Environmental Implications and Institutional Challenges of China's Wind Power Development: Integrating Input-output Analysis and Life Cycle Analysis

Xin Li

Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

The University of Leeds
Sustainability Research Institute
School of Earth and Environment

August, 2012

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Publication related to this thesis

Chapter 4 is based on work from

LI, X., HUBACEK, K. & SIU, Y. L. 2012. Wind power in China – Dream or reality? *Energy,* 37, 51-60.

I am the lead author of this paper. The content of this paper draws from my own literature review and analysis. In writing this paper, I received directions and comments from Hubacek, K. and Siu, Y.L.

Chapter 5 is based on work from

LI, X., FENG, K., SIU, Y. L. & HUBACEK, K. 2012. Energy-water nexus of wind power in China: The balancing act between CO_2 emissions and water consumption. *Energy Policy,* 45**,** 440-448.

I am the lead author of this paper. The content of this paper draws from my own calculation and analysis. Feng, K. provided data and initial model code for this research. In writing this paper, I received directions and comments from Siu, Y.L. and Hubacek, K..

Chapter 6 is based on work from

LI, X., FENG, K., SIU, Y.L. & HUBACEK, K. (under review), Challenges faced when energy meets water: CO_2 and water implications of power generation in the northern regions of China. Submitted to *Renewable and Sustainable Energy Reviews*

I am the lead author of this paper. The content of this paper draws from my own calculation and analysis. Feng, K. provided data and initial model code of this research. In writing this paper, I received directions and comments from Siu, Y.L., and Hubacek, K..

Acknowledgements

This thesis would not have been possible without support and assistance from a number of people. I would like to express my gratitude:

To my supervisor Dr. Yim Ling Siu and Professor Klaus Hubacek who have been very supportive and patient from the first day that I started my PhD. Without you, I might have dropped out after the first twelve months of my PhD. Thank you for allowing me to benefit from your knowledge, providing directions of this thesis and encouraging me throughout the entire process.

To my research support group member Dr. Tim Foxon who offered valuable suggestions which helped to shape the papers.

To Dr. Kuishuang Feng who provided data and comments on the papers. Thank you and your wife Dr. Yang Yu for being such great host during the time I visited the United States.

To my colleagues from Sustainability Research Institute and School of Earth and Environment for your help and friendship.

To my uncle Li Zhenwei and aunt Wen Lixia for your encouragement and support throughout my education.

To my father Li Zhenyu and mother Feng Guorong for your love and support in my life.

And finally, to Chen YY for your love and encouragement.

Abstract

Wind power in China has been experiencing substantial growths in the past decade. Accumulated generation capacity increased from 381.2 MW in 2001 to 62,364.2 MW in 2011, which could increase to 200 GW and 1,000 GW by 2020 and 2050, respectively. Despite the considerable growth in generation capacity and promises of a bright future, issues such as the power grid infrastructure and back-up systems, and life cycle environmental impacts of wind power development in China are largely overlooked. This thesis aims to investigate the capability of power grid infrastructure, the feasibility of back-up systems and the carbon dioxide and water implications of wind power in China. The research shows that (in Chapter 4) China's power grid infrastructure is not capable of absorbing and transmitting wind-powered outputs. In addition, back-up systems are either geographically unavailable or financially infeasible. An analysis use the input-output based hybrid life cycle analysis to estimate the CO_2 emissions and water consumption of wind power in China (in Chapter 5). The results show that China's wind energy consumes 0.64 litre/kWh of water and produces 69.9 grams/kWh of CO_2 emission, which could contribute a 23% reduction in carbon intensity and could save 800 million m^3 of water in China by 2020. A further analysis based on the integrated hybrid life cycle analysis to evaluate and compare the CO_2 emissions and water impacts of coal-fired power, wind power and solar power generation in Inner Mongolia, China. This chapter shows that substantial reductions in CO_2 emissions and water consumption can be attained if the existing coal-dominated power generation were substituted by wind power. This research concludes that China's wind power would face significant barriers due to insufficient grid infrastructure and infeasible back-up systems that are mainly resulted from institutional challenges. Nevertheless, wind power could help China to save carbon emissions and water consumption at both national and regional level.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AC – Alternating Current

AIS – Accelerated Improvement Scenario

AWPC – Asia Water Project China

BP – British Petroleum

CAE – the China Academy of Engineering

CCChina – Climate Change China organization

CCGT – Combined Cycle Gas Turbine

CCS – Carbon Capture and Storage

CDM – Clean Development Mechanism

CEC – China Electricity Council

CEG – China Electricity Group

CEPY – China Electric Power Yearbook

CHP – Combined Heat and Power

CIG – Continued Improved Scenario

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

COD – Chemical Oxygen Demand

CSG – China Southern Grid

CSP – Concentrated Solar Power

CT – Cooling Tower

CWEA – China Wind Energy Association

DC – Direct Current

EIA – Energy Information Administration

EIT – Economies-in-transition

GAQSIQ – the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China

GDP – Gross Domestic Product

GHG – Greenhouse Gas

GVA – gross value added

GW – Gigawatt

GWEC – Global Wind Energy Council

GWh – Gigawatt hour

g/kWh – gram per Kilowatt hour

HVDC – High Voltage Direct Current

Hz - Hertz

IEA – International Energy Agency

IGCC – Integrated Gasification Combined Cycle

IHLCA – Integrated Hybrid LCA

IMARBS – Inner Mongolia Autonomous Region Bureau of Statistics

IMDRC – Inner Mongolia Development and Reform Commission

IMEB – Inner Mongolia Energy Bureau

IMG – Inner Mongolia Government

IMMWR – Inner Mongolia Ministry of Water Resources

IMQSIP – Inner Mongolia Quality Supervision Inspection and Quarantine

IO – Input-Output

IPCC – Intergovernmental Panel on Climate Change

JSDRC – Jiangsu Development Reform Commission

km – kilometre

kV – kilovolt

kW – kilowatt

kWh – kilowatt hour

LCA – Life Cycle Analysis

LCI – Life Cycle Inventory

l/kWh – litre per kilowatt hour

m^3 – cubic metre

MMBtu – Million British thermal unit

MOP – Ministry of Power

MOST – Ministry of Science and Technology

MT – Million Tonnes

Mtce – Million Tonnes of coal equivalent

MW – Megawatt

MWh – Megawatt hour

MWR – the Ministry of Water Resources

NBS – National Bureau of Statistics

NDRC – National Development Reform Commission

NGCC – Natural Gas Combined Cycle

NO_x – Nitrogen Oxides

OECD – Organisation for Economic Cooperation and Development

PC – Pulverized Coal

PRO-LCA – Process-based life cycle analysis

PV – Photovoltaic

RET – Renewable Energy Technologies

RME – Rape Methyl Ester

SCORES – State Council Office for Restructuring the Economic System

SDPC – the State Development Planning Commission

SERC – State Electricity Regulatory Commission

SETC – State Economic and Trade Commission of China

SGCC – State Grid Corporation of China

SO_2 – Sulphur Dioxide

TWh – Terawatt hour

UHV – Ultra-high Voltage

UK – the United Kingdom

US – the United States of America

USDoE – United States Department of Energy

WNA – World Nuclear Association

Chapter 1 Introduction

The Chinese economy has achieved impressive annual increases in gross domestic product (GDP) per capita during the past three decades due to the open door policy implemented by Xiaoping Deng in the late 1970s. GDP per capita increased from 175.1 US dollars in 1978 to 2,634.7 US dollars in 2011[1] (WorldBank, 2012). China is now the second largest economy in the world following the United States. The impressive economic growth has resulted in considerable increases in energy demand. In 2009, China overtook the U.S. to become the largest energy consumer around the globe (IEA, 2010b). With over 70% of its energy generated by coal, China has been the largest Carbon Dioxide (CO_2) emitter since 2007 (BP, 2011). The United Nations Framework for Convention on Climate Change (UNFCCC) states the significance of mitigating greenhouse gas (GHG) emissions, the majority of which are energy-related CO_2 emissions, in order to avoid extreme weather conditions (UN, 1992). As the largest CO_2 emitter, China's contribution to CO_2 emission reduction would be vital to meet the target of limiting the global temperature rise to 2^{o}C. In addition, China's water resources are scarce and unevenly distributed. Water availability per capita in China is only one fourth of the world average (Hubacek and Sun, 2007). Over 300 million people in China do not have access to safe drinking water (Gleick, 2009). According to the Ministry of Water Resource (2012), in 2010, six northern watersheds, including Songhua River, Liao River, Hai River, Huai River, Yellow River and northwest inland rivers, accounted for 19.6 % of China's total water availability, but these regions accounted for 46.1% of the total population and 60.5% of total farmland in China. Furthermore, China is suffering from severe water pollution. 38.6% of rivers and 41.1% of lakes in China are only suitable for agriculture purposes. China's water crisis could threaten the growth of the Chinese economy (Xie et al., 2009). According to

---

[1] Figures are in constant 2000 US dollars.

the World Bank (2007), economic costs of China's water scarcity and water pollution are equivalent to about 2.3% of GDP in 2003.

