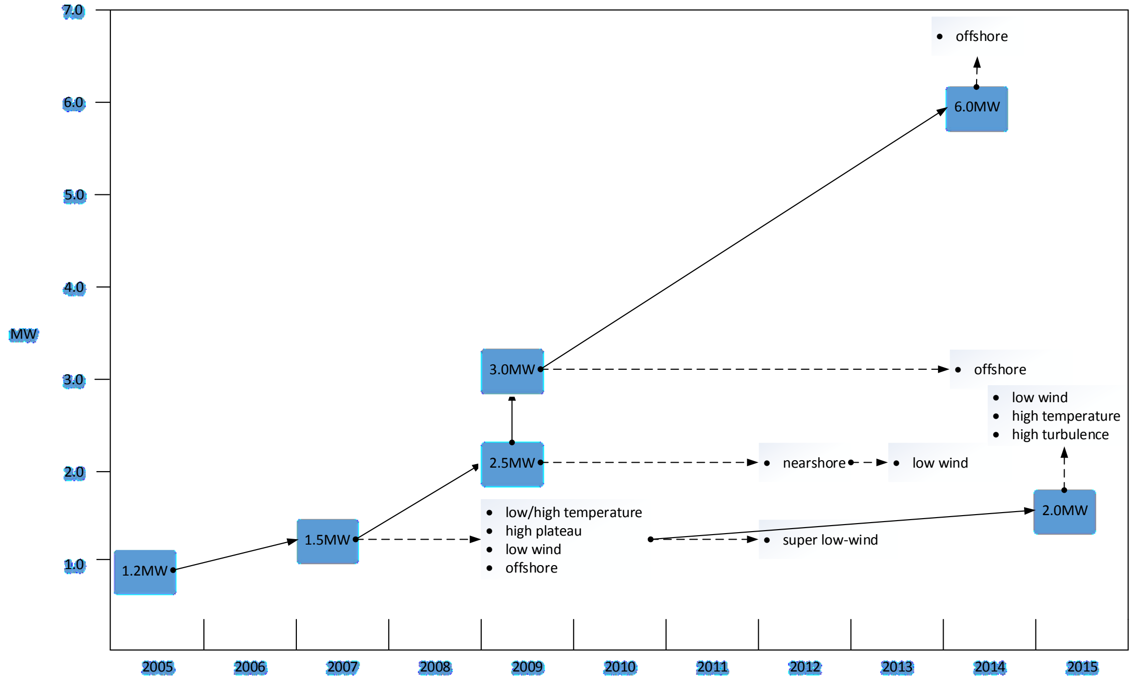
N.B. a) Yearly exchange rates and constant prices (2015 as the base year) are applied; b) only invention-type patent applications to the SIPO are considered.
Source: Goldwind's annual reports (2007-2015)

The firm accelerated the growth of R&D spending and the recruitment of R&D talents (see Figure 9-1). Among the various R&D inputs and outputs, patent filings experienced the most significant increase over the past five years (60 times since 2010), followed by R&D expense (8 times). R&D personnel and turnover increased by a factor of two. The figure reflects the fact that Goldwind is accelerating R&D activities. For example, the firm launched an ambitious 6.0MW offshore project which obtained government funds worth 100 million CNY in 2015 alone (Goldwind 2016a). The project not only focused on the design and manufacturing technologies for wind turbines but also the associated core components like inverters in which China had been relatively weak.

As direct-drive technology became widely accepted, Goldwind developed a series of 1.5MW turbines that can react to specific climate conditions (see Diagram 9-1). In 2007, Goldwind demonstrated the first Chinese 1.5MW offshore wind turbines in Bohai Bay which showed excellent operational records. It then launched R&D projects to diversify 1.5MW turbines (82/1.5MW, 77/1.5MW, 70/1.5MW) and upgrade the maximum unit capacity to 2.5MW and 3.0MW. The R&D department modified the manufacturing process, significantly shortened assembly time and improved productivity (Goldwind 2008). Not only product innovation but also process innovation occurred in the firm.

Goldwind acquired Vensys in 2008, making the firm the first Chinese manufacturer that could design and develop wind turbines with complete and self-owned IPR of direct-drive technology. The acquisition accelerated Goldwind's R&D progress and enhanced its capability to explore overseas markets (Goldwind 2009). A core task after the acquisition was to facilitate collaborations between Chinese and German companies on R&D and trial productions of new turbines. The firm then adopted the so-called R&D project-oriented management practice with an aim to breaking departmental boundaries and smooth internal communications.

Diagram 9-1 The historical evolution of Goldwind's wind turbines (2005-2015)



Source: Goldwind's annual reports (2007-2015)

N. B. a) The diagram is only for illustrative purposes and does not reflect the full picture of Goldwind's technology development progress; b) rectangles in light blue captures the optimisation of turbine models.

The commercialised 1.5MW model gained a good reputation for high yields and grid compatibility. In 2009, Goldwind demonstrated 2.5MW and 3.0MW models and started to develop 5.0MW turbines. It successfully developed control system, inverter and pitch system, allowing it to reduce the cost of some core components (Goldwind 2010). Inspired by the achievements, the firm decided to intensify R&D efforts and integrate innovation resources. The serialisation of the 1.5MW model that can react to specific climate conditions was in progress.

In 2010, the firm demonstrated five units of 2.5MW turbines respectively in China and Germany and started the mass production of 2.5MW turbines. Given the proven performance, Goldwind started to diversity the 2.5MW model to meet different climate requirements. Also, a 2.0MW model and 3.0MW hybrid direct-drive turbines were assembled and demonstrated. In the same year, Goldwind replaced the 5.0MW R&D plan with 6.0MW in response to the market trend of the increasingly larger capacity of offshore wind (Goldwind 2011).

Based on existing technology portfolios, Goldwind introduced a 1.5MW super low-wind model in 2012 while the 1.5MW high-temperature prototype was being tested. At this point, Goldwind had developed a series of the 1.5MW model that can adapt to a wide range of climate conditions, including low or high-temperature, high-plateau, (super) low-wind, nearshore and offshore settings (Goldwind 2013).

The 2.5MW turbines had excellent records at home and abroad regarding power output and reliability. Thus, Goldwind started the mass production of the 106/2.5MW (Class II wind resource area) and 109/2.5MW (nearshore) models, of which 20 units of 109/2.5MW turbines were installed in that year. The 109/2.5MW model passed the zero-voltage ride-through test by the China Electric Power Research Institute, implying that it overpassed the requirement set by China's national standards. It also indicated that Goldwind had the potential to developing offshore models with high reliability (Goldwind 2013).

In recent years, Goldwind emphasised certification while it accelerated the R&D process. As of 2013, 87/1.5MW low-wind and 109/2.5MW models were certified by TÜV Nord; 93/1.5MW, 82/1.5MW, 115/2.0MW, 109/2.5MW and 121/2.5MW models were certified by the China General Certification (CGC), meaning that they gained access to Asian, African and Latin American markets (Goldwind 2013). The 1.5MW and 2.5MW series were granted safety, CE and occupational health certificates required in the Australian, European and North American markets.

In 2015, Goldwind built the Integrative Product Development platform to quickly develop the 115/2.0MW model (Goldwind 2016a). It diversified the 2.0MW model to include 108/2.0MW IIA (low-wind and high-turbulence), 2.0MW VP (higher power outputs for the same cost) and 2.0MW high-plateau. The 121/3.0MW and 150/6.0MW offshore prototypes were demonstrated while the 3.0MW onshore model came into mass production.

Entrepreneurial activities (F1) played an increasingly important role in Goldwind's indigenous innovation after the acquisition. The firm developed a range of new products suiting Chinese climate conditions and intensified efforts in gaining technology certification from national and international bodies. Between 2005 and 2015, China's Knowledge Development (F2) increased considerably (see section 8.3.2). Goldwind's Entrepreneurial activities (F1) benefited from the overall growth of China's Knowledge Development (F2) in wind turbine technology.

9.4.3 Restructuring business units

For a long time, Goldwind focused on two core businesses - R&D and sales. This business model allowed the firm to expand production capacity rapidly and enjoy doubled growth rates annually without additional investment in component manufacturing. However, the drawbacks were obvious too. Goldwind once received an order for 700 units of turbines, but because of the bearings shortage, only half was delivered. The competitors who had a secure supply performed extremely well (Yang 2009). Business model innovation became a serious issue for Goldwind. The firm embarked on manufacturing certain key components, designed software and expanded business coverages to include technical services and wind farm development (see Table 9-3).

Table 9-3 Public funding for Goldwind's R&D projects (excluding wind turbine R&D), 2015

Category	Projects
Wind farms	Dabancheng Wind Farm Experimental Project
Software	Meteorological Forecast System for Offshore Wind Farm
	Software Platform for Equipment's Condition Monitoring, Operation & Maintenance
	Condition Monitoring and Fault Diagnosis System
Components	R&D and Industrialisation of Large Blades for Onshore Conditions
	Infrastructure Subsidy for a Blade Plant (Phase I)
	RD&D Project on 5.0MW-Class Blade
	Product Platform for 2.0MW and 3.0MW-Class Inverters
	Demonstration of Megawatt-Class Inverter with Domestic IGBT Module
	RD&D Project on 5.0MW-Class Casting
	RD&D Project on 5.0MW-Class Hybrid Tower
	R&D and Industrialisation of 6.0MW-Class Full-Power Converter
	R&D and Industrialisation of Megawatt-Class Pitch System

N.B. Goldwind received funding from various public S&T programmes, so similar R&D projects existed for certain components and software.

Source: Goldwind (2016a)

The local content policy required that all wind turbines must have a local content of at least 70%. In response to this change, many foreign MNEs such as Vestas, GE and Suzlon set up subsidiaries in China (see section 7.4.2). The rush of foreign companies imposed a big threat to Chinese manufacturers as the foreign MNEs can now benefit from cost advantage in the Chinese market. What was even worse was that Chinese component suppliers could only meet the need of a maximum of five Goldwind-sized companies. Foreign MNEs occupied more than half of China's domestic component supply. Due to the shortage of component supply, Goldwind delayed many order deliveries. The risk of losing control of supply chain drew concerns from Goldwind (Goldwind 2008, 2009, 2015).

The unit price of certain components dropped considerably owing to the effect of economies of scale, but revenues from certain key components like control systems remained rather steady. Goldwind had partly achieved self-sufficiency in generators and control systems and was determined to build tighter control in these areas (Yang 2009). The control system accounted for 10% of a turbine's cost, but Chinese manufacturers relied on import as domestic technologies could not meet the requirement. Imported components were expensive and sometimes interrupted the firm's production when shortages occurred. Also, as turbine prices continued to drop, it was wise to localise core components to compete with other firms. Goldwind built a factory in 2009, expecting to supply 3000 units of control systems annually.

One year later, Goldwind signed an agreement with Infineon Technologies AG to license a modular technology for producing megawatt-class invertors in China (Goldwind 2011). It benefited from economies of scale by producing the component itself and ensured the security of the supply chain. The company also embarked on designing and manufacturing blades. To do so, it acquired two Chinese blade suppliers and integrated their design and manufacturing capability. As a consequence, Goldwind had full ownership of the core technologies, realised self-sufficiency of blades, and lowered the cost (Goldwind 2011).

It also tightened control over the supply of raw materials. The direct-drive technology required the input of a kind of permanent magnet material - rare earth. As the importance of rare earth became recognised, the exploitation and trade were more strictly regulated by the government, pushing the price up by nearly ten times (Zhao 2012b). By collaborating with research institutes and material suppliers, Goldwind found an approach to optimising the utilisation ratio of chemical elements in rare earth (Zhao 2012b). In 2008, Goldwind strategically invested in a firm which specialised in permanent magnet materials.

For the past few decades, Goldwind had focused on the design, manufacturing and marketing of wind turbines while purchasing the components for assembly. The firm now redefined its business model to include the design and production of key components and software and wind farm development (F1: Entrepreneurial Activities). The main purpose was to gain tougher control of components supply and demonstrate its prior experience in cost control of wind farms. Goldwind received various government funding for the new technologies' R&D (F5: Resource Mobilisation).

9.5 Summary

This chapter describes a case study on the dynamics of Goldwind's technological innovation in the wider innovation context. It shows that the success of Goldwind's transition from a technology imitator to an innovator owes to the fulfilment of and its interactions with the system functions, particularly Entrepreneurial Activities (F1), Knowledge Networks (F3) and Resource Mobilisation (F6). It contributes to the scholarly literature on the interactive relationships between a structural element and the specific system functions.

The lack of Knowledge Development (F2) in China forced Goldwind to take the risk of Entrepreneurial Activities (F1) for localising foreign wind turbine technology. It was a slow and challenging process for Goldwind to shift from imitating 600kW technology to conduct joint R&D on megawatt-class technologies and to indigenous innovation. During this process, the Knowledge Networks (F3) in the forms of foreign technology licensing, technical consultancy with foreign experts, collaborative R&D with foreign institutes and acquisition of Vensys played a fundamental role in building Goldwind's Knowledge Development (F2).

Technological innovation is costly. Goldwind had huge difficulties in paying foreign experts and manufacturing localised technologies. The government provided funding for Goldwind to undertake these activities and supported its R&D projects through the state S&T programmes like the "863 Plan". Even when Goldwind had become an innovator and attempted to secure the supply of core components, the government funded many of its component and software R&D projects. The function of Resource Mobilisation (F6) fulfilled by the government significantly reduced the financial barriers many firms encountered in innovation.

Throughout Goldwind's innovation journey from its establishment to the present day, the spirit of Entrepreneurial Activities (F1) motivated the firm to adapt its innovation strategy and respond to the achievement of the system functions. The imitation of the 600kW technology, the shift of technological trajectory and the adaptive R&D strategy to satisfy the Chinese market demand for specific types of turbines, all demonstrated the role of Entrepreneurial Activities (F1) in Goldwind's success of innovation.

Despite that Goldwind is transitioning from a technology imitator to an innovator and that the firm is accelerating R&D speed, its technological gap to the frontiers is still large (see section 6.3). The less-developed functions of Knowledge Development (F2) and Knowledge Networks (F3) in China's wind turbine industry constrain Goldwind's technological innovation, even after two decades of sheer efforts (see Chapter 8). It suggests that the failures in the achievement of certain system functions negatively affect the overall performance of the innovation system and the firm. It also implies that technological catch-up is quite a long-lasting process even for some fast-industrialising economies like China.

Chapter 10 Conclusions

10.1 Overview

Energy technology innovation is a critical element in the transition to a sustainable energy system. The world's major economies have recently increased R&D spending to spur energy technology innovation (IEA 2015). As a large energy transition economy, China has emerged as a big player in renewable energy, particularly wind power. The country has developed as the largest user of wind energy, accounting for 33% of global wind power capacity (BP 2016). The rapid development of wind technology in China has attracted much interest. The two key questions are a) how does China compare with leading countries in wind technology innovation, and b) what factors have been responsible for China's successes and failures?