Power generation, which accounted for over 40% of total primary energy consumption, contributes to a significant proportion of CO_2 emissions and water consumption in China (CEC, 2012a). According to Climate Change China (2011a), 37.2% of the total CO_2 emissions in China were from coal-fired power plants in 2011. Besides, water consumption of coal-fired power generation accounted for 20% of the total freshwater consumption in China by the end of 2010 (Orszag, 2011). Hence, finding carbon and water savings to the current coal-fired power system would have a dual benefit to China.

Wind power is considered as one of the most promising renewable energy technologies to China's future power generation system (CEC, 2012a). Coupling with significant wind power potentials, China's wind power reached 62,364 MW in 2011, which surpassed all the other countries around the globe (CWEA, 2012b). The National Development and Reform Commission (NDRC) together with the International Energy Agency (IEA) have proposed a wind energy roadmap in China until 2050 (IEA/NDRC, 2011). It is projected that wind power generation capacity could reach 200 GW, 400 GW and 1,000 GW by 2020, 2030 and 2050, respectively.

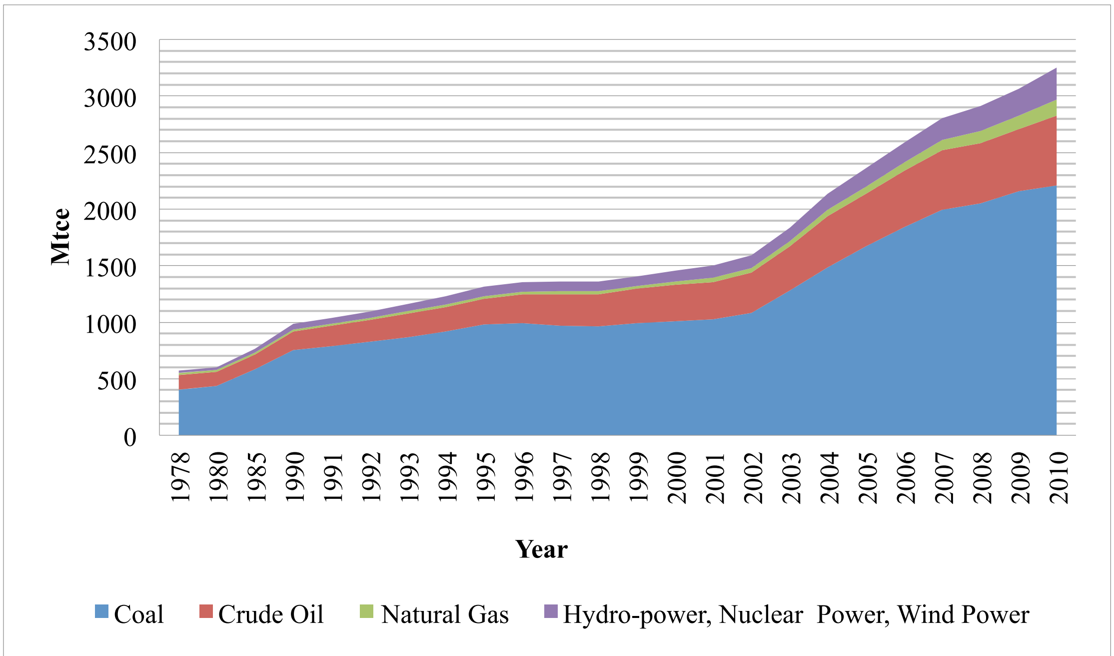
Despite its rapid recent growth and a promising future, wind power development in China has encountered a number of issues which have not been well-examined, including the availability of power grid infrastructure and the feasibility of back-up systems, and implications to CO_2 emissions and water stress (both quantity and quality). The goal of this thesis is to fill the above research gaps in the existing literature.

This chapter starts with a general background of China's energy system, including the growth of energy demand, the challenges of the existing energy systems, and the viable means to tackle these challenges. It is followed by a detailed account of China's wind power development in terms of its generation capacity and potential future growth. The research aim and objectives of this thesis are elaborated in addition to the overall structure of this thesis.

1.1 Energy in China: finding a balance between soaring demand and adverse consequences

China's energy demand increased from 571.4 million tonnes of coal equivalent (Mtce) in 1978 to 3249.4 Mtce in 2010 (NBS, 2011). Due to the relative abundance in coal reserves, the Chinese energy system has been dominated by coal. Other fossil fuels such as oil and natural gas also make up a significant proportion in energy consumption. Figure 1.1 depicts the composition and growth of energy demand in China between 1978 and 2010.

Figure 1.1 The composition and growth of energy demand in China between 1978 and 2010 (in million tonnes of coal equivalent)



Source: NBS (2011)

An increasing dependence on the use of fossil fuels has induced a few social, economic and environmental problems within and beyond the Chinese territory. Domestically, air pollution, caused by coal combustion, is one of the major environmental concerns in China (Zhang et al., 2010). With around one quarter of the Chinese territory affected by acid rain, mainly caused by coal power generation, China has been suffering from the most severe soil acidification around the globe (Liu and Diamond, 2005). The overdependence on fossil fuels also raises concerns for China's energy security. For instance, since over 50% of oil consumption relies on import, China is vulnerable to the volatile oil price, which could slow down economic growth and cause a higher inflation rate (Du et al., 2010). Internationally, China has been the largest CO_2 emitter. China's responsibility on global CO_2 emission reduction has been widely discussed (Zeng et al., 2008, Li and Richard, 2011). Besides, China's soaring demand of oil has been considered as one of the contributing factors to the rising price of crude oil (Skeer and Wang, 2007).

To ease the adverse consequence of the overdependence on fossil fuels, the Chinese government has committed to optimizing its energy system during the past few years. Two aspects are frequently addressed in Chinese government policies, namely energy efficiency improvement and energy structure diversification. For instance, the Eleventh Five Year Plan[2] (between 2006 and 2010) stated a target of energy efficiency improvement of 20% by 2010 compared to the 2005 baseline (Xinhua, 2005). In 2006, the first Renewable Energy Law was promulgated to legitimate and stimulate the development of renewable energy technology. The national strategy to climate change mitigation and adaptation was published in 2008 and revised in 2009 by the National Development Reform Commission (NDRC). The

---

[2] The Five-Year Plan is the strategic planning of five consecutive years of the economic development in China. For example, the Eighth Five-Year Plan is from 1991 to 1995, the Ninth Five-Year Plan is from 1996 to 2000 and the Tenth Five -Year Plan is from 2001 to 2005, and so on and so forth.

strategy elaborated the targets and strategies to combat climate change and advocated the diversification of energy structure and improvement of energy efficiency in the future energy plan (NDRC, 2009). In 2009, the target of reducing the CO_2 emissions by 40-45% per unit of GDP in 2020 compared with the 2005 baseline was delivered by President Hu Jintao (Qiu, 2009). In addition, energy efficiency standards on lighting, building construction and house appliances have either been imposed or are being drafted by the Chinese government (Bradsher, 2010).

As stated by the International Energy Agency (IEA) Chief Economist, Fatih Birol, it is not possible to avoid the extreme consequences of climate change until China meets its target on improving energy efficiency (Bradsher, 2010). However, a number of studies argued that the changing of lifestyles and the growing of urbanization in China is likely to cancel out the energy savings from efficiency improvement (Peters et al., 2007, Hubacek et al., 2007, Guan et al., 2008). It has been widely recognized that the diversification of the energy system with more low carbon technologies such as wind power, solar power and biomass would be fundamental to the energy system optimization in China (Zhou et al., 2011, Li et al., 2010, Pan, 2010).

1.2 Wind power in China: prosperity versus challenge

Over the last decade, wind power and hydropower have outpaced most of the other renewable energy sources in terms of capacity growth in China. Since the promulgation of the Renewable Energy Law in 2006, cumulative installed capacity of wind power had been almost doubled every year until 2010. Total wind power generation capacity increased from 381.2 MW in 2001 to 62,364.2 MW in 2011. China now has the largest wind power generation capacity around the globe. Besides, the annual growth of wind power generation capacity is substantial. For instance, newly installed capacity in 2011 amounted to 17.6 GW, which accounted for 40% of new windmills globally (CWEA, 2012b). A number of studies have been conducted to estimate the wind power potentials in China over the past years. According to He et al. (2008), the exploitable wind energy potential is 600 – 1,000 GW onshore and 100 – 200 GW offshore. Without considering the limitations of wind energy such as variable power outputs and seasonal variations, McElroy et al. (2009) concluded that if the Chinese government committed to an aggressive low carbon energy future, wind power would be able to generate 6.96 million Gigawatt hour (GWh) of electricity by 2030, which would be sufficient to satisfy China's electricity demand in 2030.

Despite great hope, many studies have raised concerns about the Chinese government policies of increasing power generation from wind and developing domestic wind power manufacturing industry. A critical review of the concerns raised by these studies is given in Chapter 2. In addition to the concerns, there are a number of research areas/issues that are either underexplored or have not been fully addressed by the existing literature. For example, there are limited studies which assess the capability of grid infrastructure and the availability of back-up systems in China which are critical to the development of wind power. Besides, the extent to which the substitution of coal-fired power by wind power could contribute to the CO_2 emission reduction is still unknown at both national and regional level in China. Last but not least, although power generation represents the second largest water usage among all economic sectors, (life-cycle) water use in power generation is largely ignored in most studies. One may wonder if the substitution of coal-fired power plants with wind power could possibly help to reduce water consumption.

1.3 Research aim and objectives

This thesis aims to examine the environmental implications and institutional challenges of China's wind power development, specifically focused on CO_2 emissions and water stress (both in quantity and quality). To fulfil this aim, this thesis needs to

- Objective 1: examine challenges of wind power development in China in terms of grid infrastructure and back-up systems and suggest possible solutions.

Despite the substantial growth in wind power generation capacity, a significant proportion of wind-powered outputs were curtailed in China (I introduce the curtailments in detail in Chapter 2). The curtailments imply challenges of insufficient grid infrastructure and lack of flexible power generation units. Only a couple of studies touched on the challenges of grid infrastructure in the integration of wind power in China, such as Wang (2010) and Liao et al. (2010). However, both studies failed to elaborate the challenges in detail. Furthermore, wind power is not a stand-alone energy source; it needs to be complemented by other energy sources when wind does not blow. Although the viability and feasibility of the combination of wind power with other power generation technologies have been discussed widely in other countries, none of the studies reviewed the situation in the Chinese context. Thus, there is a need to further investigate these issues since they are critical to the development of wind power in China.

- Objective 2: compare the economy-wide emissions and water consumption of wind power with other power generation technologies at national level in order to understand the environmental benefits as well as the repercussions (see Chapter 5).

At the end of 2010, China's contribution to global CO_2 emissions reached 25.1%. Power generation accounted for 37.2% of CO_2 emissions and 20% of water consumption in China. Even though there is an increasing number of studies using life cycle analysis (LCA) to examine CO_2 emissions required by different types of power generation technologies, there are very few studies focusing on China. Furthermore, the nexus between water consumption and energy production has largely been ignored. As one of the most promising low carbon energy sources in the future energy system, China's wind power needs to be examined in terms of CO_2 emissions and water consumption.

- Objective 3: estimate the life cycle CO_2 emissions and water quantity-quality of wind power and compare to other power generation technologies such as pulverized coal and solar PV at regional level in China (see Chapter 6).

Nation-wide energy-water nexus analysis might be too coarse to reflect the water conditions at regional level, especially in China which has large territorial coverage and uneven water distribution. The contributions of wind power to CO_2 emission reduction and water consumption reduction are not known at regional level. Of all the regions in China, Inner Mongolia is selected because 1) the growth of energy intensive industries, such as coal mining and processing, raw chemical materials and products and nonferrous smelting and processing, has stimulated power demand in Inner Mongolia (IMARBS, 2010). At the end of 2010, Inner Mongolia had the third largest power generation capacity (64.6 GW) of all regions in China with coal contributing 92.6% of total power generation (SERC, 2011a); 2) As of 2011, Inner Mongolia has the largest wind power generation capacity in China (17.6 GW), which is estimated to increase to 31.2 GW by 2015 and 58.1 GW by 2020 (Li et al., 2010); 3) Inner Mongolia has one of the largest solar power potentials in China (Calvin, 2010). Since the Chinese government has committed to promoting renewable energy sources (NDRC, 2007b), the percentage share of renewable energy to total energy supply will be considerable in the future. In particular, the region like Inner Mongolia has a large potential for renewable energy sources. Furthermore, the focus of existing studies is largely on the amount of water needed during the life-cycle phases of power generation (Cooper and Sehlke, 2012, Chandel et al., 2011, Cooley et al., 2011). To the best of my knowledge, no study has addressed the problem of water quality impacts of electricity production.

1.4 The structure of this thesis

This thesis is structured as follows:

Chapter 2 provides a critical review of China's wind power development at both national and regional level, in terms of the power generation system, and the total generation capacity of wind power and its potential future growth.

Chapter 3 looks at the research methods: input-output analysis and life cycle analysis, and gives justifications for the chosen models for use in this thesis (i.e. input-output analysis based hybrid life cycle analysis and integrated hybrid life cycle analysis). Also, rationales of the chosen environmental indicators, namely CO_2 emissions, water consumption and water quality impacts, adopted in this thesis are given too.

Chapter 4 gives a critical assessment of two major barriers (i.e. the availability of power grid infrastructure and the feasibility of back-up systems) which are largely overlooked or have not been fully addressed by the existing literature.

Chapter 5 focuses on applying the input-output based hybrid life cycle analysis to evaluate CO_2 emissions and water consumption of wind power in China. A new wind power sector is created by disaggregating the existing electricity sector using the national input-output tables of China.

Chapter 6 applies the integrated hybrid life cycle analysis to examine and compare the life cycle CO_2 emissions and water impacts of coal-fired power, wind power and solar power generation in Inner Mongolia in China as a detailed case study.

Chapter 7 provides a summary of the significant research findings and contributions of the current research, including implications and recommendation of the current and future energy plans in China. Discussions on the extent to which the stated research aim and objectives are met by the current research, research limitations and the future research agenda are also given in this chapter.

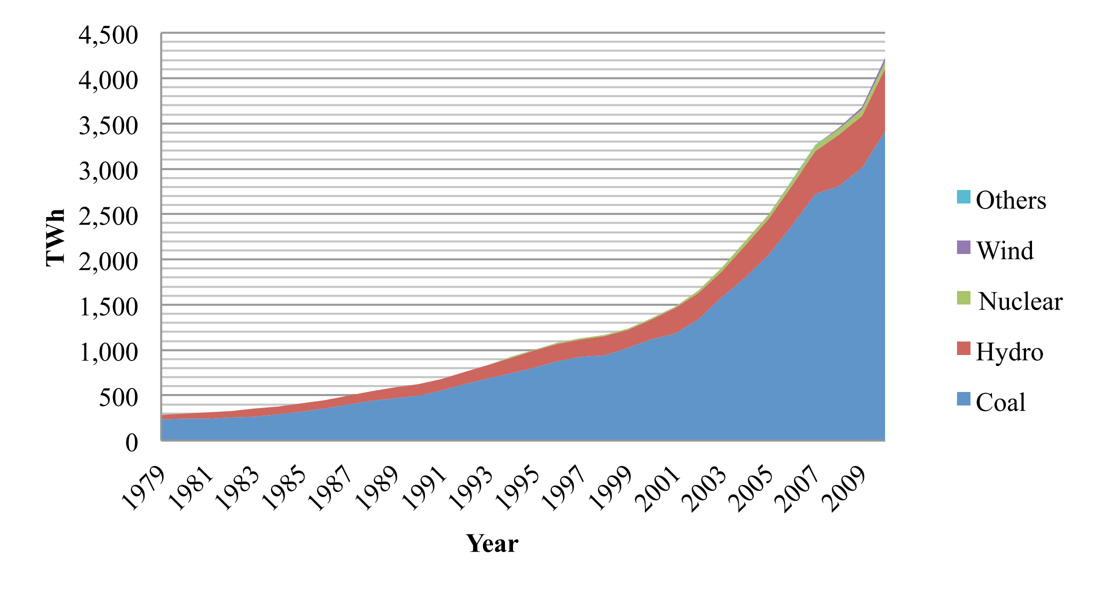
Chapter 2 A critical review on China’s wind power development