This thesis has answered these two questions by drawing upon innovation systems theory and a host of pioneering research on innovation metrics. It has derived an indicator framework consisting of inputs, outputs and outcomes for measuring the performance of energy innovation systems (EISs) and has applied it to the wind turbine industry across China, Demark, Germany and the USA. After identifying China's comparative performance, it has moved on to conduct a structural analysis of China's wind energy innovation system to illustrate the presence and conclude the characteristics of the major actors, networks and institutions. The functional analysis of the system has been carried out to specify the functional patterns and problems. The correlations between the structural elements, functional patterns and system performance are explored. A case study on a pioneering Chinese manufacturer (Goldwind) is conducted to understand the interactive relationships between a particular structural element and the system functions. The micro-level analysis shows the dynamics of the firm's technological learning and innovation over time.

It demonstrates that China has caught up fast in inputs and certain outputs but significantly lags behind the leading countries in others especially outcomes. There are close correlations between the structural elements, functional patterns and system performance. China's progress in wind energy innovation has been highly related to the fulfilment of the system functions which are underpinned by the presence and capability (or quality) of structural elements. The case study shows that the interactive relationships between a firm (or a structural element) and the system functions can have a profound impact on the firm's innovation capability.

The national border does not define the boundary of an innovation system. It is necessary to take advantage of both domestic and foreign developed knowledge and technology via effective transnational linkages. It is valuable for countries to tap into the global innovation networks for advancing and maintaining technological competitiveness. For catch-up countries, Knowledge Development (F2) and Knowledge Networks (F3) are usually bottlenecks for them.

China's development experience provides useful implications of how to facilitate wide-scale innovation in renewable energy. The government's long-term perspective on the low-carbon society is vital to avoid carbon lock-in and switch to the new energy development pathway. To accelerate the generation, adoption and diffusion of new energy technology, a better governance of innovation system is required for China. At the global scale, international co-operations is crucial to spurring widespread innovation and diffusion of renewable energy technology.

This chapter presents the main findings (section 10.1) and policy implications (section 10.2) of the thesis. The novelty and contribution are summarised in section 10.3. Section 10.4 concludes the research and makes suggestions for future work.

10.2 Main findings

10.2.1 System performance

The performance of China's wind energy innovation system

Chapter 6 compares the performance of China's wind energy innovation system at both nation and firm levels. It shows that China catches up fast in inputs (e.g. R&D expenditure and asset finance) and certain outputs (e.g. SCI publications, manufacturing capacity and installed capacity) but considerably lags the leading countries in many others (e.g. patent filings, unit capacity, revenue and export). There is still a large gap between China and the world leaders in wind technology innovation, particularly in invention capability.

At the national level, China leads in R&D investment, SCI publications and manufacturing capacity, but considerably lags behind in EPO and USPTO patent filings, unit capacity and technology exports. China's wind energy R&D expenditure is slightly lower than Germany's, reaching 206 million USD. It has become the largest producer of SCI publications in wind turbine technology. The country's share of SIPO filings is the largest (46%), but the share of EPO or USPTO patent applications is very small (less than 1%), far lagging behind the other countries. China is shortening the time lag to the leading countries regarding developing the maximum unit capacity of wind turbines but has just demonstrated 6.0MW offshore turbines while Denmark and Germany have already commercialised 7.0-8.0MW models. China's manufacturing capacity is the world's largest but much less competitive than Denmark and Germany in the international market. Only 0.3 billion USD of wind turbines were exported by China in 2015, compared to 3.2 billion USD by Denmark and 2.4 billion USD by Germany.

At the firm level, the national champion of each country is selected to make cross-company comparisons, namely Goldwind for China, Vestas for Denmark, Siemens for Germany and GE for the USA. Goldwind has emerged as a top R&D investor and manufacturer but significantly lags behind Siemens and Vestas in patent filings, unit capacity, product revenue and technology export. Goldwind spent 250 million USD on R&D activities in 2015, compared to 234 million USD by Vestas (BNEF 2016). It surpassed Vestas in manufacturing capacity, but its revenue was only half of the latter (4.8 billion USD vs. 9.4 billion USD). In 2015, Vestas exported 71GW of wind turbines while Goldwind just closed 115MW of trade deals. Particularly, Goldwind's patent applications to the EPO, USPTO and SIPO were far less than Vestas, Siemens and GE.

10.2.2 Success and failure factors

The success or failure of an innovation system may be attributable to a set of systemic factors (or systemic problems). The diagnosis of systemic problems requires a systemic approach to avoid the fragmented evidence. The thesis adopts the "coupled structure-functional analysis" to identify the factors that are responsible for China's successes and failures. It has explored the correlations between the structural elements, functional patterns and system performance. What has been observed is that China's innovation performance is highly related to the system's functions which are affected by the presence and capability (quality) of the structural elements.

The presence and capability of structural elements

Chapter 7 maps out the structural elements (i.e. actors, networks and institutions) of China's wind energy innovation system. It is clear that China has created the necessary elements for the wind energy innovation system, although they emerged recently. The shorter history and limited experience of the Chinese stakeholders caused by their late entrance into the industry negatively affected China's innovation performance. It was not until 2005 when the majority of the major actors, networks and institutions began to emerge.

The presence of structural elements is not a problem now, but the crucial issue lies in their relatively weak capability or quality. To be specific, the institutional governance is fragmented and misaligned; the interactions between university and firms are not sufficiently strong; the research or technological capability of universities and firms has yet to be improved. For example, the Chinese government has approved at least seventeen state labs or national engineering centres for wind technology, but they are so dispersed that the coordination of research activities and the knowledge exchange has become very difficult. The Chinese firms still need to import the core components, software and facilities albeit at high cost. Issues like these hamper the functionality of China's wind energy innovation system.

The functioning of the innovation system

Chapter 8 analyses the functional patterns and problems of China's wind energy innovation system. It shows that the Creation of Legitimacy (F7), Guidance of the Search (F4), Resource Mobilisation (F6) and Market Formation (F5) have been mostly active. Entrepreneurial Activities (F1), Knowledge Development (F2) and Knowledge Networks (F3) have been vital in stimulating Chinese firms' technological imitation and learning, but they are underdeveloped.

The functioning of the innovation system has corresponded to the overall performance. Resource Mobilisation (F6) and Knowledge Development (F2) contributed to the growth of inputs (e.g. R&D investment) and outputs (e.g. SCI publications and SIPO patents). The Guidance of the Search (F4), the Creation of Legitimacy (F7) and Knowledge Exchange (F3) had an impact throughout the energy technology innovation chain while the functions of Market Formation (F4) and Entrepreneurial Activities (F1) encouraged the Chinese firms to imitate and acquire foreign technology, expand manufacturing capability and deploy wind technology at a massive scale. The functional analysis demonstrates that the innovation and diffusion of China's wind turbine technology resulted from the fulfilment of the associated system functions.

10.2.3 Dynamics of Goldwind's innovation

There are many studies on the macro structure and functions of the TISs, but few have analysed the micro-level dynamics of a firm's technological learning and innovation. Without knowledge at the firm level, it seems impossible to formulate adequate innovation policy at the macro level

(Lundvall, Vang, et al. 2009). The case study on Goldwind (Chapter 9) shows that the firm's transition from a technology imitator to an innovator relates to the fulfilment of the system functions, i.e. Entrepreneurial Activities (F1), Knowledge Networks (F3) and Resource Mobilisation (F6).

The weakness of Knowledge Development (F2) in the Chinese market forced Goldwind to take the risk of Entrepreneurial Activities (F1) for imitating foreign technology. During this process, the Knowledge Networks (F3) in the forms of licensing agreements, technology consulting with foreign experts, collaborative R&D with foreign institutes and acquisition of Vensys played a crucial role in improving Goldwind's technological capability. The function of Resource Mobilisation (F6) fulfilled by the government via the state S&T programmes and special funds significantly reduced the financial difficulties Goldwind encountered in the processes of R&D and manufacturing. Among the various system functions, the spirit of Entrepreneurial Activities (F1) perhaps played the most fundamental role in stimulating the firm's innovation strategy that was responsive to the fulfilment of the system functions and the changes of the wider context.

10.3 Policy implications

China's experience in wind energy innovation provides useful implications as well as challenges that need to be addressed to accelerate the technological change of energy innovation systems. This section draws lessons for building an effective energy innovation system globally.

10.3.1 Adhering to the low-carbon development path

A major obstacle to promoting renewable energy technologies (RETs) may perhaps be the political divide on climate change. Some countries show less strong belief than others about the danger of global climate change. The general public in the USA and China seems less aware of the dangerous effects of climate change (Stokes, Wike, and Carle 2016). However, the Chinese government has kept investing heavily in RETs to decarbonise the electricity system and reduce air pollutants. The Chinese government's long-term perspective on developing RETs is paying off. China has emerged as the largest renewable energy investor and user (REN21 2016).

The concepts like resource-saving, environment-friendly and low-carbon society frequently appeared in high-level government documents and the Premier's "Work Report". There is little doubt that the government's adherence to a low-carbon development path plays a vital role in transitioning the energy sector. This can be an important implication for other developing countries which hope to avoid carbon lock-in and path dependency. Soete (1985) argued that industrialising countries can strive to shift to the most advanced technologies rather than follow the conventional development path forged by the highly industrialised countries. China is not the originator of RETs but has adopted the advanced energy technology when it is mature enough. It may represent a pathway where the miracle begins.

10.3.2 Improving the governance of the innovation system

The innovation and diffusion of RETs are often blocked by a set of systemic problems (Negro, Alkemade, and Hekkert 2012a), which also applies to China's wind energy innovation system. Countries should intentionally govern the innovation systems through suitable tools. The conceptual framework of the energy technology innovation chain (i.e. research, development, demonstration, market formation and diffusion) as well as the structure-functional analysis are valuable for diagnosing and solving systemic problems.

The coupled structure-functional analysis reflects the fact that China's wind energy innovation system needs better governance. The *12th Five-Year Plan for Wind Power Development* (NEA 2012) used the term "wind technology innovation system" in a practical way to strengthen China's technological capability in wind energy. However, it may eventually become simply a slogan if the relevant policies and measures are not well formulated and implemented in reality. For example, while a superpower in wind energy, China has not established an organisation that is responsible for facilitating the generation, adoption and diffusion of wind technology. The relevant structural elements of a successful innovation system are often missing or weak for developing countries. The establishment or restructuring of structural elements requires close government-industry-university interactions so that the actors are fully aware of the need for change.

Coordination among governmental departments represents another aspect of improving China's governance of wind energy innovation system. The Ministry of Science and Technology (MOST) and the National Energy Administration (NEA) are in charge of drafting the S&T plans and industrial policies respectively, but misaligned and fragmented policies can hardly constitute a well-functioning innovation system. The various state labs, R&D centres, industrial associations and test and certification bodies cannot collaborate effectively without a powerful organisation that takes responsibility for governing the innovation system. The duplicative constructions of research institutes lead to low efficiency or even waste of economic resources. The governance of the innovation system does not exclusively apply to the wind turbine industry but also matters for other energy technologies.

The governance of innovation systems needs to pay attention to the particular system functions. China has made great efforts in R&D spending, technological learning and imitation, but the functions of Knowledge Development (F2) and Knowledge Networks (F3) are still problematic. Chinese firms often struggle with technological catch-up and rely on licensing technology from advanced economies. Technology leaders will not license the latest technology at any price, and thus catching-up countries often follow the technological trajectory forged by the originators at a high cost. Functions such as Entrepreneurial Activities (F1) and Knowledge Development (F2) are especially important for developing countries for imitating, modifying, developing and manufacturing RETs. As illustrated by the functional analysis, China should take measures to strenthen Knowledge Development (F2) and Knowledge Networks (F3).

10.3.3 Facilitating international co-operations on RETs

International collaboration on renewable energy knowledge and technology transfer, regulation and market analysis, and policy dialogue and co-ordination will support the scale-up of energy technology innovation to put the world on the CO_2 emissions reduction trajectory (IEA 2015). This collective activity can strengthen the mechanism to inform parties of the technology innovation trend, and to increase the capacity of local innovation. Achievements in technology innovation by multi-stakeholders will, in turn, build greater confidence in the feasibility and increase the ambition of climate mitigation goals (IEA 2015, IPCC 2014).

The diffusion of advanced energy technology across countries can stimulate continuous technological innovations. China's rapid development of wind power has well evidenced the importance of international co-operations on RETs. The reliability and cost of wind turbines and solar PV have improved significantly and they are almost ready to compete with the established fossil fuels (IRENA 2016). Currently, a major obstacle that hinders the innovation and diffusion of RET at the global scale is the trade dispute. For example, the EU has re-extended tariffs on Chinese solar panels, accusing China of dumping and subsidies (Beesley 2017).

Trade protectionism may not be an effective solution as it may boost the price and harm the wider diffusion of the technology. An alternative method may be that countries play on their own strengths to maximise the overall efficiency. The policymakers in developed countries are concerned with the shrinking need for domestic manufacturing which often hires relatively low-skilled labour. However, the policy initiatives such as training high-skilled workers, improving productivity and managing advanced machinery may work better than trade protectionism. It is very clear that the global diffusion of technology has lifted thousands of millions of people from extreme poverty and boosted the local economy. International dialogue and co-operation are important for facilitating the wide-scale innovation and diffusion of RETs.

10.3.4 Tapping into the global innovation networks

A key feature of technological innovation in China, Japan, India and South Korea's wind turbine industry has been the internationalisation of R&D activities (see section 2.5). The multinational enterprises (MNEs) in the subsequent markets (vs. initial markets like Denmark and Germany) have embarked upon cross-border activities to scan the trend of new technologies or tap into the overseas innovation systems. The role of R&D internationalisation in enhancing a nation's technological capability is controversial (see section 3.3.3), but this research supports the argument that it is an alternative approach to growing and maintaining technological competitiveness.

In the past, scholars tended to argue that MNEs in advanced economies (AMNEs) located their R&D activities abroad in technological fields where they were strong at home (see Patel and Vega (1999), Bas and Sierra (2002)). However, the paradigm of offshoring R&D is changing (Awate, Larsen, and Mudambi 2014). Emerging economies are becoming an important destination for innovation in certain technological areas. For example, Vestas built an R&D centre in Beijing to focus on high-voltage engineering and software development. R&D internationalisation now occurs in both developed and developing countries. The transnational linkages of R&D activities are an important approach to improving EMNEs' technological capability.

China has triggered a set of technological and institutional innovations, similar to the pathway of Japan in the post-era of WWII observed by Freeman (1987). The difference is that China faces two new contexts – globalisation of innovation and climate change. These two factors have obviously affected China's energy innovation strategy and policy. Countries copy each other when they try to learn good practices from others, but they finally build a different system that may prove to be more efficient (Nelson 1993). China's experience in developing wind energy is to some extent such as a case. The Chinese stakeholders have benefited from their international counterparts in both technology and policy areas. The international factors such as global networks of production and innovation and the wave of green energy investment may be as equally important as the domestic policy to stimulate technological innovation and diffusion. It is beneficial to take advantage of both national and international factors.

10.4 Novelty and contribution

This thesis contributes to the innovation systems literature in methodological, empirical and theoretical ways. The following summarises the respective contributions.

10.4.1 Methodological contributions

The adoption of a "mixed methods" approach

The studies on innovation systems (ISs) are often either qualitative descriptions that suffer from empirical evidence or mathematical models that cannot well reflect the contextual dynamics. Both the methods have their strengths and weaknesses. Recently, scholars have advocated adopting a combination of quantitative and qualitative methods (or "mixed methods") in a single study to supplement each other and gain greater confidence in the results.