While the majority of studies on China’s wind power focus on the favourable government policies that promote the growth of power generation capacity, some studies centre on the wind power potentials and the development of domestic wind turbine manufacturing industries. The aim of this chapter is to provide a critical review on wind power development in China based on the existing literature. It starts with an overview of China’s power generation system in terms of generation capacity growth, power mix and future energy projections. It is followed by an introduction of the potentials of China’s wind power. Then a portrait of the development of China’s wind power at both national and regional level is presented, starting from the early 1990s up to the present. The development of domestic wind turbine manufacturing is also discussed. This chapter ends by introducing the barriers of wind power development in China.

2.1 An overview of power generation in China

China’s electricity generation has been increasing from 282 Terawatt hours (TWh) in 1979 to 4,227.8 TWh in 2010 (CEG, 2007, SERC, 2011a). Coal represents approximately 80% of total power generation in China and 13.3% of the world's total proven coal reserves (BP, 2011). Hydropower is the second largest power generation source, which is followed by nuclear power, wind power, and other energy sources. Figure 2.1 depicts China’s electricity generation by source between 1979 and 2010.

Figure 2.1 China's electricity generation by source from 1979 to 2010



Source: 1979 – 2006 data are from China Energy Databook Version 7.0 (CEG, 2007); 2007 – 2009 data are from the China Electric Power Yearbook (CEPY, 2008, CEPY, 2009, CEPY, 2010); 2010 data are from State Electricity Regulatory Commission (SERC, 2011a).

Due to the overdependence on coal, China's electricity generation accounted for 9.3% of the global CO_2 emissions and 37.2% of the domestic CO_2 emissions in 2010 (CCChina, 2011b). In recent years, the ever growing concerns on climate change and energy-related environmental repercussions have induced wide-range discussions on the transition to a low carbon electricity system in China (Chen et al., 2011, Kahrl et al., 2011, Wang and Watson, 2010, Zhang, 2010). Correspondingly, energy development strategies regarding nuclear power, wind power and other low emission power generation technologies have been introduced and implemented by the Chinese government such as the Mid-Long Term Nuclear Power Development Plan (NDRC, 2007a) and the Mid-Long Term Renewable Energy Development Plan (NDRC, 2007b). Although the percentage of total power generation from nuclear power and wind power is minor, a significant growth trend is noticeable in recent years. For example, wind power generation increased from 2.84 TWh in 2006 to 49.4 TWh in

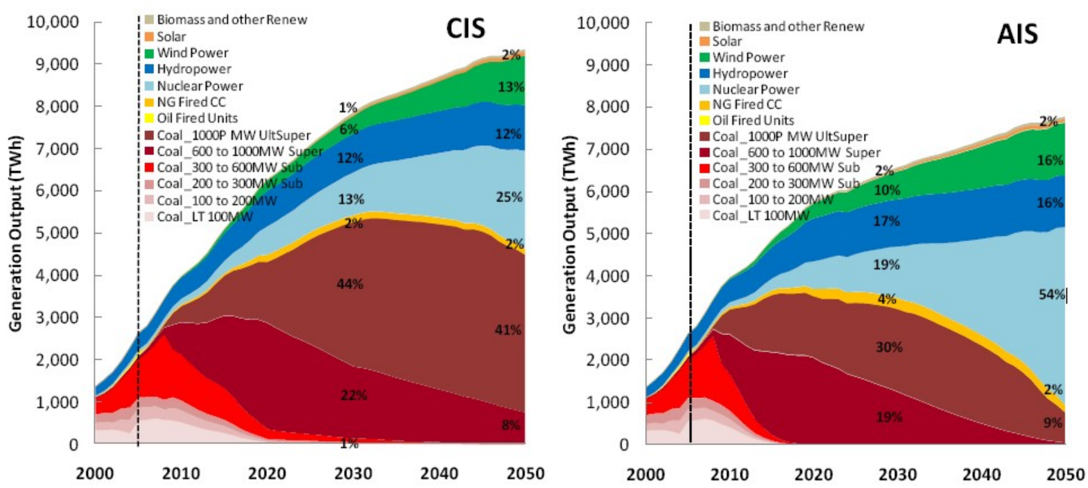
2010. In August 2011, 26 nuclear reactors (out of 60 reactors globally) have been built in China, according to the World Nuclear Association (WNA, 2011).

2.1.1 China's energy mix outlook

China's power generation growth will continue at a rapid speed. According to Dai et al. (2009), based on the 2008 level, China's total electricity demand will increase by 78% and 145%, in 2020 and 2030, respectively.

Zhou et al. (2011) provided projections for China's electricity generation by source up to 2050 based on two scenarios: a baseline scenario (also known as continued improved scenario, CIS) and an accelerated improvement scenario (AIS). Figure 2.2 gives a summary of Zhou's projections.

Figure 2.2 The baseline (CIS) and accelerated improvement (AIS) scenario projections for China's electricity generation by source from 2000 to 2050



Source: Zhou et al. (2011) page 5

The differences between CIS and AIS projection are significant in terms of total electricity generation and electricity mix. As a result of end-use energy efficiency improvements, total electricity generation substantially declines from approximately 9,000 TWh in CIS to 7,800 TWh in AIS. Radical changes to the share of coal power generation (from about 50% in CIS to 9% in AIS) and the share of nuclear power generation (from 25% in CIS to 54% in AIS) are also noticeable in AIS. However, the AIS projection of China's electricity mix may not be reliable as the construction of coal power plants has not experienced a significant decline in recent years. In fact, approximately 900 MW of coal-fired power generation units are installed in China every week (EIA, 2011). Considering that lifespan of coal-fired power plants is usually more than 40 years, such radical changes are not appropriate without aggressive government policy on carbon emissions restriction. In addition, the provision of 54% of total electricity demand would require more than 500 GW of nuclear capacity[3] by 2050. With less than 1% of the global uranium reserve distributed in China (Zhou and Zhang, 2010), the over-dependence on nuclear power would compromise the national energy security, which is inconsistent with the principle of safeguarding energy security in the Mid-Long Term Development Plan for Nuclear Power (NDRC, 2007a).

A number of studies have discussed the potentials of CO_2 emission mitigation in China. For example, Zhang et al. (2012) adopted a superstructure optimal planning model to compare three carbon mitigation scenario projections under the assumption that the future power generation mix will be influenced by factors such as fuel price, power demand, carbon mitigation policy, energy efficiency of power generation technologies, etc. Zhang et al. concluded that the existing coal-dominated power generation system has significant potentials in reducing China's total CO_2 emissions. Focusing on greenhouse gas (GHG) emissions, Ou et al. (2011) quantified