The thesis employs six concrete methods in the aim of producing more comprehensive and convincing results. These methods include bibliometric analysis, patent analysis, scaling analysis, historical analysis, semi-structured interviews and case study. The combinative use of the bibliometric, patent and scaling analyses have enriched the measurements for technological innovation by examining not only scientific publications but also technical inventions and commercialised technologies. In other words, they have better reflected the process of energy technology innovation from basic research to applied research and market formation.

The historical analysis is employed in Chapters 7, 8 and 9. While Chapter 6 is empirical in character, it compares the performance of China's wind energy innovation system with other countries with a series of historical (time-series) data. It helps unfold the technological change of the innovation system, the emergence and evolution of the complex structural elements and functional patterns, as well as the dynamics of a firm's transition from a technology imitator to an innovator. Without the historical analysis, the innovation journey can hardly be explored.

Many studies have been mainly concerned with the macro institutional structure without examining how the firm – a focal actor of the IS has innovated in the dynamic reality. Some analysed the innovation dynamics of a firm but did not link the micro-level dynamics to the wider context (e.g. the fulfilment of the system functions). The case study on Goldwind demonstrates how the firm imitated and innovated in the context of the wider innovation system. It is especially useful for illustrating how a structural element can interact with and react to the specific system functions.

Indicators for energy innovation systems

There are numerous studies on innovation indicators, but a few have linked them into the energy innovation systems. The thesis employs two broad types of indicators for characterising China's wind energy innovation system. One is used for measuring the overall performance of the system (Chapter 6) and the other is to measure the fulfilment of the system functions (Chapter 8). The former is termed as "system-level indicators" while the latter is "function-level indicators".

Regarding the ***system-level indicators***, the existing indicator frameworks suffer from several problems, such as constrained to inputs (e.g. R&D expenditure) and failed to consider outputs and outcomes. Moreover, inconsistent conclusions were produced partly due to the lack of quantitative metrics and data. For example, some argued that China achieved a technological leapfrog, others, however, insisted that China's technological capability of wind turbine industry remained limited and that Chinese firms still relied on foreign technology.

To avoid the fragmented evidence and enable a more holistic assessment, this thesis derives an indicator framework consisting of inputs, outputs and outcomes for measuring the performance of energy innovation systems (EISs) (see Chapter 5). It enables to identify the strengths and weaknesses across the energy technology innovation chain. The indicator framework is applied to the wind turbine industry across China, Denmark, Germany and the USA (see Chapter 6). It identifies China's relative strengths and weaknesses between the multiple innovation stages.

The indicators for measuring system functions are derived according to the definitions of the system functions and the existing literature on ***function-level indicators*** (see Chapter 8). It points out that the quality of historical events as indicators for measuring system functions are subjected to the coverage of data (historical events) and that even text mining techniques may have coverage problems because many events recorded in books and magazines that have not been digitalised cannot be recognised by programming. Instead, this thesis derives a set of indicators that can be interpreted from the established statistical databases or the required data can be easily obtained and does not suffer from coverage problems too much.

System-level and function-level indicators are different regarding their measurement purposes. The former is concerned with the overall performance of the system, namely the historical progress of transforming inputs to outputs and outcomes; the latter focuses on the fulfilment of the system functions, namely whether the key processes are active and functioning well. Despite this, they also share some overlaps. Some indicators (e.g. publications and patents) are suitable for both purposes because they are generic indicators that characterise the fundamentals (e.g. knowledge production) of an innovation system. They can be adapted for use in different contexts. The appropriateness of indicators depends on the questions to be addressed.

Methodological issues in nation and firm-level comparisons

It is assumed that country size have an effect on quantitative results, so both nation and firm-level comparisons are made to identify China's comparative performance. The two types of comparisons generate two different pictures of the countries' innovation performance. Nation-level comparison ranks China an innovation leader except for EPO and USPTO filings and technology export, whereas firm-level comparison ranks Vestas (a Danish firm) the highest. This suggests that the traditional research that merely relied on nationally aggregated data may produce biased information. Large countries tend to be ranked higher by this method.

The excellent performance of Vestas implies that country size has an effect on nation-level comparisons, but it does not necessarily ensure that the country can be more innovative. Small countries can be very technologically competitive. It also indicates that large countries can catch up fast in R&D expenditure, but it is a hard and slow process for them to leapfrog the existing frontiers in technological capability. This may be attributable to the effect of cumulative R&D efforts. Innovation is a continuous and cumulative process in nature. China's poor performance in patent filings and leading turbines may relate to the deficit in cumulative R&D investment.

Despite the difference, nation and firm-level comparisons have shown consistent findings. They both indicate that China catches up fast in wind energy R&D and is heading for the top R&D investor. They indicate that China's manufacturing capacity is huge at both national and firm levels, but the country lags significantly in EPO and USPTO filings, revenue and export. The consistency between the nation and firm-level comparisons enhance the reliability of quantitative results. Moreover, the effect of cumulative R&D is observed in both comparisons. A combination of the nation and firm-level comparisons can produce more comprehensive and accurate results.

10.4.2 Empirical contributions

Empirical findings

There have been some papers that described China's wind energy innovation, but they addressed certain aspects of the innovation system or did not empirically examine the system performance, functional patterns and structural elements. There is a need for a more comprehensive study.

Some attributed China's rapid development of wind power to the mobilisation of economic resources such as finance, industrial funds and subsidies (see Gallagher (2014), Zhao, Guo, and Fu (2014) and Hu et al. (2013)), while others emphasised the roles of the legislative background, a clear tariff structure and a strong industrial base (see GWEC and IRENA (2012)). Klagge, Liu, and Campos Silva (2012) analysed China's wind energy innovation system, but it was descriptive and lacked empirical evidence. Gosens and Lu (2013a), Gosens and Lu (2014) and Gosens, Lu, and Coenen (2015) investigated the system with more quantitative data but had not explored the correlations between the system performance, functional patterns and structural elements.

This thesis empirically studied China's wind energy innovation system in a systemic manner. The empirical findings are summarised in sections 10.2. Briefly, Chapter 6 quantitatively compares the performance of China's wind energy innovation system with Denmark, Germany and the USA, Chapter 7 maps out the presence and evolution of the major actors, networks and institutions with visualised data, Chapter 8 analyses the functions of the system with both quantitative and qualitative data, and Chapter 10 illustrates the historical dynamics of Goldwind's technological learning and innovation with data sourced from a variety of original Chinese references.

Data and sources

Empirical analysis of China's wind energy innovation system requires data-based evidence. This thesis has collected quantitative and qualitative data from a wide range of English and original Chinese references that have rarely been analysed in the existing research to provide new and more comprehensive evidence. Sections 4.3 and 8.3.6 have mentioned the challenges of collecting the required data during this research and the methods of processing and cross-checking the reliability of the data. A list of data sources for empirically studying the Chinese wind turbine industry is provided in Table A2-2. The data used for producing all the figures and diagrams in this thesis is attached in the appendices. In summary, the thesis improves the reliability of results by referring to a range of quantitative and qualitative data. The current energy innovation statistics at both the national and international levels need to be improved, and the approach to quantifying data (e.g. the presence of actors) needs to be well designed.

10.4.3 Theoretical contributions

To the TIS framework

The innovation systems framework was criticised for the lack of a operationalised definition, which made it look more like a policy tool rather than a theory (Edquist 2005). The proposal of the system functions embedded in the technological innovation system (TIS) framework has to some extent developed a consistent analytical framework for studying innovation systems. By carefully scanning the state-of-the-art literature on innovation systems, it is found that ***structure***, ***functions***, ***performance*** and ***micro-level dynamics of innovation*** have become the central topics. This thesis has attempted to theoretically link them in a single study to offer a new perspective for studying TISs.

The terms such as actors, networks and institutions which comprise the structure of an innovation system are the widespread concepts in innovation systems literature. However, the traditional analyses on the macro institutional and social structure consisting of these elements were often static and overlooked the evolutionary dynamics of the system. The coupled structure-functional analysis appears more suitable for identifying the causal mechanisms between component arrangements and functionality. The incorporation of system performance into the framework bridges the gap of our understanding towards the relationships between the innovation system's functional patterns and the overall performance. The micro-level study on Goldwind unfolds the interactive relationships between a particular structural element (a firm) and the specific system functions (e.g. Guidance of the Search and Resource Mobilisation). The integration of these four aspects helps to understand the details of the structural elements, functional patterns and system performance as well as their correlations.

To technological catch-up of developing countries

The empirical findings in this thesis contribute to the scholarly literature on technological catch-up of developing countries. Specifically, it sheds light on the time lag of technological catch-up, the characteristics of structural elements, the functional patterns of the innovation system and the innovation strategy of catch-up firms.

Some large developing countries like China can catch up fast in R&D expenditure, but it is a hard and slow process for them to leapfrog the technological frontiers in the existing regime. The time lags between China and the world leaders in commercialising the maximum unit capacity of wind turbines are shortening, but it is a long way ahead for China to achieve the same technological capability as the leading countries own. Chinese firms still need to import core components, facilities and software from overseas companies. While the advanced countries' and firms' R&D expenditure declined or remained stagnant recently, they have continued to perform more innovatively than China. A possible explanation for this may be that advanced countries and firms can continue to benefit from the prior R&D investment and achievement without the growth of R&D expenditure for a certain period (see Laurens et al. (2016)). As they will not transfer the latest technologies at any price, catch-up countries need to accumulate the relevant knowledge and technology from the beginning and in a continuous manner.

The deficits in technological capability of developing countries highly relate to the presence and capability (or quality) of structural elements. The major actors, networks and institutions of China's wind energy innovation system did not emerge until 2005. Many wind turbine manufacturers entered the industry from the neighbouring industries like machinery and electronics. Before 2005, they simply licensed technology from foreign companies and rarely built collaborative relationships with domestic universities and institutes. Moreover, the government had just approved the establishment of state labs for wind technology around 2010. These imply that the problems in the presence, evolution and characteristics of structural elements embedded in the innovation systems of developing countries constrain the innovation performance.

The functional patterns of innovation systems in developing countries differ from those in developed countries. The motors of the innovation systems are often pulled by certain functions (e.g. Knowledge Development) in developed countries during the development and take-off periods. Developing countries like China may start from the Guidance of the Search (F4), Creation of Legitimacy (F7), Market Formation (F5) and Resouce Mobilisation (F6). The functions of Knowledge Development (F2) and Knowledge Networks (F3) represent the bottlenecks for developing countries. However, Entrepreneurial Activities (F1) are critical for both developed and developing countries.

The firms in developing countries are often forced to license foreign technology due to the lack of Knowledge Development (F2) and Knowledge Networks (F3) in the domestic innovation systems. They may follow two ways of technological catch-up. One is the traditional pathway of importing → digesting → absorbing → re-innovating, and the other is to adopt a global talent sourcing strategy (e.g. Envision Energy). The Chinese wind turbine industry demonstrates that the latter approach can accelerate technological catch-up more quickly. It implies the importance of tapping into the global innovation networks for developing countries.

To the model of state-led innovation system

A unique characteristic for China is that the state plays a leading role in the establishment and development of the (wind energy) innovation system. The government spent a large amount to build labs, R&D centres and other infrastructure. Currently, policy makers aim to reform the NIS so that it is an enterprise-centred innovation system just like those in developed countries. It is a very challenging research question as to whether it is good for China to retain strong state leadership in the innovation system, or how the so-called enterprise-centred innovation system will work as the economy becomes more mature.

The Chinese wind turbine industry has clearly demonstrated that the state plays an influential role in the build-up of the wind energy innovation system, such as the fulfilment of system functions of Guidance of the Search, Market Formation and Creation of Legitimacy. It may be necessary for the government to provide financial support to accelerate firms' innovation activities when they are struggling for technological catch-up (Sun and Liu 2010). However, excessive interventions by government bodies have also led to redundancy and even waste of economic resources. This model brings about advantages but also causes negative results.

Institutions constitute a key analytical element in innovation system studies. Chinese institutional arrangements differ from those in many Western countries in terms of policy-making process, corporate ownership and management of universities and institutions. China is a state with a strong degree of hierarchical control and emphasis on public governance institutions and ownership. The more top-down approach has led to a unique? science-management style (see Qiu (2014)). While China, as a state directed economy, may be able to arrive at a shared vision across society relatively quickly and can catch up fast in innovation investment, the outputs and outcomes are finally by a set of systemic factors. Since innovation systems theory is strongly shaped by Northern European and Japanese case studies, it may be worthwhile exploring the innovation processes, patterns and performance in a different context like China.

10.5 Research gaps and opportunities

This thesis has attempted to study China's wind turbine industry in a systemic approach with a variety of quantitative and qualitative data. It aims to be offered as a methodological, empirical and theoretical contribution to the literature on innovation systems. Despite the sheer efforts, some issues have not been well explored and may represent fruitful areas for future research.

Indicators for energy innovation systems

The thesis has derived two broad types of indicators, namely the system-level indicators consists of inputs, outputs and outcomes as well as the function-level indicators that relate to reflecting the fulfilment of the system functions. Further discussions on the coverage of the indicators and their efficacy will improve the validity of the indicator frameworks.

The empirical correlations among the indicators have not been studied. Chapter 6 shows that the growth patterns of inputs, outputs and outcomes of the innovation systems between China and developed countries are different. It is worth exploring the relationships across indicators. This applies to both the system-level and function-level indicators. By investigating the empirical relationships between indicators, analysts may identify the generic growth patterns across countries and find out the factors that have influenced the system's functionality most.

Analysis of the specific functions and structural elements

This thesis has been ambitious to include all the system functions and structural elements. The case study on Goldwind is conducted to demonstrate the effect of the system functions (mainly Entrepreneurial Activities, Guidance of the Search and Resource Mobilisation) on a firm's technological innovation, but the other structural elements and system functions are analysed in a relatively loose way. For example, it can be valuable to examine the function of Knowledge Development fulfilled by other actors such as universities, state labs and institutes. It is recommended analysing the specific functions and structural elements in the future work.

Constructive dialogues on energy innovation statistics

A key message from this research is that the current statistics on energy innovation are yet to be improved. They suffer from several issues in the inconsistencies of data across databases and the coverage and the timeliness of data (see sections 4.3 and 8.3.6). Constructive dialogues on the limitations, use and improvement of the current energy innovation statistics can be helpful.

The data used in this paper are collected from a range of public and private sources. It is found that commercial databases (e.g. Bloomberg Terminal) play an important role in closing data gaps that may not be filled by official agencies like the IEA, but that the transparency of their methods in data collection and compilation needs to be improved. Despite considerable efforts by the author, some data is still unavailable from existing data repositories, which means only some of the proposed indicators have been applied. The missing indicators caused by data constraints may inspire future efforts to improve data infrastructure and statistics.

As much of the required data cannot be gained from the existing statistics, manual collections by the author are vital for achieving the research purposes. Chapter 7 draws three diagrams to show the presence and continuity of the major actors, networks and institutions of China's wind energy innovation system. However, the accuracy and quality are subject to the coverage of quantitative and qualitative evidence. It is recommended that future research begin with a well-designed approach to collecting data in a more thorough way.

Methodological issues

This thesis has employed absolute metrics rather than normalised indicators for between-country comparisons. The purpose is to characterise China's role in the global energy isystem, so it is appropriate to employ absolute metrics. Besides, a firm-level comparison has been conducted to avoid relying only on nationally aggregated data which may exaggerate the innovative capability of large countries. A combination of national and firm-level comparisons produces a more comprehensive picture and establishes greater confidence in the results. However, normalised indicators should be used for understanding the effectiveness of innovation systems. The central challenge is that large economies may fall behind smaller countries if the outputs and outcomes are simply divided by GDP or population. However, normalised indicators can be particularly insightful when countries have similar sizes. Further discussions on normalisation of indicators are helpful to improve the robustness of cross-country comparisons.

Another methodological issue is the adoption of bibliometric and patent data for quantifying innovation performance. As it is explained in Chapter 4, bibliometric analysis suffers from language bias and not all innovations are patented. While other indicators such as unit capacity and technology export are used to supplement the efficacy of the indicator sets, the limitations of bibliometric and patent analyses should be acknowledged. These two types of data are useful to estimate a country's science and technological capability but they cannot make a definite assessment of a country's innovation performance.

If using the data in these appendixes, please cite this thesis. Thank you. The author.

Appendix A Introduction

Appendix A-1 The global greenhouse gas emissions by sector

Unit: Billion tonnes of CO_2 equivalent

Year	Energy	Industrial processes and product use	Agriculture	Waste	Other
1990	16.00457802	1.500438923	2.202464084	0.680378503	0.00748426
1991	15.53573857	1.401887498	2.078538418	0.675617385	0.000038115
1992	15.11822868	1.370349496	2.04518353	0.679350486	0.000036391
1993	15.07902065	1.333544413	2.020419059	0.684982567	0.000035545
1994	19.13886853	1.780070558	3.037053931	0.891970879	0.008520548
1995	14.88359333	1.413404246	1.920048019	0.682279123	0.000029938
1996	15.30914724	1.422195714	1.900018236	0.682565577	0.000029376
1997	15.25070815	1.440399196	1.87407289	0.672107325	0.000031401
1998	15.24263425	1.402966374	1.90267514	0.660362416	0.000029703
1999	15.38114312	1.377426587	1.86033156	0.654922716	0.000028617
2000	17.11660812	1.551991684	2.366198135	0.867671315	0.009349059
2001	15.72444597	1.341567279	1.871433547	0.648876302	0.000029919
2002	15.81159049	1.345947953	1.881403443	0.64884044	0.00002758
2003	16.13819193	1.354643977	1.894930108	0.655775946	0.000032339
2004	16.41819983	1.420338926	2.003541722	0.650442644	0.010313065
2005	22.22083036	2.173829421	2.726645034	0.769526547	0.000033532
2006	16.46631262	1.436900008	1.912512941	0.653897307	0.000033927
2007	16.62935138	1.464359664	1.924726363	0.650445783	0.000031631
2008	16.38283109	1.415566802	1.909773801	0.648876895	0.000031496
2009	15.45539576	1.246579487	1.91688116	0.640607005	0.000026269
2010	16.0159273	1.3626871	1.942303775	0.628346921	0.000029875
2011	15.30946326	1.325821147	1.845396461	0.580765741	0.000029418
2012	15.19639178	1.320929229	1.857746234	0.57810185	0.000027112
2013	14.79008176	1.240314366	1.404462587	0.521605628	0.000027374
2014	13.95188623	1.201497401	1.387206811	0.502195833	0.000028212

N.B. The datasets covered OECD member states and a few non-OECD countries (i.e. Brazil, China, Colombia, Costa Rica, India, Indonesia, Lithuania, Russia and South Africa).

Source: OECD (2015c)

Appendix A-2 China's energy intensity compared to the OECD and world average

Unit: Primary energy consumption: toe; GDP: constant 2010 million USD; energy intensity: koe per USD

Year	China			World			OECD		
	Primary energy consumption	GDP	Energy intensity	Primary energy consumption	GDP	Energy intensity	Primary energy consumption	GDP	Energy intensity
1970	202218672.26	186835.80	1.08	4909899311.18	18901101.83	0.26	3471445968.23	14552689.43	0.24
1971	239791642.59	200026.40	1.20	5112105129.38	19705157.99	0.26	3561906092.21	15105195.22	0.24
1972	258446478.65	207647.41	1.24	5381975759.91	20825155.91	0.26	3738342063.02	15937660.03	0.23
1973	272688508.74	223760.85	1.22	5687695611.05	22171540.35	0.26	3946442199.17	16919333.83	0.23
1974	281121777.73	228929.72	1.23	5712886255.74	22612353.98	0.25	3888491298.07	17107999.18	0.23
1975	314912181.00	248892.40	1.27	5735595014.61	22817861.09	0.25	3807558336.81	17172555.58	0.22
1976	331571494.70	244984.79	1.35	6048244018.22	24019438.35	0.25	4016709626.44	18005075.59	0.22
1977	361678793.64	263530.13	1.37	6259240208.81	24979396.36	0.25	4103298811.52	18745572.50	0.22
1978	396617853.68	294275.26	1.35	6453893912.21	26003222.64	0.25	4174281780.65	19569127.11	0.21
1979	408159137.43	316640.18	1.29	6679677424.19	27071561.69	0.25	4291938989.52	20348855.24	0.21
1980	417398851.20	341359.30	1.22	6638348350.87	27603824.65	0.24	4188601088.43	20966610.16	0.20
1981	411582590.23	359015.81	1.15	6603819818.50	28139989.17	0.23	4094329071.50	21412943.14	0.19
1982	429533527.95	391091.82	1.10	6571198084.24	28283625.63	0.23	3977722609.35	21472824.12	0.19
1983	456861130.22	433467.45	1.05	6670012029.39	28998470.76	0.23	3986069316.51	22067151.21	0.18
1984	490182817.43	499090.84	0.98	6987759162.88	30320902.56	0.23	4172274381.79	23085590.66	0.18
1985	529918412.91	566185.59	0.94	7178985502.20	31506944.69	0.23	4236772256.86	23994692.32	0.18
1986	555305573.21	616800.94	0.90	7335249208.54	32529703.82	0.23	4287462312.78	24707363.34	0.17
1987	598768279.84	688898.38	0.87	7593523690.36	33703860.18	0.23	4418241670.91	25559537.75	0.17
1988	643120567.79	766292.77	0.84	7880055188.70	35258799.06	0.22	4572204066.60	26757176.67	0.17
1989	674601625.93	798368.77	0.84	8050143352.62	36586320.47	0.22	4672474140.91	27803602.59	0.17
1990	681407138.42	829561.95	0.82	8136054752.02	37665345.15	0.22	4708407195.63	29057353.03	0.16

1991	716171039.96	906662.07	0.79	8195076745.18	38181053.63	0.21	4759493441.55	29537489.60	0.16
1992	753239056.04	1035554.63	0.73	8259065796.70	38863292.12	0.21	4825895770.62	30178156.90	0.16
1993	810246479.11	1179160.96	0.69	8309496732.50	39506124.32	0.21	4907412784.28	30583218.61	0.16
1994	858791361.31	1333066.92	0.64	8418770086.70	40701296.57	0.21	5002856918.38	31513736.92	0.16
1995	884977686.67	1479027.44	0.60	8588905866.28	41905235.95	0.20	5137289154.81	32398847.67	0.16
1996	932174703.62	1625870.80	0.57	8839543917.16	43300989.41	0.20	5323737528.00	33386061.65	0.16
1997	936954559.67	1775951.18	0.53	8933995773.92	44925426.16	0.20	5394536601.05	34517669.70	0.16
1998	938176825.57	1915143.37	0.49	8998113336.75	46018338.79	0.20	5398340525.63	35471697.49	0.15
1999	969666097.37	2061986.73	0.47	9160180911.84	47542487.49	0.19	5489408187.18	36617322.05	0.15
2000	1003107990.3	2237080.51	0.45	9388250378.93	49606895.85	0.19	5611562963.25	38084621.55	0.15
2001	1059632750.1	2423651.02	0.44	9501309310.85	50587416.00	0.19	5582078966.95	38608623.96	0.14
2002	1156001954.6	2644946.01	0.44	9715282151.25	51695540.18	0.19	5643447033.96	39203936.73	0.14
2003	1347981549.3	2910382.29	0.46	10081840839.8	53196863.17	0.19	5710680395.16	39971348.40	0.14
2004	1576917953.2	3204657.55	0.49	10562635124.8	55577791.90	0.19	5811172254.35	41242693.92	0.14
2005	1793699052.9	3569853.14	0.50	10940029283.6	57702944.78	0.19	5874093689.30	42350009.96	0.14
2006	1967983565.8	4023919.87	0.49	11267825215.9	60229093.58	0.19	5892466558.46	43591172.63	0.14
2007	2140073528.3	4596579.52	0.47	11617325908.2	62831127.41	0.18	5933591304.13	44681882.74	0.13
2008	2222280063.1	5040346.60	0.44	11780824549.7	63989623.83	0.18	5885487745.99	44763125.88	0.13
2009	2322120448.8	5514129.77	0.42	11598489128.2	62901460.13	0.18	5615075779.64	43184239.72	0.13
2010	2487358052.3	6100620.36	0.41	12181351842.6	65651412.35	0.19	5833823111.02	44434693.11	0.13
2011	2687895174.2	6682402.54	0.40	12450425488.8	67685603.57	0.18	5784277886.81	45208229.42	0.13
2012	2795264935.3	7207389.60	0.39	12622094465.4	69340674.64	0.18	5732553409.12	45749414.30	0.13
2013	2903949463.6	7766512.59	0.37	12873142468.1	71058905.59	0.18	5788053532.55	46341270.39	0.12
2014	2970313646.8	8333286.73	0.36	13020593146.3	72970105.10	0.18	5749944546.28	47204947.54	0.12
2015	3013963096.7	8909477.69	0.34	13147341168.8	74888839.19	0.18	5758897267.41	48245407.19	0.12

Source: Calculated from BP (2016) and World Bank (2016b).

Appendix A-3 Wind energy R&D (a) and asset finance (b) by the major economies

Unit: million USD

Year	China (a)	Germany (a)	USA (a)	China (b)	Germany (b)	USA (b)
2005	68.50	208.04	77.62	1275.22	3164.50	3587.74
2006	80.25	191.52	74.57	2874.31	4289.40	7535.14
2007	103.31	228.55	105.40	5255.39	3836.47	10959.60
2008	125.31	245.46	111.46	14204.30	3196.15	15825.96
2009	144.45	244.44	265.27	21565.96	4867.31	8766.37
2010	178.29	239.06	150.32	24376.95	7198.66	16330.09
2011	239.25	263.84	160.10	22252.71	8924.23	10106.66
2012	244.08	275.49	169.59	26827.29	3305.31	13697.06
2013	279.94	318.52	142.41	28873.86	9066.12	12126.08
2014	245.40	301.57	132.78	40738.93	11683.65	10513.12
2015	260.37	278.47	104.08	49829.18	12388.97	14023.75

N.B. The data was converted into 2015 constant prices using yearly exchange rates.

Source: Calculated from BNEF (2016).

Appendix A-4 Solar power R&D (a) and asset finance (b) by the major economies

Unit: million USD

Year	China (a)	Germany (a)	USA (a)	China (b)	Germany (b)	USA (b)
2005	315.44	314.62	339.45	2.59	608.13	87.23
2006	371.46	390.99	276.20	2.17	302.73	457.50
2007	462.81	419.09	418.35	28.82	1835.67	763.26
2008	569.73	374.47	444.75	617.51	1509.28	1605.20
2009	651.98	376.32	710.25	1199.99	3353.64	1238.37
2010	807.67	415.91	598.48	3198.35	3059.80	3385.89
2011	1041.79	421.12	871.65	9672.58	3223.83	23149.57
2012	1163.03	462.93	561.27	21593.27	4137.55	11253.88
2013	1257.48	463.46	601.83	25491.63	251.71	5819.90
2014	1276.46	463.26	462.88	37741.34	205.66	9511.41
2015	1353.48	361.62	441.77	57616.52	282.91	15699.17

N.B. The data is converted into 2015 constant prices using yearly exchange rates.

Source: Calculated from BNEF (2016).

Appendix A-5 Gross domestic expenditure on R&D (a) and R&D intensity (b)

Unit: gross domestic R&D expenditure (billion USD, 2010 constant prices, PPP); R&D intensity (%)

Year	China (a)	EU-28 (a)	OECD (a)	USA (a)	China (b)	EU-28 (b)	OECD (b)	USA (b)
2000	40.89	239.04	771.11	333.15	0.89	1.67	2.13	2.62
2001	46.63	247.72	796.33	338.69	0.94	1.69	2.17	2.64
2002	57.25	252.82	800.79	333.15	1.06	1.70	2.15	2.55
2003	66.72	255.02	818.90	342.93	1.12	1.69	2.15	2.55
2004	79.68	257.71	835.36	347.14	1.21	1.66	2.12	2.49
2005	95.54	263.88	871.67	361.07	1.31	1.66	2.15	2.51
2006	112.69	277.54	915.86	377.21	1.37	1.68	2.18	2.55
2007	129.15	288.12	960.86	395.49	1.37	1.69	2.22	2.63
2008	149.01	302.20	998.88	415.34	1.44	1.76	2.29	2.77
2009	187.54	301.98	986.25	411.37	1.66	1.84	2.34	2.82
2010	213.46	308.25	1000.70	410.09	1.71	1.84	2.30	2.74
2011	242.77	320.34	1037.43	421.10	1.78	1.88	2.33	2.77
2012	281.08	326.04	1052.57	420.49	1.91	1.92	2.34	2.71
2013	316.30	328.09	1080.76	433.25	1.99	1.93	2.37	2.74
2014	344.65	337.50	1114.85	445.85	2.02	1.95	2.39	2.76
2015	376.86	344.49	1140.97	462.77	2.07	1.95	2.40	2.79

N.B. R&D intensity is calculated as percentage of gross domestic R&D expenditure percentage of GDP.

Source: OECD (2016a)

Appendix A-6 Wind turbines export by Chinese firms

Unit: MW

Year	World total	Europe	North America	Other regions	Ave. unit capacity
2007	2.34	n/a	n/a	n/a	n/a
2008	14.5	n/a	10	2.34	0.89
2009	28.8	3.75	6	19	1.42
2010	11.1	1.5	5.05	9	1.47
2011	213.1	56	146.5	18.06	1.98
2012	430.5	192	154.2	84.25	1.93
2013	692.4	249.85	8	434.5	2.11
2014	368.8	117.25	22	229.5	1.72
2015	274.5	93	37	144.5	1.72

Source: Calculated from CWEA (2015b) and CWEA (2016b).