---

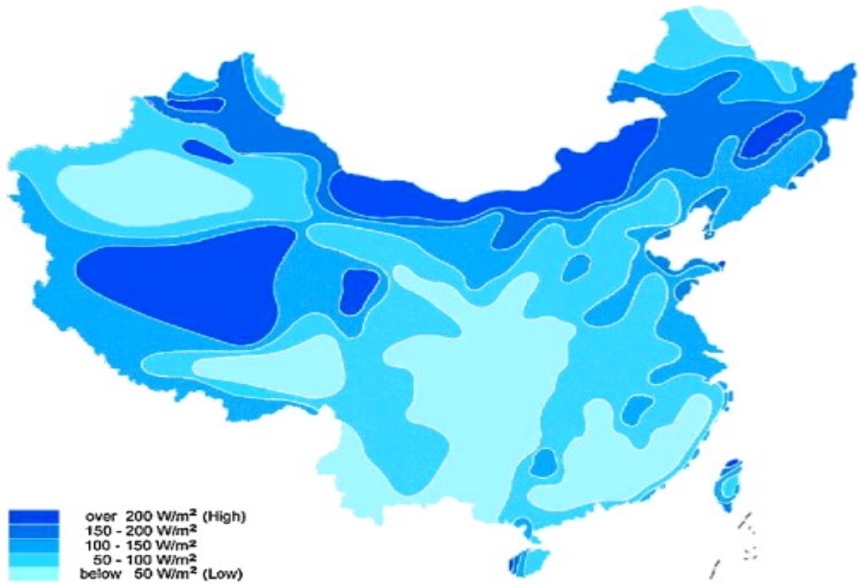
[3] Total electricity generation is about 7,500 TWh in AIS. The average operating hours of nuclear power plant are 7,793 in 2007 according to China Electric Power Yearbook (2008).

the mitigation potentials due to the applications of carbon-neutral technologies in the coming decade. Their study showed that GHG emissions of China's power generation are 297.7 g/MJ (or 1071.7 g/kWh). The diversification of electricity mix through replacing fossil fuels by renewable energy and nuclear power can reduce the GHG emissions to 220.5 g/MJ (or 793.7 g/kWh) in 2020. A further reduction to 169.1 g/MJ (or 608.5 g/kWh) can be achieved by introducing carbon capture and storage (CCS) technology.

2.2 Wind power potentials and future growth

There are many factors driving wind power development in China. One of them is the significant potential of China's wind energy sources. According to the China Meteorological Administration, exploitable onshore wind energy (at the height of 50 metres) amounts to 2,380 GW. Effective wind density in these regions is between 200 and 300 Watt/m^2. The effective working hours for wind turbine are between 5,000 hours to 7,000 hours. Onshore wind resources are unevenly distributed and concentrated in the northeast and northwest regions of China (Zhao et al., 2009). For example, Inner Mongolia Autonomous Region (northern China) accounts for about 60% of the total onshore wind potentials with the remaining potential in the other inland areas such as the southwest and northwest (Southern part of Xinjiang and northern part of Tibet). Although China's offshore wind power has very limited potential (amounted to 200 GW), the wind farms are closer to the demand centres (i.e. cities on the coastal area of China). McElroy et al. (2009) estimated the potentials with a hypothetical 1.5 MW wind turbine and concluded that wind generated electricity could reach 24.7 trillion kWh annually, which is seven times the current national electricity consumption in China. Figure 2.3 describes the wind energy potential in China.

Figure 2.3 The wind power potentials in China



Source: Li et al., (2007)

Wind power is expected to play an important role in the future power mix in China. A number of studies have provided projections for the future deployment of wind turbines in China. For example, Fang (2007) projected the wind power capacity would reach 128 GW according to provincial wind power development plans. Li et al. (2008) estimated that, with a conservative growth rate of 20% annually, 100 GW wind power will be installed by the end of 2020, which means that wind power will represent approximately 8.5% of electricity generation capacity and will account for 4% of total electricity supply. In 2011, The National Development and Reform Commission (NDRC) together with the International Energy Agency (IEA) have proposed a wind energy roadmap in China until 2050 (IEA/NDRC, 2011). The projected wind power generation capacity and the corresponding electricity generation are depicted in Table 2.1.

Table 2.1 Targeted installed capacity, electricity generation and share of total electricity generation of wind power in China, 2020 - 2050

Year	Generation capacity (GW)	Electricity generation (TWh)	Share of total electricity generation (%)
2020	200	400	5
2030	400	840	8.4
2050	1000	2200	17

Source: IEA/NDRC (2011)

2.3 Wind power development in China: a national perspective

Wind power outpaced all other renewable energy sources in terms of generation capacity in China, except for hydropower. This section gives a detailed discussion on three main stages of development of China's wind power, according to the growth of generation capacity. The three stages of development are pre-2000s, from 2000 to 2005, and from 2006 until the present.

2.3.1 Pre-2000s: the early stages

Since the late 1980s, China has started to invest in grid-connected wind power projects. At the early stage, development of wind power industry depended on financial loans from foreign countries. There were no domestic manufacturers; thus, all of the wind turbines were imported. In addition, the electricity price for wind power was very low. For example, electricity price for Dabancheng wind farm in Inner Mongolia was less than 0.3 Yuan/kWh, which was almost the same as coal generated electricity (Li and Gao, 2007).

Since China participated in the negotiations of a couple of international treaties, including the Montreal Protocol on Substances that Deplete the Ozone Layer and the Kyoto Protocol in the 1990s, it raised the public's concerns on the environmental repercussions associated with fossil-fuel combustion, promoted the interests on renewable energy sources from the decision-makers, and provided a basis for the renewable energy system in China (Lema and Ruby, 2007). In 1994, the Ministry of Power (MOP) promulgated the *Provisions for On-Grid Wind Farm Management*. It stipulated the responsibilities of grid companies such as coordinate the integration of wind power plant to the nearest power grid and introduce a fixed tariff for wind electricity (which is calculated by a combination of the generation cost, the interest payment and a reasonable profit of 15%). A report presented by the combination of the Ministry of Science and Technology (MOST), The State Development Planning Commission (SDPC) and The State Economic and Trade Commission (SETC)[4] stated that

'There is no doubt that this policy was enormously helpful in promoting the development of wind power in China... the effective collapse of this policy is one of the main reasons for the slower pace of development in the wind power industry over the last couple of years.'

- MOST/SDPC/SETC (2002), page 21.

In addition, the Chinese government has enacted a number of regulations and policies in the 1990s. For example, in 1996, in order to promote the

---

[4] The State Development Planning Commission was merged with the State Council Office for Restructuring the Economic System (SCORES) and part of the State Economic and Trade Commission (SETC) to create the National Development Reform Commission (NDRC) in 2003. The SETC was reorganized and separated into State-Owned Assets Supervision and Administration Commission of the State Council, NDRC and Ministry of Commerce in 2003.

growth of domestic wind turbine manufacturing, the national government adjusted customs duty of imported wind power equipment, which was previously exempted in the early 1990s (Brennand, 2001). The import of spare parts is preferable to the import of entire wind power generators. Correspondingly, the tariff ratios for wind power generators and spare parts were adjusted to 12% and 3%, respectively (Liu et al., 2002). In the same year, the SDPC initiated a *Ride the Wind Programme*, which aimed to facilitate technology transfer through the establishment of joint ventures.

Nevertheless, the wind power industry still experienced a stagnant period from 1993 and 2000. Lema and Ruby (2007) considered it as a major coordination failure in the Chinese bureaucracy. The authors argued that the commissions at equal hierarchical levels, which are supposed to cooperate in order to facilitate the diffusion of wind energy, competed against each other over issues such as fund allocation and division of labour. MOST/SDPC/SETC (2002) pointed out ‘four lacks’ in policy mechanisms that hinder the growth, including the lack of a clear target in generation capacity; the lack of incentives; the lack of long-term loans; and the lack of private and foreign investment. In fact, the slow progress was not only induced by the lack of effective policies. The higher cost of wind power (0.70 – 0.75 yuan/kWh, twice the cost of coal-fired electricity); a major reform of China’s power system during that period[5] and the cheap price of fossil fuels all contributed to the slow progress of wind power during the 1990s.

---

[5] China’s electricity system experienced a major reform since the late 1990s. Ministry of Power was abolished in 1998 in order to separate management and operation of the electricity industry. Previously, the Ministry of Power is in charge of power system investment, planning as well as surveillance. State Power Corporation was established in 1996, which had been responsible for the power system operation since 1998. The corporation was further separated into five power generation companies and two power grid companies in 2002.

2.3.2 2000 – 2005: the experimental phases

The situation has been changed since the early 2000s. In 2003, the national development reform commission (NDRC) implemented a *Concession Bidding Programme*, which aimed at promoting the development of domestic wind turbine manufacturing, decreasing generation cost, facilitating grid connection of wind farms and finally achieving scale of economy through tender schemes (Li and Gao, 2007). Although the concession bidding programme promoted the growth of wind power installed capacity between 2003 and 2005, there are many criticisms on its selection criteria, which weighted bidding price heavier than all the other factors such as financial and technical capabilities of investors and strategic planning of the project (Li et al., 2008).

In response to the situation, NDRC issued a *Notice on Wind Power Plant Construction and Management in 2005*. The notice revised the selection criteria, which downgraded the weight ratio of bidding price to 40%. It emphasized that the approval of wind farm projects should also be based on scale and location of wind farms, which need to coordinate with power system operation and power grid capability. It also distinguished the responsibility of national and regional development reform commissions in order to speed up procedures in the approval of wind farm projects. For all wind farms with less than 50 MW of generation capacity, regional development reform commission is in charge of the approval processes. A mandatory requirement of 70% domestic produced wind power facilities was also established to promote the growth of domestic wind turbine manufacture industry. Nevertheless, unreasonable bidding prices still existed during the bidding process. For example, Li et al. (2006) pointed out that the winning bidding prices (from 0.379 yuan per kWh to 0.519 yuan per kWh) were significantly lower than the actual cost of wind power (from 0.566 to 0.703 yuan per kWh) in the concession bidding system between 2003 and 2006.

2.3.3 2006 – present: the take-off phases

Since 2006, NDRC has enacted a few legislations. For example, the *Renewable Energy Law*, which was promulgated in 2006, has provided legitimacy for the development of renewable energy in China. The Law stipulates the obligation and responsibility of stakeholders, including local authorities, electricity regulatory commissions, grid operators and investors. It prioritizes the development of renewable energy sources over other energy sources. Specific funding to support the research and development of renewable energy technologies and to support the decentralised renewable energy system at remote areas is established.

'Despite the general character the law was an unequivocal declaration of intent to promote renewable energy both as a part of the energy mix and as an area of industrial and technological development.'

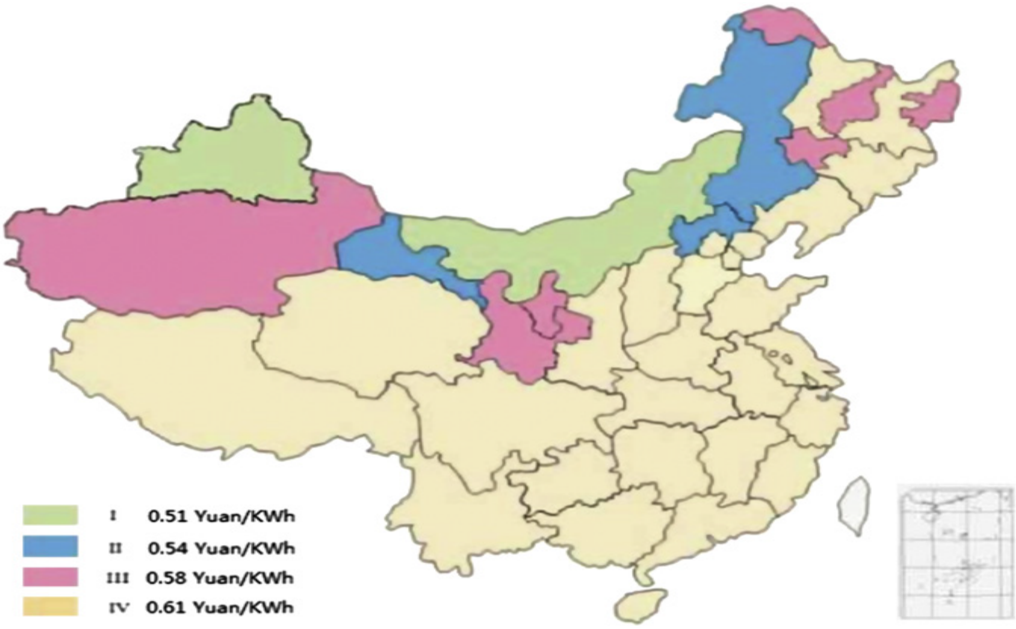
- Lema and Ruby (2007)

Following upon the *Renewable Energy Law*, the target of renewable energy development is presented in the *Medium-Long Term Development Plan for Renewable Energy* in 2007. For example, total wind power generation capacity was predicted to reach 5 GW in 2010 and 30 GW by the end of 2020, respectively. In addition, electricity operators which have installed electricity generation capacity over 5 GW were requested to install 3% and 8% of their total generation capacity from non-hydro renewable sources by 2010 and 2020, respectively (NDRC, 2007b). The mandatory target forces power operators, including China Huaneng Group, China Datang Corporation, China Guodian Corporation, China Huadian Corporation and China Power Investment Corporation, which are known as the top five power groups, and another thirteen power companies to invest in renewable energy industry (Xinhua, 2012). Wind power projects which have abundant wind resources and convenient access to the power grid are very attractive to these power generation groups. Liu and Kokko (2010) recognized the mandatory target as *‘more effective than any of the incentives operating through the pricing system’.*

The growth of wind power generation capacity, which doubled every year from 2005 to 2010, was beyond expectation. The 5GW-by-2010 target was fulfilled three years in advance. Hence, in 2008, the *11th Five-year Renewable Energy Development Plan* revised the target and extended it to 10 GW by the end of 2010. Furthermore, the plan emphasizes the development of domestic wind turbine manufacturing and projects several large-scale wind farm locations (with total generation capacity over 10 GW) in Gansu, Inner Mongolia, Hebei, and Jilin.

After years of research and discussions, NDRC issued a *Notice on Improving the Pricing Policy of Grid-Connected Wind Power* and finalised the pricing mechanism of wind power in 2009. Wind power price is classified into four categories, ranging from 0.51, 0.54, 0.57 to 0.61 yuan/kWh, according to the potential of wind resources and conditions of wind farm sites (better conditions and higher potentials have lower prices). Figure 2.4 illustrates regional wind power price differences in China.

Figure 2.4 Regional difference in the unit cost of wind power in China

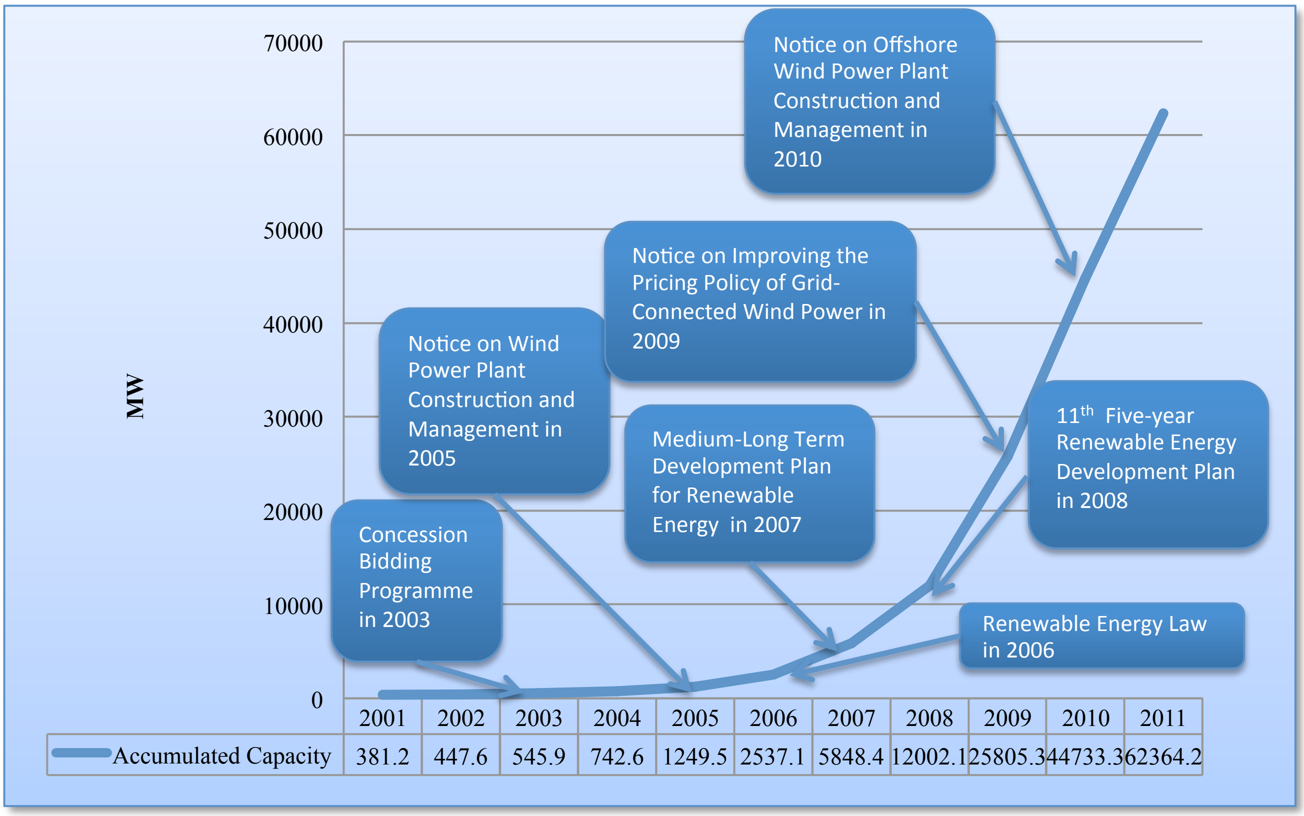


Source: Yang et al. (2012a)