Appendix A-7 China’s wind power capacity and the Five-Year Plan targets

Unit: capacity (GW); share (%)

Year	Cumulative capacity	Five-Year Plan targets	Country share	Annual capacity
1985	0.000	n/a	n/a	0.000
1986	0.001	n/a	n/a	0.001
1987	0.001	n/a	n/a	0.000
1988	0.001	n/a	n/a	0.000
1989	0.004	n/a	n/a	0.003
1990	0.004	n/a	n/a	0.000
1991	0.005	n/a	n/a	0.001
1992	0.009	n/a	n/a	0.004
1993	0.015	n/a	n/a	0.006
1994	0.028	n/a	n/a	0.013
1995	0.039	n/a	0.81	0.011
1996	0.062	n/a	1.02	0.023
1997	0.146	n/a	1.92	0.084
1998	0.200	n/a	2.00	0.054
1999	0.262	n/a	1.95	0.062
2000	0.352	0.2	1.96	0.090
2001	0.406	n/a	1.64	0.054
2002	0.473	n/a	1.48	0.067
2003	0.571	n/a	1.43	0.098
2004	0.769	n/a	1.60	0.198
2005	1.264	1.2	2.14	0.495
2006	2.588	n/a	3.49	1.324
2007	5.875	n/a	6.24	3.287
2008	12.12	n/a	9.95	6.246
2009	25.85	n/a	16.15	13.73
2010	44.78	10	22.66	18.93
2011	62.41	n/a	26.09	17.63
2012	75.32	n/a	26.46	12.91
2013	91.41	n/a	28.51	16.09
2014	114.6	n/a	30.82	23.20
2015	145.1	100	33.38	30.50

Source: Compiled from Shi (2007), CWEA (2015b) and Chinese government documents.

Appendix A-8 China's electricity capacity by fuels

Unit: GW

Year	Hydro	Fossil-fuels	Nuclear	Wind	Solar	Others
1985	26.41	60.64	n/a	0	n/a	n/a
1986	27.54	66.28	n/a	0.001	n/a	n/a
1987	30.19	72.71	n/a	0.001	n/a	n/a
1988	32.7	82.8	n/a	0.001	n/a	n/a
1989	34.58	92.06	n/a	0.004	n/a	n/a
1990	36.05	101.84	n/a	0.004	n/a	n/a
1991	37.88	113.59	n/a	0.005	n/a	n/a
1992	40.68	125.85	n/a	0.009	n/a	n/a
1993	44.89	138.02	n/a	0.015	n/a	n/a
1994	49.06	148.74	n/a	0.028	n/a	n/a
1995	52.18	162.94	n/a	0.039	n/a	n/a
1996	55.58	178.86	n/a	0.1	0.001	n/a
1997	59.73	192.41	n/a	0.1	0.003	n/a
1998	65.07	209.88	n/a	0.2	0.005	n/a
1999	72.97	223.43	n/a	0.3	0.01	n/a
2000	79.35	237.54	n/a	0.4	0.019	n/a
2001	83.01	253.14	n/a	0.4	0.03	n/a
2002	86.07	265.55	n/a	0.5	0.045	n/a
2003	94.9	289.77	n/a	0.6	0.055	n/a
2004	105.24	329.48	n/a	0.8	0.064	n/a
2005	117.39	391.38	n/a	1.3	0.068	n/a
2006	130.29	483.82	n/a	2.6	0.08	n/a
2007	148.23	556.07	n/a	5.9	0.1	n/a
2008	172.6	602.86	n/a	12.1	0.14	n/a
2009	196.29	651.08	n/a	25.9	0.3	n/a
2010	216.06	709.67	n/a	44.8	0.8	n/a
2011	232.98	768.34	n/a	62.4	3.5	n/a
2012	249.47	819.68	n/a	75.3	6.7	n/a
2013	280.44	870.09	n/a	91.4	17.69	n/a
2014	304.86	932.32	20.08	114.6	28.33	0.19
2015	319.54	1005.54	27.17	145.1	43.48	0.09

Source: Compiled from CEC (2016).

Appendix A-9 China’s electricity generation by fuels

Unit: TWh

Year	Hydro	Fossil-fuels	Nuclear	Wind	Solar	Others
1985	92.4	318.3	n/a	n/a	n/a	n/a
1986	94.5	355.1	n/a	n/a	n/a	n/a
1987	100.2	397.1	n/a	n/a	n/a	n/a
1988	109.2	435.9	n/a	n/a	n/a	n/a
1989	118.5	466.2	n/a	n/a	n/a	n/a
1990	126.3	495	n/a	n/a	n/a	0.1
1991	124.8	552.7	n/a	n/a	n/a	0.1
1992	131.5	622.7	n/a	0.1	n/a	0.1
1993	151.6	686.8	1.6	0.2	n/a	0.1
1994	166.8	747	14.8	0.4	n/a	0.5
1995	186.8	807.4	12.8	0.6	n/a	3
1996	186.9	878.1	14.3	0.1	n/a	1.5
1997	194.6	925.2	14.4	0.2	n/a	2.7
1998	204.3	938.8	14.1	0.4	n/a	2.5
1999	212.9	1004.7	15	0.5	n/a	2.5
2000	243.1	1107.9	16.7	0.6	n/a	2.5
2001	261.1	1204.5	17.5	0.7	n/a	2.6
2002	274.6	1352.2	25.1	0.8	n/a	2.5
2003	281.3	1579	43.3	1	0.1	2.5
2004	331	1810.4	50.5	1.3	0.1	2.5
2005	396.4	2043.7	53.1	1.9	0.1	5.4
2006	414.8	2374.1	54.8	3.7	0.1	7.1
2007	471.4	2720.7	62.1	5.5	0.1	9.9
2008	565.5	2803	68.4	13.1	0.2	14.8
2009	571.7	3011.7	70.1	27.6	0.3	20.8
2010	686.7	3416.6	73.9	44.6	0.7	24.9
2011	668.1	3900.3	86.4	70.3	2.6	31.7
2012	855.6	3925.5	97.4	96	6.4	33.8
2013	892.1	4221.6	111.6	141.2	15.5	38.4
2014	1060.1	4303	132.5	159.8	23.1	46.5
2015	1112.7	4230.7	170.8	185.1	39.2	52.9

Source: Compiled from CEC (2016).

Appendix B Methodology

Appendix B-1 Diagnostic questions for semi-structured interviews

类型（Functions）	诊断性问题（Diagnostic questions）
创业活动 F1: Entrepreneurial Activities	• 中国风电行业有足够的创业者吗？（Are there enough entrepreneurs in wind turbine industry?） • 创业者主要从事什么类型的业务？（What types of businesses are mainly involved, R&D or manufacturing?） • 创业者从事研发活动的程度如何？（To what extent do entrepreneurs conduct R&D activities?） • 中国风电行业有哪些可选择的技术？（How is the variety of technological options?）
知识发展 F2: Knowledge Development	• 中国风电行业知识创造的数量和质量如何？（What is the knowledge base in terms of quality and quantity?） • 知识创造处于国际领先水平吗？（Does China lead in knowledge generation?） • 这些创造的知识是基础性的还是应用性的？（Is the knowledge basic or applied?） • 知识创造的资助方是谁？（Who finances the knowledge development?） • 风能技术有在国家重大技术攻关项目中得到体现吗？（Is wind technology included national major S&T programs?） • 相关技术得到国际机构的认证了吗？（Are the relevant technologies certificated by international organisations?）
知识网络 F3: Knowledge Networks	• 中国风电行业的各个行为主体之间的合作关系紧密吗？（Are there strong interactions between university, industry and government? ） • 知识扩散的渠道有哪些？（What are the channels for knowledge dissemination） • 这些渠道有效吗？（Are these channels effective?） • 创造的知识与实际需求相匹配吗？（Does the knowledge correspond with the real needs? ） • 知识的使用者多吗？（Are there enough knowledge users?）
探索引导 F4: Guidance of the Search	• 中国风电行业有共同的发展目标或远景吗？（Is there a shared development goal among various stakeholders? ） • 这个目标是笼统的还是具体的？（Is this objective generic or specific? ） • 这个目标是由具体的项目、政策或组织机构支持的吗？（Are

	there enough programs or policies to support this objective?） • 当前的体制机制有助于创新吗？（Does the institutions well support wind technology innovations?）
市场形成 F5: Market Formation	• 中国风电市场的总体状况是怎样的？（How does the wind market look like? ） • 哪些企业占据主导地位？国有企业还是民营企业？（Who takes the lead in market, public or private enterprises? ） • 市场形成过程中有制度方面的激励或阻碍吗？（Are there institutional incentives/barriers to market formation?） • 需要开辟一个新的市场还是对现有的市场进行拓展？（Is there a need to create a new market or open up the existing one?）
资源流动 F6: Resource Mobilisation	• 中国风电技术的研发有足够的资金支持吗？（Are there sufficient financial resources for the system development? ） • 这些资金是根据实际需求配置的吗？（Do they correspond with the system’s needs? ） • 这些资金主要用于哪些方面？研发、示范还是安装？（What are they mainly used for, R&D, demonstration or deployment? ） • 有适量的政府资金支持吗？（Are there adequate public funding? ） • 企业可以容易地获得这些资金吗？（Can companies easily access the funding?）
合法性建立 F7: Creation of Legitimacy	• 风电技术的投资有相关法律的支持吗？（Is investment in the technology seen as a legitimate decision? ） • 对发展风能有很强的抵制吗？（Is there much resistance to wind technology? ） • 这些抵制来源于哪些行为主体和哪些方面？（Where are the opponents from? ）

Source: Adapted from Hekkert et al. (2011)

Appendix B-2 Data sources for wind power industry

Types	Names	Data coverage	Websites
Databases	China Energy Statistical Yearbook	China energy statistics	n/a
	China Statistical Yearbook	macroeconomic & energy data	http://www.stats.gov.cn/tjsj/ndsj/2015/indexeh.htm
	China Energy Data Book	China energy statistics	https://china.lbl.gov/research-projects/china-energy-databook
	Bloomberg Terminal	global wind power statistics (incl. R&D)	n/a
	4C offshore	global offshore wind statistics (incl. project details)	http://www.4coffshore.com/
	Electronic Wind Performance Reporting System	wind plant data in California dating back to 1985	http://wprs.ucdavis.edu/
	The Master Data Register of Wind Turbines	a national database which contains all Danish power-producing wind turbines (incl. location, technical specifications and output for each wind turbine)	https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/overview-energy-sector
	BP Statistical Review of World Energy	global energy statistics	http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
	UN Commodity Trade Database	international trade in wind power equipment	https://comtrade.un.org/db/default.aspx
	PATSTAT (Worldwide Patent Statistical Database)	wind technology patents filed at the European Patent Office and US Patent and Trademark Office	https://www.epo.org/searching-for-patents/business/patstat.html#tab1
	PIAS (Patent Information Analysis System)	wind technology patents filed at the China State Intellectual Property Office	n/a
	Web of Science	customised data for bibliometric analysis	http://wok.mimas.ac.uk
	Gains Model	emission factors for fossil fuels	http://gains.iiasa.ac.at/models/
Organisations	China Electricity Council	China electricity sector statistics	http://www.cec.org.cn/nengyuanyudianlitongji/
	Chinese Wind Energy Association	China wind power statistics	http://www.cwea.org.cn/
	Chinese Wind Power Equipment Association	China wind power statistics	http://www.cweea.com.cn/plus/list.php?tid=15

Publications	China Nation Renewable Energy Centre	China renewable energy statistics and reports	http://www.cnrec.org.cn/
	IRENA	global renewable energy statistics (incl. capacity, cost, employment)	http://www.irena.org/Publications/index.aspx?mnu=cat&PriMenuID=36&CatID=141
	Global Wind Energy Council	global wind power statistics	http://www.gwec.net/
	World Wind Energy Association	wind power reports and statistics	http://www.wwindea.org/information-2/publications/
	Wind Europe	European wind power statistics (incl. offshore)	https://windeurope.org/about-wind/
	European Technology & Innovation Platform on Wind Energy	R&D initiatives for Europe	https://etipwind.eu/library/
	NREL National Wind Technology Center	US wind technology reports	http://www.nrel.gov/nwtc/
	American Wind Energy Association	US wind power statistics	http://www.awea.org/
	U.S. Energy Information Administration	US and global energy statistics	http://www.eia.gov/
	International Energy Agency	global energy statistics	http://www.iea.org/statistics/
	China Economic and Social Development Statistical Bulletin	macroeconomic & energy data	http://www.stats.gov.cn/tjsj/zxfb/201602/t20160229_1323991.html
	China Environment Bulletin	China environment statistics	http://www.zhb.gov.cn/hjzl/zghjzkgb/lssj/zxhjzkgb/
	IEA Wind Annual Reports	IEA and partnership countries' wind power reports	https://www.ieawind.org/
	Wind Technologies Market Report	US wind power statistics	https://energy.gov/eere/wind/downloads/2015-wind-technologies-market-report
	German Wind Energy Institute (DEWI Magazine)	German wind power statistics	http://www.dewi.de/dewi_res/index.php?id=22
	Wind Farms in China (SHI Pengfei)	China wind power statistics (1986-2007)	n/a
	China Wind Power Industry Map	China wind power statistics	n/a
	Renewables Global Status Report	global renewable energy statistics	http://www.ren21.net/status-of-renewables/global-status-report/
	Global Trends in Renewable Energy Investment	global renewable energy investment statistics	http://fs-unep-centre.org/publications

Appendix C System performance

Appendix C-1 SCI publications (a) and top 10% SCI publications (b) in wind turbine technology

Unit: counts

Year	China (a)	Denmark (a)	Germany (a)	USA (a)	China (b)	Denmark (b)	Germany (b)	USA (b)
2005	27	14	35	166	3	10	7	44
2006	45	22	40	144	10	10	15	41
2007	50	29	49	161	5	12	9	39
2008	66	33	53	207	7	10	8	29
2009	91	38	47	227	19	18	15	62
2010	101	44	54	226	14	18	13	32
2011	147	58	67	321	10	16	9	54
2012	257	81	94	383	9	15	7	29
2013	337	91	88	445	13	5	2	23
2014	427	102	127	471	6	1	1	7
2015	560	101	139	495	2	0	0	2

Source: Calculated from WoS (2016).

Appendix C-2 EPO (a), USPTO (b) and SIPO (c) patent filings in wind turbine technology

Unit: fractional counts

Year	China (a)	Denmark (a)	Germany (a)	USA (a)	China (b)	Denmark (b)	Germany (b)	USA (b)	China (c)	Denmark (c)	Germany (c)	USA (c)
2000	0.0	10.0	84.0	1.0	0.0	9.0	33.0	52.7	n/a	n/a	n/a	n/a
2001	0.0	8.3	129.7	15.0	0.0	7.0	69.5	62.8	n/a	n/a	n/a	n/a
2002	0.0	19.0	92.0	7.0	0.0	26.3	44.2	64.3	n/a	n/a	n/a	n/a
2003	0.0	33.2	142.3	16.5	0.0	28.0	61.3	100.1	n/a	n/a	n/a	n/a
2004	0.0	32.0	110.5	31.3	0.0	30.7	54.0	105.6	68.0	13.0	18.0	8.0
2005	2.5	35.0	75.7	54.7	3.5	33.0	40.1	150.5	128.0	16.0	20.0	19.0
2006	8.0	76.7	130.1	43.8	12.2	72.6	80.8	199.1	175.0	14.0	6.0	40.0
2007	1.6	127.9	171.8	62.3	4.1	124.4	102.9	297.5	330.0	32.0	36.0	40.0
2008	7.0	171.8	259.0	127.1	12.8	128.4	157.5	396.2	376.0	49.0	50.0	80.0
2009	30.1	237.1	302.0	171.3	34.1	137.3	150.4	491.9	545.0	52.0	71.0	129.0
2010	24.3	276.5	397.7	150.3	29.8	185.4	215.7	416.7	579.0	77.0	82.0	141.0
2011	25.8	307.4	417.9	133.1	40.3	206.5	187.6	387.6	821.0	71.0	130.0	147.0
2012	n/a	n/a	n/a	n/a	12.6	120.4	101.8	273.9	803.0	84.0	123.0	96.0
2013	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	790.0	38.0	89.0	26.0
2014	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	808.0	28.0	76.0	21.0
2015	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	722.0	0.0	41.0	13.0

N.B. Patent data after 2011 was unavailable from the PATSTAT.