The development of onshore wind power has experienced a substantial growth. A step-forward was taken in early 2010, when the *Notice on Offshore Wind Power Plant Construction and Management* was issued by the NDRC. The notice defines the offshore wind power project and responsibility of national and regional authorities in offshore wind power construction and management. It covers issues regarding project planning and approval, wind farm construction and operation, environmental impact assessment, etc.

Figure 2.5 shows the accumulated installed capacity with corresponding government policy since 2001. Total installed capacity of wind power experienced a steady increase from 381.2 MW in 2001 to 1249.5 MW in 2005. Between 2006 and 2010, wind power generation had been almost doubled every year. With 45,894 wind turbines installed, total wind power generation capacity had reached 62,364.2 MW by the end of 2011 (CWEA, 2012b). The newly installed capacity amounted to 17.6 GW, which accounted for approximately 40% of growth in global wind energy capacity in 2011.

Figure 2.5 China's wind power generation capacity growth and the selected government policies between 2001 and 2011



2.4 Wind power development in China: a regional perspective

Of all the regions in China, Inner Mongolia has the largest wind power generation capacity, which amounted to 17.59 GW in 2011, followed by Hebei (6.97 GW) and Gansu (5.4 GW). A list of the top 10 regions in wind power generation capacity is shown in Table 2.2.

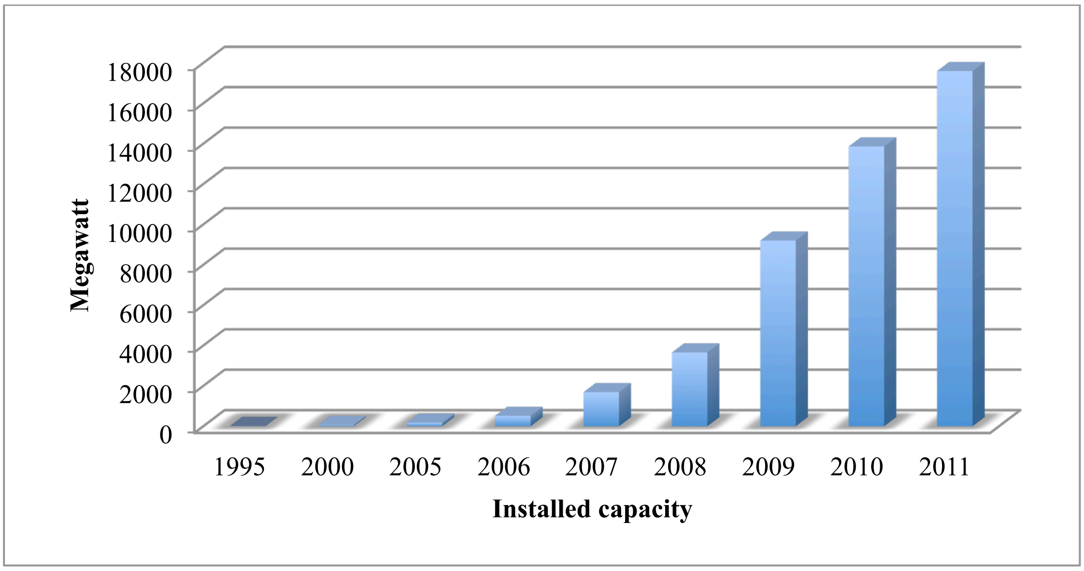
Table 2.2 China's top 10 regional wind power generation capacity in 2011.

Province	Wind power generation capacity (MW)
Inner Mongolia	17,594.4
Hebei	6,969.5
Gansu	5,409.2
Liaoning	5,249.3
Shandong	4,562.3
Jilin	3,563.4
Heilongjiang	3,445.8
Ningxia	2,886.2
Xinjiang	2,316.1
Jiangsu	1,967.6
Others	8,400.4
Total	62,364.2

Source: CWEA (2012b)

Inner Mongolia is one of the first regions to use wind power in China, which can be traced back to the 1970s. Decentralized wind power was used to provide electricity supply for herdsmen in remote areas during its early development. Centralized (or on-grid) wind power was not used until 1989, in which a wind farm with total generation capacity of 1MW was deployed with financial support from the United States (Ling and Cai, 2012). Total generation capacity increased from 8.2 MW in 1995 to 17,594.4 MW in 2011 (See Figure 2.6).

Figure 2.6 Growth of wind power generation capacity in Inner Mongolia, China.



Source: Ling and Cai (2012)

The substantial increase in power generation capacity in China's regions are also attributed to the establishment of favourable government policy (Liu and Kokko, 2010). For example, Inner Mongolia is the first province to establish provincial wind power policies in China. In the middle 2000s, Inner Mongolia Development Reform Commission (IMDRC) issued *Inner Mongolia 11th Five-Year Plan for Wind Power Development and Future Prospective in 2020, Method to Inner Mongolia Wind Power Development, Utilization and Management, and Principles on Allocations of Wind Resources in Inner Mongolia and Entry Requirements of Enterprises,* which supplemented national policies by incorporating regional situations such as the technical capability of wind farm developers and the wind power potentials (Li et al., 2010). In 2011, IMDRC revised and extended existing wind power policies. Electricity demand management was included in the new policy. For example, the new *Method to Inner Mongolia Wind Power Development, Utilization and Management Implementation Details* encourages a vertical integration of power generation industry and energy-intensive industries. The purposes of the integration are to utilize the excessive wind powered outputs and to avoid losses in wind power curtailments (Ling and Cai, 2012). Also, the *Inner Mongolia 12th Five-Year Plan on Wind Power Development and Grid Integration* projects wind power generation capacity to reach 33 GW by 2015. The projection is based on the demand within Inner Mongolia and the transmission capability to deliver wind power to other regions.

Regions in China have centred on different directions on addressing wind power development. For example, in 2008, Jiangsu[6] Development Reform Commission (JSDRC) issued a *Development Plan for Wind Power Equipment.* The plan projected scale and structure of the manufacturing industry and the technical and financial capability of manufacturers by 2020 (JSDRC, 2008)

At present, eight wind farm locations in seven provinces, with over 10 GW of wind power generation capacity each, have been planned or are under construction, which are expected to be complete by 2020 (see Chapter 4 for wind farm locations, Figure 4.3).

2.5 Development of domestic wind power manufacturing industry

Besides considerable wind power potentials and favourable government policies, some studies pointed out that growth of domestic wind turbine manufacture, in terms of productivity and technical capability, have stimulated wind power development in China (Li et al., 2010, Zhao et al., 2009). Lema and Ruby (2006) conducted a case study in China to evaluate the significance of the development of domestic wind turbine manufacturing industry. Two policy models - the fast track and the slow track - are used in their study. The fast track policy model is referred to the immediate

[6] Jiangsu, located in the east coast, is one of the most developed economic regions in China.

abatement of emissions from installing the greatest number of wind turbines with the shortest time period while the slow track policy model is referred to a development of domestic wind equipment manufacture at early stage and a subsequent development of the wind power industry. Lema and Ruby found that the development of Chinese wind power industry was distinguished by these two policy models according to two periods of time. Before 2000, the Chinese government implemented the fast track policy model to encourage the fast deployment of wind turbines and to maximize the environmental and economic benefits of wind power development. However, the growth wind power generation capacity was not significant. After 2000, the slow track policy model was implemented to encourage the expansion of the wind power manufacture industry domestically. The authors argued that the slow track policy model would maximize the potential of wind power development, although the fast track policy model would have an immediate effect. The implication of this study showed that countries with capabilities in terms of finance, technology, resources etc. should realize the substantial effect of the slow track policy model.