Source: EPO and USPTO (2016), SIPO (2016).

Appendix C-3 Annual capacity of wind turbines delivered by manufacturers

Unit: MW

Year	Goldwind	United Power	Mingyang	Envision Energy	Vestas	Siemens	Enercon	GE
2004	40	0	0	0	2783	507	1288	918
2005	132	0	0	0	3186	629	1640	2025
2006	416	0	0	0	4239	1103	2316	2326
2007	830	0	1.5	0	4503	1397	2769	3283
2008	1132	24	174	14	5581	1947	2806	5239
2009	2727	768	573	137	4766	2265	3221	4741
2010	3740	1643	1052	251	5842	2325	2846	3796
2011	3789	2859	1178	348	5213	2540	3188	3542
2012	2609	2029	1183	544	6020	4114	3538	6696
2013	4112	1488	1297	1128	4893	2776	3687	2458
2014	4593	2592	2262	1963	6253	5068	3956	4624
2015	7840	2800	2510	2700	7300	3100	3000	5900

Source: BNEF (2016).

Appendix C-4 Export of wind power generating sets

Unit: million USD

Year	China	Denmark	Germany	USA
2005	0.275719	835.62199	515.115422	3.03259
2006	2.260347	1098.38176	727.886622	71.80935
2007	59.63233	1464.6844	863.036608	12.5282
2008	173.7783	1086.6188	1799.01505	19.91536
2009	124.3311	1375.98904	851.389406	106.3634
2010	49.79085	1584.95301	1115.21818	296.4777
2011	334.2952	1931.24187	1227.98907	239.5009
2012	455.1511	1595.79153	2980.81862	371.0781
2013	465.8991	2816.87184	2749.96854	413.7903
2014	303.7128	3708.78599	2164.36757	537.5659
2015	291.2373	3149.74938	2357.97525	148.9135

N.B. a) The data is converted into 2015 constant prices using yearly exchange rates; b) HS Code: 850231.

Source: United Nations (2016).

Appendix C-5 Wind power consumption by the major economies

Unit: TWh

Year	China	Denmark	Germany	USA
2005	1.9	6.7	27.2	18
2006	3.7	6.2	30.7	26.9
2007	5.5	7.2	39.7	34.8
2008	13.1	7	40.6	55.9
2009	27.6	6.8	38.6	74.6
2010	44.6	7.9	37.8	95.6
2011	70.3	9.9	48.9	121.4
2012	96	10.4	50.7	142.2
2013	141.2	11.2	51.7	169.5
2014	158.4	13.2	56	183.6
2015	185.1	14.3	88	192.9

Source: BP (2016).

Appendix C-6 Emission factors from fossil fuel power plants

Unit: g/kWh

Countries	CO_2	SO_2	NO_X	$PM_{2.5}$	PM_{10}
China	1067	5.7	1.9	0.40	1.26
Denmark	1235	0.3	1.2	0.03	0.09
Germany	725	0.4	0.5	0.03	0.08
USA	735	1.5	1.0	0.02	0.05

Source: IIASA's GAINS Model (IIASA 2015).

Appendix C-7 Carbon dioxide emissions reduction by wind power

Unit: million tonnes

Year	China	Denmark	Germany	USA
2005	2.0273	8.2745	19.72	13.23
2006	3.9479	7.657	22.2575	19.7715
2007	5.8685	8.892	28.7825	25.578
2008	13.9777	8.645	29.435	41.0865
2009	29.4492	8.398	27.985	54.831
2010	47.5882	9.7565	27.405	70.266
2011	75.0101	12.2265	35.4525	89.229
2012	102.432	12.844	36.7575	104.517
2013	150.6604	13.832	37.4825	124.5825
2014	169.0128	16.302	40.6	134.946
2015	197.5017	17.6605	63.8	141.7815

N.B. CO_2 emissions reduction is calculated by referring to the emission factors (see Table A3-5).

Source: IIASA (2015) and BP (2016).

Appendix C-8 R&D expenditure (a) and R&D intensity (b) by Goldwind and Vestas

Unit: R&D expenditure (million USD); R&D intensity (%)

Year	Goldwind (a)	Vestas (b)	Goldwind (b)	Vestas (b)
2005	n/a	75.7399864	n/a	2.02926765
2006	7.8667805	100.299922	5.80332052	2.4232664
2007	13.258869	148.815268	4.27058628	2.55089673
2008	30.044603	159.583642	3.93416876	1.97183489
2009	17.108819	117.575243	1.33131084	1.81139144
2010	16.171597	188.26269	0.71148038	2.16764165
2011	104.43771	269.138346	5.55748018	3.47840711
2012	108.77413	319.613487	6.27270057	3.53380514
2013	125.30232	321.336545	6.33835894	4.04337422
2014	187.0364	280.433078	6.5275285	3.08247334
2015	250.77733	234.211779	5.27941154	2.50504598

N.B. The data is converted into 2015 constant prices using yearly exchange rates.

Source: BNEF (2016).

Appendix C-9 Corporate revenue from wind turbine sales

Unit: billion USD (current price)

Year	Vestas	Goldwind	Gamesa	Nordex	Siemens
2005	4457.5	61.5	2169.7	384.4	n/a
2006	4842.5	191.2	3002.8	645.3	n/a
2007	6663.5	406.2	3930.1	1024.6	1816.66231
2008	8876.8	926.6	5619.5	1670.5	3144.518543
2009	7082.3	1561.3	4444.2	1649.3	3977.041568
2010	9180.1	2582.2	3629.1	1289.5	4438.778861
2011	8126.1	1974	4185.2	1276.6	5141.120616
2012	9278.9	1779	3426.7	1382.7	6577.328057
2013	8081.5	1983.9	3102.4	1898.5	n/a
2014	9179.9	2852.2	3781.1	2304.3	n/a
2015	9349.6	4750.1	3889.2	2697.4	n/a

Source: BNEF (2016) and company annual reports.

Appendix C-10 EPO (a), USPTO (b) and SIPO (c) patent fillings by manufacturers

Unit: fractional count

Year	Goldwind (a)	Vestas (a)	Siemens (a)	GE (a)	Goldwind (b)	Vestas (b)	Siemens (b)	GE (b)	Goldwind (c)	Vestas (c)	Siemens (c)	GE (c)
2000	0	1	2	6	0	2	0	1	0	1	0	0
2001	0	1	2	8	0	1	0	3.3	0	0	1	0
2002	0	9	6	7	0	7.9	4.5	5.6	1	1	0	2
2003	0	16	0	21	0	7.3	0	21.2	0	8	2	11
2004	0	11	4	18	0	5.4	1.5	26.4	0	8	0	6
2005	0	15	0	45	0	3.9	0.5	48.3	0	10	0	10
2006	0	45	19	35	0	12.7	6.5	40.0	0	4	0	27
2007	0	67.5	36	48	0	15.8	15.3	35.9	1	30	3	25
2008	0	77	58.5	134	0	7.9	21.3	40.0	1	37	22	58
2009	0	111.5	65.5	146	0	16.2	17.9	46.3	0	41	33	99
2010	0	119.5	155.5	125	0	26.1	27.2	49.4	7	60	35	113
2011	1.5	114.5	187.5	96.5	1.1	43.8	31.9	51.5	8	56	58	131
2012	n/a	n/a	n/a	n/a	1	22	18.7	64.7	8	54	69	83
2013	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	13	26	44	12
2014	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	13	21	49	11
2015	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	72	0	38	9

N.B. Patent data after 2011 was unavailable from the PATSTAT.

Source: EPO and USPTO (2016), SIPO (2016).

Appendix C-11 Maximum unit capacity of commercialised wind turbines over time

Unit: MW

Year	Goldwind	Vestas	Siemens	GE
1978		0.4		
1979				
1980			0.03	
1981			0.55	
1982				
1983				
1984				0.1
1985				0.33
1986				
1987		0.75		
1988		1.5		
1989	0.15			
1990				
1991				
1992				
1993				
1994				0.36
1995				
1996		2		
1997				0.625
1998				0.75
1999				1.75
2000		2.3		1.8
2001				
2002	0.6	3		
2003		4.2		3
2004			2.3	
2005	0.75			
2006				
2007				
2008	1.5		3.6	
2009				
2010				
2011	2.5	6	6	
2012				3.6
2013				
2014				3.75
2015	3	8	7	

Source: DEA (2016) and company websites.

Appendix C-12 Export of wind turbines by manufacturers

Unit: MW

Year	Goldwind	Vestas
2007	0	3965.0
2008	0	5670.0
2009	4.5	4494.5
2010	4.5	4494.5
2011	189	5734.23
2012	87.3	5088.23
2013	361.3	5951
2014	223.3	4629
2015	114.5	6204

Source: BNEF (2016), CWEA (2016b), CWEA (2015b)

Appendix C-13 Synthesis of China’s inputs, outputs and outcomes

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	147.20	159.65	176.83	184.48	213.22	230.11	263.99	256.89	281.93	243.15	260.37
	Asset finance (billion USD)	1.28	2.87	5.26	14.20	21.57	24.38	22.25	26.83	28.87	40.74	49.83
Output	SCI publications (counts)	27.00	45.00	50.00	66.00	91.00	101.00	147.00	257.00	337.00	427.00	560.00
	SCI top 10% publications (counts)	3.00	10.00	5.00	7.00	19.00	14.00	10.00	9.00	13.00	6.00	2.00
	EPO (fractional counts)	2.50	8.00	1.57	7.00	30.07	24.25	25.82	n/a	n/a	n/a	n/a
	USPTO (fractional counts)	3.50	12.23	4.07	12.75	34.08	29.83	40.32	n/a	n/a	n/a	n/a
	SIPO (fractional counts)	128.00	175.00	330.00	376.00	545.00	579.00	821.00	803.0	790.0	808.0	722.0
	Manufacturing capacity (GW)	0.15	0.55	1.84	4.56	10.52	15.41	13.73	11.93	15.27	22.07	30.38
	Installed capacity (GW)	1.26	2.59	5.88	12.12	25.85	44.78	62.41	75.32	91.41	114.61	145.11
	Export (million USD)	0.28	2.26	59.63	173.78	124.33	49.79	334.30	455.15	465.90	303.71	291.24
Outcome	Power generation (TWh)	1.9	3.7	5.5	13.1	27.6	44.6	70.3	96	141.2	158.4	185.1
	CO_2 emissions reduction (million tonnes)	2.027	3.948	5.869	13.978	29.449	47.588	75.010	102.432	150.660	169.013	197.502

N.B. The monetary data is converted into 2015 constant prices using yearly exchange rates.

Source: Compiled from WoS (2016), EPO and USPTO (2016), SIPO (2016), BP (2016) and BNEF (2016).

Appendix C-14 Synthesis of China's inputs, outputs and outcomes (indexed value)

Indexed value: 2010=1

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D expenditure	0.64	0.69	0.77	0.80	0.93	1.00	1.15	1.12	1.23	1.06	1.13
	Asset finance	0.05	0.12	0.22	0.58	0.88	1.00	0.91	1.10	1.18	1.67	2.04
Output	SCI publications	0.27	0.45	0.50	0.65	0.90	1.00	1.46	2.54	3.34	4.23	5.54
	Top 10% SCI publications	0.21	0.71	0.36	0.50	1.36	1.00	0.71	n/a	n/a	n/a	n/a
	EPO applications	0.10	0.33	0.06	0.29	1.24	1.00	1.06	n/a	n/a	n/a	n/a
	USPTO applications	0.12	0.41	0.14	0.43	1.14	1.00	1.35	n/a	n/a	n/a	n/a
	SIPO applications	0.22	0.30	0.57	0.65	0.94	1.00	1.42	n/a	n/a	n/a	n/a
	Manufacturing capacity	0.01	0.04	0.12	0.30	0.68	1.00	0.89	0.77	0.99	1.43	1.97
	Installed capacity	0.03	0.06	0.13	0.27	0.58	1.00	1.39	1.68	2.04	2.56	3.24
Outcome	Export revenue	0.01	0.05	1.20	3.49	2.50	1.00	6.71	9.14	9.36	6.10	5.85
	Power generation	0.04	0.08	0.12	0.29	0.62	1.00	1.58	2.15	3.17	3.55	4.15
	CO_2 emissions reduction	0.04	0.08	0.12	0.29	0.62	1.00	1.58	2.15	3.17	3.55	4.15

Source: Calculated from Appendix C-13.

Appendix C-15 Synthesis of Denmark's inputs, outputs and outcomes

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	RD&D (million USD)	15.83	14.10	20.09	13.36	20.43	42.86	24.30	18.26	30.43	28.36	28.83
	Asset finance (billion USD)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Output	SCI publications (counts)	14.00	22.00	29.00	33.00	38.00	44.00	58.00	81.00	91.00	102.00	101.00
	SCI top 10% publications (counts)	10	10	12	10	18	18	16	15	5	1	0
	EPO applications (fractional counts)	35.0	76.7	127.9	171.8	237.1	276.5	307.4	n/a	n/a	n/a	n/a
	USPTO applications (fractional counts)	33.0	72.6	124.4	128.4	137.3	185.4	206.5	n/a	n/a	n/a	n/a
	SIPO applications (fractional counts)	16.0	14.0	32.0	49.0	52.0	77.0	71.0	84.0	38.0	28.0	0.0
	Manufacturing capacity (GW)	3.19	4.24	4.50	5.58	4.77	5.84	5.21	6.02	4.89	6.25	7.30
	Installed capacity (GW)	3.09	3.10	3.09	3.16	3.41	3.81	3.93	4.14	4.75	4.78	4.93
Outcome	Export (million USD)	835.62	1098.38	1464.68	1086.62	1375.99	1584.95	1931.24	1595.79	2816.87	3708.79	3149.75
	Power generation (TWh)	6.7	6.2	7.2	7	6.8	7.9	9.9	10.4	11.2	13.2	14.3
	CO_2 emissions reduction (million tonnes)	8.2745	7.657	8.892	8.645	8.398	9.7565	12.2265	12.844	13.832	16.302	17.6605

N.B. a) RD&D budgets are from IEA RD&D Database; b) the monetary data is converted into 2015 constant prices using yearly exchange rates.

Source: Compiled from WoS (2016), EPO and USPTO (2016), SIPO (2016), BP (2016) and BNEF (2016).

Appendix C-16 Synthesis of Denmark's inputs, outputs and outcomes (indexed value)

Indexed value: 2010=1

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	RD&D	0.37	0.33	0.47	0.31	0.48	1.00	0.57	0.43	0.71	0.66	0.67
	Asset finance	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Output	SCI publications	0.32	0.50	0.66	0.75	0.86	1.00	1.32	1.84	2.07	2.32	2.30
	SCI top 10% publications	0.56	0.56	0.67	0.56	1.00	1.00	0.89	n/a	n/a	n/a	n/a
	EPO applications	0.13	0.28	0.46	0.62	0.86	1.00	1.11	n/a	n/a	n/a	n/a
	USPTO applications	0.18	0.39	0.67	0.69	0.74	1.00	1.11	n/a	n/a	n/a	n/a
	SIPO applications	0.21	0.18	0.42	0.64	0.68	1.00	0.92	n/a	n/a	n/a	n/a
	Manufacturing capacity	0.55	0.73	0.77	0.96	0.82	1.00	0.89	1.03	0.84	1.07	1.25
	Installed capacity	0.81	0.81	0.81	0.83	0.89	1.00	1.03	1.09	1.25	1.25	1.29
Outcome	Export	0.53	0.69	0.92	0.69	0.87	1.00	1.22	1.01	1.78	2.34	1.99
	Power generation	0.85	0.78	0.91	0.89	0.86	1.00	1.25	1.32	1.42	1.67	1.81
	CO_2 emissions reduction	0.85	0.78	0.91	0.89	0.86	1.00	1.25	1.32	1.42	1.67	1.81

Source: Calculated from Appendix C-15.

Appendix C-17 Synthesis of Germany's inputs, outputs and outcomes

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	273.183	249.939	288.404	304.643	292.986	282.270	304.903	308.809	343.375	313.512	278.468
	Asset finance (billion USD)	3.16450	4.28940	3.83647	3.19615	4.86731	7.19866	8.92423	3.30531	9.06612	11.6837	12.3890
Output	SCI publications (counts)	35	40	49	53	47	54	67	94	88	127	139
	SCI top 10% publications (counts)	7	15	9	8	15	13	9	7	2	1	0
	EPO applications (fractional counts)	75.7	130.1	171.8	259.0	302.0	397.7	417.9	n/a	n/a	n/a	n/a
	USPTO applications (fractional counts)	40.1	80.8	102.9	157.5	150.4	215.7	187.6	n/a	n/a	n/a	n/a
	SIPO applications (fractional counts)	20.0	6.0	36.0	50.0	71.0	82.0	130.0	123.0	89.0	76.0	41.0
	Manufacturing capacity (GW)	2.27	3.42	4.17	4.75	5.49	5.17	5.73	7.65	6.46	9.02	6.10
	Installed capacity (GW)	18.38	20.57	22.18	23.82	25.66	27.09	29.05	31.26	34.27	39.19	45.02
Outcome	Export (million USD)	515.115	727.887	863.037	1799.02	851.389	1115.218	1227.99	2980.82	2749.9	2164.37	2357.98
	Power generation (TWh)	27.2	30.7	39.7	40.6	38.6	37.8	48.9	50.7	51.7	56	88
	CO_2 emissions reduction (million tonnes)	19.72	22.2575	28.7825	29.435	27.985	27.405	35.4525	36.7575	37.4825	40.6	63.8

N.B. The monetary data is converted into 2015 constant prices using yearly exchange rates.

Source: Compiled from WoS (2016), EPO and USPTO (2016), SIPO (2016), BP (2016) and BNEF (2016).

Appendix C-18 Synthesis of Germany's inputs, outputs and outcomes (indexed value)

Indexed value: 2010=1

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D	0.97	0.89	1.02	1.08	1.04	1.00	1.08	1.09	1.22	1.11	0.99
	Asset finance	0.44	0.60	0.53	0.44	0.68	1.00	1.24	0.46	1.26	1.62	1.72
Output	SCI publications	0.65	0.74	0.91	0.98	0.87	1.00	1.24	1.74	1.63	2.35	2.57
	SCI top 10% publications	0.54	1.15	0.69	0.62	1.15	1.00	0.69	n/a	n/a	n/a	n/a
	EPO applications	0.19	0.33	0.43	0.65	0.76	1.00	1.05	n/a	n/a	n/a	n/a
	USPTO applications	0.19	0.37	0.48	0.73	0.70	1.00	0.87	n/a	n/a	n/a	n/a
	SIPO applications	0.24	0.07	0.44	0.61	0.87	1.00	1.59	n/a	n/a	n/a	n/a
	Manufacturing capacity	0.44	0.66	0.81	0.92	1.06	1.00	1.11	1.48	1.25	1.75	1.18
	Installed capacity	0.68	0.76	0.82	0.88	0.95	1.00	1.07	1.15	1.27	1.45	1.66
Outcome	Export	0.46	0.65	0.77	1.61	0.76	1.00	1.10	2.67	2.47	1.94	2.11
	Power generation	0.72	0.81	1.05	1.07	1.02	1.00	1.29	1.34	1.37	1.48	2.33
	CO_2 emissions reduction	0.72	0.81	1.05	1.07	1.02	1.00	1.29	1.34	1.37	1.48	2.33

Source: Calculated from Appendix C-17.

Appendix C-19 Synthesis of the U.S. inputs, outputs and outcomes

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	110.988	100.373	134.608	136.920	320.974	177.519	181.492	185.364	150.743	135.648	104.078
	Asset finance (billion USD)	3.58774	7.53514	10.9596	15.8260	8.76637	16.3301	10.1067	13.6971	12.1261	10.5131	14.0238
Output	SCI publications (counts)	166	144	161	207	227	226	321	383	445	471	495
	SCI top 10% publications (counts)	44	41	39	29	62	32	54	29	23	7	2
	EPO applications (fractional counts)	54.7	43.8	62.3	127.1	171.3	150.3	133.1	n/a	n/a	n/a	n/a
	USPTO applications (fractional counts)	150.5	199.1	297.5	396.2	491.9	416.7	387.6	n/a	n/a	n/a	n/a
	SIPO applications (fractional counts)	19.0	40.0	40.0	80.0	129.0	141.0	147.0	96.0	26.0	21.0	13.0
	Manufacturing capacity (GW)	2.03	2.33	3.28	5.24	4.74	3.80	3.54	6.70	2.46	4.62	5.90
	Installed capacity (GW)	9.18	11.64	16.88	25.24	35.16	40.27	47.08	60.21	61.29	66.15	74.74
Outcome	Export (million USD)	3.03259	71.8094	12.5282	19.9154	106.363	296.478	239.501	371.078	413.790	537.566	148.914
	Power generation (TWh)	18	26.9	34.8	55.9	74.6	95.6	121.4	142.2	169.5	183.6	192.9
	CO_2 emissions reduction (million tonnes)	13.23	19.7715	25.578	41.0865	54.831	70.266	89.229	104.517	124.583	134.946	141.782

N.B. The monetary data is converted into 2015 constant prices using yearly exchange rates.

Source: Compiled from WoS (2016), EPO and USPTO (2016), SIPO (2016), BP (2016) and BNEF (2016).

Appendix C-20 Synthesis of the U.S. inputs, outputs and outcomes (indexed value)

Indexed value: 2010=1

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D	0.63	0.57	0.76	0.77	1.81	1.00	1.02	1.04	0.85	0.76	0.59
	Asset finance	0.22	0.46	0.67	0.97	0.54	1.00	0.62	0.84	0.74	0.64	0.86
Output	SCI publications	0.73	0.64	0.71	0.92	1.00	1.00	1.42	1.69	1.97	2.08	2.19
	SCI top 10% publications	1.38	1.28	1.22	0.91	1.94	1.00	1.69	n/a	n/a	n/a	n/a
	EPO applications	0.36	0.29	0.42	0.85	1.14	1.00	0.89	n/a	n/a	n/a	n/a
	USPTO applications	0.36	0.48	0.71	0.95	1.18	1.00	0.93	n/a	n/a	n/a	n/a
	SIPO applications	0.13	0.28	0.28	0.57	0.91	1.00	1.04	n/a	n/a	n/a	n/a
	Manufacturing capacity	0.53	0.61	0.86	1.38	1.25	1.00	0.93	1.76	0.65	1.22	1.55
	Installed capacity	0.23	0.29	0.42	0.63	0.87	1.00	1.17	1.50	1.52	1.64	1.86
Outcome	Export	0.01	0.24	0.04	0.07	0.36	1.00	0.81	1.25	1.40	1.81	0.50
	Power generation	0.19	0.28	0.36	0.58	0.78	1.00	1.27	1.49	1.77	1.92	2.02
	CO_2 emissions reduction	0.19	0.28	0.36	0.58	0.78	1.00	1.27	1.49	1.77	1.92	2.02

Source: Calculated from Appendix C-19.

Appendix C-21 Synthesis of Goldwind's inputs, outputs and outcomes

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	n/a	7.866781	13.25887	30.0446	17.10882	16.1716	104.4377	108.7741	125.3023	187.0364	250.7773
Output	EPO applications (fractional counts)	0	0	0	0	0	0	1.5	n/a	n/a	n/a	n/a
	USPTO applications (fractional counts)	0	0	0	0	0	0	1.142857	n/a	n/a	n/a	n/a
	SIPO applications (fractional counts)	0	0	1	1	0	7	8	16	14	13	71
	Unit capacity (MW)	0.75	0.75	0.75	1.5	1.5	1.5	2.5	2.5	2.5	2.5	3
	Manufacturing capacity (GW)	0.132	0.416	0.83	1.132	2.727	3.74	3.789	2.609	4.112	4.593	7.84
Outcome	Revenue (billion USD)	n/a	0.135557	0.31047	0.763684	1.285111	2.272951	1.879228	1.734088	1.976889	2.865348	4.7501
	Export (GW)	0	0	0	0	0.0045	0.0045	0.189	0.08725	0.36125	0.22325	0.1145

N.B. The monetary data is converted into 2015 constant prices using yearly exchange rates.

Source: Compiled from WoS (2016), EPO and USPTO (2016), SIPO (2016), BP (2016), BNEF (2016) and Goldwind's annual reports.

Appendix C-22 Synthesis of Goldwind's inputs, outputs and outcomes (indexed value)

Indexed value: 2010=1

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	n/a	0.5	0.8	1.9	1.1	1.0	6.5	6.7	7.7	11.6	15.5
Output	EPO applications*	0.0	0.0	0.0	0.0	0.0	0.0	1.0	n/a	n/a	n/a	n/a
	USPTO applications*	0.0	0.0	0.0	0.0	0.0	0.0	1.0	n/a	n/a	n/a	n/a
	SIPO applications*	0.0	0.0	0.1	0.1	0.0	0.9	1.0	2.0	1.8	1.6	8.9
	Unit capacity	0.5	0.5	0.5	1.0	1.0	1.0	1.7	1.7	1.7	1.7	2.0
	Manufacturing capacity (GW)	0.0	0.1	0.2	0.3	0.7	1.0	1.0	0.7	1.1	1.2	2.1
Outcome	Revenue (billion USD)	n/a	0.1	0.1	0.3	0.6	1.0	0.8	0.8	0.9	1.3	2.1
	Export (GW)	0.0	0.0	0.0	0.0	1.0	1.0	42.0	19.4	80.3	49.6	25.4

N.B. * The data is indexed based on the year of 2011.

Source: Calculated from Appendix C-21.

Appendix C-23 Synthesis of Vestas' inputs, outputs and outcomes

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	75.73999	100.2999	148.8153	159.5836	117.5752	188.2627	269.1383	319.6135	321.3365	280.4331	234.2118
Output	EPO applications (fractional counts)	15	45	67.5	77	111.5	119.5	114.5	n/a	n/a	n/a	n/a
	USPTO applications (fractional counts)	3.9	12.7	15.8	8.0	16.2	26.1	43.9	n/a	n/a	n/a	n/a
	SIPO applications (fractional counts)	10	4	30	37	41	60	56	n/a	n/a	n/a	n/a
	Unit capacity (MW)	4.2	4.2	4.2	4.2	4.2	4.2	6	6	6	6	8
	Manufacturing capacity (GW)	3.186	4.239	4.503	5.581	4.766	5.842	5.213	6.02	4.893	6.253	7.3
Outcome	Revenue (billion USD)	n/a	4.139038	5.833841	8.093154	6.49088	8.685139	7.737402	9.044457	7.947237	9.097664	9.3496
	Export (GW)	n/a	n/a	3.96499	5.67002	4.49445	5.73427	5.08825	5.951	4.629	6.204	7.286

N.B. The monetary data is converted into 2015 constant prices using yearly exchange rates.

Source: Compiled from WoS (2016), EPO and USPTO (2016), SIPO (2016), BP (2016) and BNEF (2016).

Appendix C-24 Synthesis of Vestas' inputs, outputs and outcomes (indexed value)

Indexed value: 2010=1

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	0.4	0.5	0.8	0.8	0.6	1.0	1.4	1.7	1.7	1.5	1.2
Output	EPO applications*	0.1	0.4	0.6	0.7	1.0	1.0	1.0	n/a	n/a	n/a	n/a
	USPTO applications*	0.1	0.3	0.4	0.2	0.4	0.6	1.0	n/a	n/a	n/a	n/a
	SIPO applications*	0.2	0.1	0.5	0.7	0.7	1.1	1.0	n/a	n/a	n/a	n/a
	Unit capacity	1.0	1.0	1.0	1.0	1.0	1.0	1.4	1.4	1.4	1.4	1.9
	Manufacturing capacity (GW)	0.5	0.7	0.8	1.0	0.8	1.0	0.9	1.0	0.8	1.1	1.2
Outcome	Revenue (billion USD)	n/a	0.5	0.7	0.9	0.7	1.0	0.9	1.0	0.9	1.0	1.1
	Export (GW)	n/a	n/a	0.7	1.0	0.8	1.0	0.9	1.0	0.8	1.1	1.3

N.B. * The data is indexed based on the year of 2011.

Source: Calculated from Appendix C-23.

Appendix C-25 Synthesis of Siemens' inputs, outputs and outcomes

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Output	EPO applications (fractional counts)	0	19	36	58.5	65.5	155.5	187.5	n/a	n/a	n/a	n/a
	USPTO applications (fractional counts)	0.5	6.5	15.3	21.3	17.9	27.2	31.9	n/a	n/a	n/a	n/a
	SIPO applications (fractional counts)	0	0	3	22	33	35	58	n/a	n/a	n/a	n/a
	Unit capacity (MW)	2.3	2.3	2.3	3.6	3.6	3.6	6	6	6	6	7
	Manufacturing capacity (GW)	0.629	1.103	1.397	1.947	2.265	2.325	2.54	4.114	2.776	5.068	3.1
Outcome	Revenue (billion USD)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Export (GW)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

N.B. The monetary data is converted into 2015 constant prices using yearly exchange rates.

Source: Compiled from WoS (2016), EPO and USPTO (2016), SIPO (2016), BP (2016) and BNEF (2016).

Appendix C-26 Synthesis of Siemens' inputs, outputs and outcomes (indexed value)

Indexed value: 2010=1

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Output	EPO applications*	0.0	0.1	0.2	0.3	0.3	0.8	1.0	n/a	n/a	n/a	n/a
	USPTO applications*	0.0	0.2	0.5	0.7	0.6	0.9	1.0	n/a	n/a	n/a	n/a
	SIPO applications*	0.0	0.0	0.1	0.4	0.6	0.6	1.0	n/a	n/a	n/a	n/a
	Unit capacity	0.6	0.6	0.6	1.0	1.0	1.0	1.7	1.7	1.7	1.7	1.9
	Manufacturing capacity (GW)	0.3	0.5	0.6	0.9	1.0	1.0	1.1	1.8	1.2	2.3	1.4
Outcome	Revenue (billion USD)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Export (GW)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

N.B. * The data is indexed based on the year of 2011.

Source: Calculated from Appendix C-25.

Appendix C-27 Synthesis of GE’s inputs, outputs and outcomes

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Output	EPO applications (fractional counts)	45	35	48	134	146	125	96.5	n/a	n/a	n/a	n/a
	USPTO applications (fractional counts)	48.3	30.0	35.9	40.0	46.3	49.4	51.5	n/a	n/a	n/a	n/a
	SIPO applications (fractional counts)	10	27	25	58	99	113	131	n/a	n/a	n/a	n/a
	Unit capacity (MW)	3	3	3	3	3	3	3	3.6	3.6	3.75	3.75
	Manufacturing capacity (GW)	2.025	2.326	3.283	5.239	4.741	3.796	3.542	6.696	2.458	4.624	5.9
Outcome	Revenue (billion USD)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Export (GW)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

N.B. The monetary data is converted into 2015 constant prices using yearly exchange rates.

Source: Compiled from WoS (2016), EPO and USPTO (2016), SIPO (2016), BP (2016) and BNEF (2016).

Appendix C-28 Synthesis of GE’s inputs, outputs and outcomes (indexed value)

Indexed value: 2010=1

Category	Metrics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Input	R&D (million USD)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Output	EPO applications*	0.5	0.4	0.5	1.4	1.5	1.3	1.0	n/a	n/a	n/a	n/a
	USPTO applications*	0.9	0.8	0.7	0.8	0.9	1.0	1.0	n/a	n/a	n/a	n/a
	SIPO applications*	0.1	0.2	0.2	0.4	0.8	0.9	1.0	n/a	n/a	n/a	n/a
	Unit capacity	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.2	1.3	1.3
	Manufacturing capacity (GW)	0.5	0.6	0.9	1.4	1.2	1.0	0.9	1.8	0.6	1.2	1.6
Outcome	Revenue (billion USD)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Export (GW)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

N.B. * The data is indexed based on the year of 2011.

Source: Calculated from Table A3-26.

Appendix D Functional analysis

Appendix D-1 Goldwind: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
1989	0.15	licensing	Bonus	Denmark
1997	0.6	licensing	Jacobs	Germany
1999	0.6	indigenous	n/a	n/a
2001	0.75	licensing	REpower	Germany
2004	1.5	joint R&D	Vensys	Germany
2008	2.5, 3.0, 5	M&A	Vensys	Germany
2009	3	indigenous	n/a	n/a
2012	6	indigenous (prototype)	n/a	n/a

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a) and Zhang et al. (2009).

Appendix D-2 United Power: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
2007	1.5	joint R&D	Aerodyn	Germany
2011	1.5, 2	indigenous	n/a	n/a
2011	6 (offshore)	indigenous (prototype)	n/a	n/a
2013	6 (offshore)	indigenous	n/a	n/a

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a) and Zhang et al. (2009).

Appendix D-3 Sinovel: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
2005	1.5	licensing	Fuhrlander	Germany
2006	1.5	licensing	AMSC	Austria
2007	3	joint R&D	AMSC	Austria
2010	5 (offshore)	indigenous	n/a	n/a
2011	6 (offshore)	indigenous	n/a	n/a

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a) and Zhang et al. (2009).

Appendix D-4 XEMC: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
2000	0.6	indigenous	n/a	n/a
2004	1.3	indigenous	n/a	n/a
2006	2	licensing	Lagerwey BV	Netherlands
2007	2	indigenous	n/a	n/a
2009	5 (offshore)	M&A	Darwind	Netherlands
2012	5 (offshore)	indigenous	n/a	n/a

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a) and Zhang et al. (2009).

Appendix D-5 Shanghai Electric: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
2006	1.25	licensing	DeWind	Netherlands
2009	2	joint R&D	Aerodyn	Germany
2010	3.6 (offshore)	indigenous	n/a	n/a
2012	5 (offshore)	indigenous (prototype)	n/a	n/a

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a), Zhang et al. (2009) and Qi (2010).

Appendix D-6 Dongfang: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
2004	1.5	licensing	REpower	Germany
2009	1.5	indigenous	n/a	n/a
2010	2.5	licensing	AMSC	Austria
2010	3.6	indigenous	n/a	n/a
2012	5	joint R&D	ASMC	Austria

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a) and Zhang et al. (2009).

Appendix D-7 Windey: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
1972	0.018	indigenous	n/a	n/a
1997	0.2	indigenous	n/a	n/a
1999	0.25	indigenous	n/a	n/a
2003	0.75	licensing	Repower	Germany
2006	0.8	joint R&D	Repower	Germany
2008	1.5	indigenous	n/a	n/a
2011	2.5	joint R&D	Garrad Hassan	UK
2012	5 (offshore)	indigenous (prototype)	n/a	n/a
2013	2	indigenous	n/a	n/a

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a) and Zhang et al. (2009).

Appendix D-8 Mingyang: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
2006	1.5-2	licensing	Aerodyn	Germany
2009	n/a	overseas R&D centre	DTU	Denmark
2010	2.5-3	joint R&D	Aerodyn	Germany
2012	n/a	overseas R&D centre	NCUS	USA
2013	6.5 (offshore)	indigenous (prototype)	n/a	n/a
2014	6.5 (offshore)	indigenous	n/a	n/a

N.B. NCUS - North Carolina State University

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a) and Zhang et al. (2009).

Appendix D-9 Haizhuang: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
2006	0.85	licensing	Frisia	Germany
2010	2	joint R&D	Aerodyn	Germany
2011	2.5	indigenous	n/a	n/a
2012	n/a	overseas R&D centre	n/a	Denmark
2012	5	joint R&D	Mecal, KK-Electronics, Lehnhoff Consulting	Netherlands, Denmark, Germany

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a), Zhang et al. (2009) and Qi (2012).

Appendix D-10 Envision Energy: technology development trajectory

Year	Turbine size (MW)	Type	Collaborator	Collaborator's country origin
2008	n/a	indigenous	n/a	n/a
	n/a	overseas R&D centre	n/a	Germany
2010	n/a	overseas R&D centre	n/a	Denmark
	n/a	overseas R&D centre	n/a	USA
2013	4	indigenous (prototype)	n/a	n/a
2013	n/a	overseas R&D centre	n/a	USA
2013	3.6	indigenous (prototype)	n/a	n/a
2014	n/a	overseas R&D centre	n/a	USA
2015	3	joint R&D (prototype)	LM, SKF Winergy, Siemens, ABB	Denmark, Germany, Switzerland

N.B. Envision Energy has nearly 20 models range from 1.5MW to 4.0MW.

Source: Company websites, Gosens and Lu (2013b), Lema and Lema (2013), Silva and Klagge (2013), Ru et al. (2012a), Zhang et al. (2009) and (Weston 2015).

Appendix D-11 Market share of annual additions of wind turbines by manufacturers

Year	Chinese firms	Joint ventures	Foreign firms
1995	0.3	3.6	96.1
1996	0.0	0.2	99.8
1997	0.2	0.0	99.8
1998	0.3	1.0	98.8
1999	0.2	0.7	99.1
2000	0.2	2.5	97.4
2001	4.3	8.9	86.9
2002	25.5	32.8	41.7
2003	29.7	11.3	58.9
2004	20.4	32.8	46.9
2005	29.4	0.2	70.6
2006	41.3	3.7	55.1
2007	56.0	1.5	42.5
2008	73.0	7.0	20.0
2009	76.6	9.6	13.8
2010	81.4	8.6	10.0
2011	77.9	13.4	8.7
2012	92.4	0.1	7.5
2013	94.9	1.94	3.16
2014	95.1	3.2	1.66
2015	99.6	0.13	0.27

Source: Calculated from Shi (2007), CWEA (2015b) and CWEA (2016b).

Appendix E Case study

Appendix E-1 Goldwind’s R&D investment, patent filings and revenue

Type	2007	2008	2009	2010	2011	2012	2013	2014	2015
R&D expense (billion CNY)	0.13	0.25	0.17	0.21	0.78	0.7	0.78	1.14	1.56
Revenue (billion CNY)	3.1	6.46	10.74	17.6	12.84	11.32	12.31	17.7	30.01
R&D intensity (%)	4.19	3.87	1.58	1.19	6.07	6.22	6.33	6.46	5.19
R&D personnel (counts)	217	321	396	695	853	820	726	972	1377
Share of R&D personnel (%)	25.7	20.6	15.7	17.8	18.3	23.1	17.3	19.4	21.1

Source: Goldwind’s annual reports (2007-2015)

Appendix E-2 Goldwind’s R&D personnel by degrees

Type	2007	2008	2009	2010	2011	2012	2013	2014	2015
Postgraduate	122	171	225	334	493	418	476	581	854
Share of postgraduate (%)	14.5	11.0	8.9	8.6	10.6	11.8	11.3	11.6	13.1
Undergraduate	414	697	1018	1588	1870	1660	1821	2187	2832
Share of undergraduate (%)	49.1	44.8	40.3	40.6	40.1	46.7	43.5	43.7	43.4
Total	843	1557	2527	3908	4665	3558	4191	5002	6526

Source: Goldwind’s annual reports (2007-2015)

Appendix E-3 Goldwind’s SIPO patent grants by types

Type	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cumulative patent grants	10	16	25	45	61	183	290	321	551
of which invention patents	n/a	1	1	2	8	24	38	51	122
of which utility patents	n/a	14	23	41	50	n/a	n/a	n/a	n/a
of which design patents	n/a	1	1	2	3	n/a	n/a	n/a	n/a

Source: Goldwind’s annual reports (2007-2015)

Appendix E-4 Goldwind's annual additions by types of unit capacity

Unit capacity	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
600kW	n/a	48	0	0	0	0	0	0	0	0	0
750kW	n/a	396	757	737	813	240	0	0	5.25	0	0
1.2MW	1.2	1.2	1.2	0	0	0	0	0	0	0	0
1.5MW	n/a	0	24	395	1904	3488	3489	2219	2795	3822	4808
1.65MW	n/a	0	0	0	0	0	0	0	0	0	9.9
2.0MW	n/a	0	0	0	0	0	0	0	0	12	1412
2.5MW	n/a	0	0	0	2.5	8	105	300	933	600	1283
3.0MW	n/a	0	0	0	3	0	6	3	18	0	231
6.0MW	n/a	0	0	0	0	0	0	0	0	0	6

Source: CWEA (2016b) and CWEA (2015b).

Appendix E-5 Goldwind's cumulative additions by types of unit capacity

Unit capacity	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
600kW	n/a	213	213	213	213	220	220	220	220	220	220
750kW	n/a	445	1202	1939	2752	2992	2992	2992	2997	2997	2997
1.2MW	n/a	2.4	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
1.5MW	n/a	47.5	71.5	466	2370	5858	9347	11565	14360	18182	22989
1.65MW	n/a	0	0	0	0	0	0	0	0	0	9.9
2.0MW	n/a	0	0	0	0	0	0	0	0	12	1424
2.5MW	n/a	0	0	0	2.5	10	115	415	1348	1948	3230
3.0MW	n/a	0	0	0	3	3	9	12	30	30	261
6.0MW	n/a	0	0	0	0	0	0	0	0	0	6

Source: CWEA (2016b) and CWEA (2015b).

Appendix F Wind power policies

Appendix F-1 Time of China’s major wind power policies

Year	Title
1994	Regulation on Grid Connection and Management of Wind Farms
1995	Double Increase Programme
1996	The 9th Five-Year Plan for New and Renewable Energy Development
1997	Ride the Wind
1998	Further Modifications to Import Duties on Wind Turbine Components
1999	Notice on Next Steps in Developing Renewable Energy
2000	National Debt Wind Power Programme
2001	The 10th Five-Year Plan for New and Renewable Energy Industry
2001	Reduced Value Added Tax for Renewable Energy
2003	Wind Power Concession Programme
2003	Preferential Tax Policies for Renewable Energy
2005	Measures for Operation and Management of Clean Development Mechanism Projects
2005	Notice on the Requirements for the Administration of the Construction of Wind Farms
2005	Renewable Energy Law
2006	The 11th Five-year Plan for Renewable Energy Development
2006	Renewable Energy Price and Cost-Sharing Management
2006	Renewable Electricity Surcharge
2007	Special Fund for the Industrialization of Wind Power Equipment
2007	Medium and Long-Term Development Plan for Renewable Energy
2007	National Climate Change Program
2008	International S&T Cooperation Programme for New and Renewable Energy
2008	The 11th Five-Year Plan for Renewable Energy
2008	Interim Measures for the Administration of Special Funds for Wind Power Equipment
2009	Offshore Wind Development Plan
2009	Renewable Energy Law (Amendments)
2009	Onshore Wind Feed-in Tariff
2009	Notice of the Removal of Local Content Requirement on Wind Power Equipment
2009	Improved Wind Power Pricing Policy
2010	Import Duty Removal on The Wind and Hydro Technological Equipment
2010	Market Entry Standards for Wind Equipment Manufacturing Industry
2010	Interim Measure on the Management of Offshore Wind Farms
2012	The 12th Five-Year Plan for Renewable Energy
2012	The Special Plan for Wind Power Science and Technology Development
2012	Renewable Power Quota Management (Draft)
2012	The 12th Five-Year Plan for Renewable Energy

2012	Interim Measures on Renewable Energy Development Fund Imposition and Management
2012	The 12th Five-Year Plan for National Strategic Emerging Industries
2012	Renewable Energy Electricity Feed-in Tariff
2012	The Renewable Energy Tariff Surcharge and Grant Funds Management Approach
2012	The Notice on New Energy Demonstration City and Industrial Park
2012	China Energy White Paper
2013	The Notice on Integrating and Accommodating Wind Power
2013	Notice on the Improvement of the Grid Connection and Assimilation of Wind Power
2013	Renewable Electricity Generation Bonus
2013	Adjustment of Renewable Electricity Surcharge
2014	Notice on Offshore Wind Power Price Policy
2014	The Offshore Wind Power Development Plan
2014	The Initiative to Create New Energy Demonstration Cities
2014	Notice on Regulating the Standardisation of Wind Power Equipment
2015	Interim Measures on Renewable Energy Development Funds
2015	Guidance to Promoting New Energy Micro-Grid Demonstration Project
2015	Guidance to Improving Power Operation and Facilitating Clean Energy Development
2015	Notice on Pilot Programmes for Locally Consumed Renewable Energy Power

N.B. The state S&T programmes for wind technology were excluded.

Source: IEA and IRENA (2016), Dai and Xue (2015), Surana and Anadon (2015b) and Gosens and Lu (2013b).

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