One of the motivations of using domestic wind power facilities is that it helps to reduce the capital cost of wind farms significantly. Li and Gao (2007) found that domestic produced wind turbines and components were 20% cheaper than their foreign counterparts, which was very significant as the cost of wind turbines and components accounts for approximately 70% of the total cost of wind power projects. By the end of 2011, domestic wind power facilities accounted for 85% of the accumulated wind power generation capacity (CWEA, 2012b), which was a considerable increase from 30.9% in 2006 (Shi, 2007).

2.6 Barriers in wind power development

The institutional settings of China's power system have impeded the development of wind energy in China. At present, local authorities manage the power system in each province. For political reasons, local authorities tend to compete against each other and are reluctant to cooperate. As a result, power exchange between provinces is only considered as a contingency plan to overcome sudden power losses. Additional power transmission would have to go through complex administrative procedures, which is a significant drawback to wind power considering its variable power outputs. Thus, the co-ordination between regions would provide a great opportunity to promote the use of wind power in China. It should start with easing the barriers in interregional power transmission. A power-pool created in the Nordic power grid has exemplified the successful co-ordination between countries in power exchanges. It could also be an opportunity in creating a power-pool to promote regional power transmission in China.

In addition, Existing energy plans in China provided limited guidance to the wind power development. For example, the Mid-Long Term Renewable Energy Plan in 2006 stated the national target of wind power generation capacity at 5 GW by 2010 and 10 GW by 2020, which significantly underestimated the growth of wind power industry. Regions endowed with wind resources promoted the development of wind power industry as it is considered as a viable means to stimulating the local economy. Wind turbines are deployed regardless of the actual power demand. Hence, the harness of wind power generation should have a long term, strategic plan which needs to incorporate power demand within the region and among regions adherent to the region.

Furthermore, the substantial growth in power generation capacity only tells half of the story. In fact, a significant proportion of wind-powered outputs were curtailed in China. China Wind Energy Association (CWEA) investigated wind power curtailments in 2011. 42% of the total wind power generation capacities located in 10 regions of China were included (CWEA, 2012a). Total power losses amounted to 5.98 billion kWh, which accounted for 16.9% of the total power generation7. Gansu, Inner Mongolia and Jilin, which represent four of the eight wind farm locations, experienced most severe wind power curtailments. Power losses in these provinces account for 25.3%, 23.1% and 21.0% of the total wind power generation, respectively. By contrast, Hebei (3.9%), Shandong (1.2%) and Guangdong (1.0%) which are either adjacent to demand centres (Hebei) or are demand centres theirselves (Shandong and Guangdong) have the least power losses.

The purpose of curtailments was to safeguard power system operation (CWEA, 2012a). Power system operators aim to maintain the security of power system by keeping supply and demand in balance. Demand varies over time but follows a similar pattern on an hour-by-hour basis every day. By contrast, supply is less predictable due to the variable nature of wind, which could result in excessive supply (supply > demand) or inadequate supply (supply < demand) in power system operation. During the period of excessive supply, additional power generation can be delivered to other locations if grid infrastructure is sufficient within the region and interconnected among regions. Inadequate supply can be compensated by power reserves, which are held to provide power supply during power plant outages, uncertain variations in load and fluctuations in power generations (such as wind) at different timescales (Holttinen, 2005).

The curtailments imply challenges of insufficient grid infrastructure and lack of flexible power generation units. However, only a couple of studies touched on the challenges of grid infrastructure in the integration of wind power in China. For instance, Wang (2010) studied grid investment, grid security, long-distance transmission and the difficulties of wind power integration. Liao et al. (2010) criticised the inadequacy of transmission lines in the wind power development. However, both studies failed to elaborate the challenges in

---

[7] Total power generation equals actual power generation plus curtailed power generation.

detail. Furthermore, wind power is not a stand-alone energy source; it needs to be complemented by other energy sources when wind does not blow. Although the viability and feasibility of the combination of wind power with other power generation technologies have been discussed widely in other countries, none of the studies reviewed the situation in the Chinese context. Thus, there is a need for further investigation of these issues since they are critical to the development of wind power in China.

Last but not least, existing government policies, such as the Renewable Energy Law and Mid-Long Term Renewable Energy Development Plan, have already stipulated the responsibility of grid companies in integrating wind farms and have established corresponding incentives to promote the coordination. However, grid operators are reluctant to implement the government policy as the incorporation of wind power could have a significant impact on power grid operation. Thus, policy implementation should be reinforced to guarantee the participation of power grid companies in wind power integration. Given the unwillingness of grid companies and its monopoly in gird operation, it would be necessary to impose penalties if grid operators refuse to coordinate.

2.7 Chapter two summary

This chapter provides a general overview of the power generation system in China. 80% of China’s power generation has been provided by coal. Hydropower, nuclear power and wind power accounts for the remaining 20%. The overdependence on coal in China’s power generation has resulted in soaring CO_2 emissions since the late 1970s. Since 2007, China has been the largest CO_2 emitter. 37.2% of total CO_2 emissions are derived from coal-fired power generation.

Wind power is expected to play a significant role in China's power system. Accumulated generation capacity increased from 381.2 MW in 2001 to 62,364.2 MW in 2011, which could increase to 200 GW, 400 GW and 1,000 GW by 2020, 2030 and 2050, respectively. The recent growth in generation capacity depends on a number of factors such as potentials of wind power in power supply, favourable national and regional government policies and the development of domestic wind turbine manufacturing industry. Nevertheless, the capacity growth is exciting but not convincing. A significant proportion of wind-powered output is curtailed due to insufficient power grid infrastructure and infeasible back-up systems, which is considered as a result of the institutional barriers in China. These issues are largely ignored or overlooked in the previous studies. Hence, an in-depth discussion of the institutaional challenges in wind power development is given in Chapter 4 in addition to a set of recommended solutions. Before that, the adopted research design and methods are depicted in the next chapter in conjunction with the justifications of the chosen models and environmental indicators for use in this thesis.

Chapter 3 Research Design and Methodology

3.1 Introduction

In Chapter 2, a critical review of the existing literature on the historical development of the Chinese energy system, with specific focus on the potential scale of development of wind power to mitigate CO_2 emissions and help to alleviate water stress. Findings from the review show that China is fully embracing a significant, rapid growth in wind power (in terms of annually installed generation capacity and total number of wind farms) and the wind energy market (in terms of domestic wind turbines manufacturing industry), The growth is exciting but not convincing, particularly casting doubt on whether it is a viable means for CO_2 reduction and water saving.

This chapter describes the research design and methods adopted in this study to provide supportive evidence to verify the validity of the above claim. It explains why a set of models was selected, the insufficiencies of these models, the rationales and procedures for advancing the selected models to treat wind power as a separate economic sector (rather than as part of the energy sector) of an economy, and reasons of using a case study (Inner Mongolia) to supply further evidence on the usefulness of the advanced models.

One of the research themes of this research study is to examine the environmental implications of wind power development in China in terms of CO_2 emissions and water quantity-quality impacts. There are various methods that can be carried out to fulfil the task. For example, Dalla Marta et al. (2011) used a crop growth model to simulate crop yields, which in turn was used to determine water requirements of biofuels in Tuscany, Italy. Some studies examined the environmental impacts of energy systems by multiplying total cost with a national average energy intensity (Zhang et al., 2008, Heinloth, 1983). Of all research methods, three methods are frequently used including input-output (IO) analysis, process based life cycle analysis (PRO-LCA), and hybrid analysis that combines IO and LCA (Lenzen and Munksgaard, 2002).

Interpreting the flows of goods and services within a specific economy, IO analysis is considered as one of the most effective tools to examine interrelationship between economic sectors for a given time period. Since the late 1960s, IO analysis has been used to examine the relationships between economic systems and environment (Miller and Blair, 2009). A number of studies used IO analysis to examine the environmental impacts of power generation systems in various locations, such as Zhang et al. (2007) for hydropower in China and Proops et al. (1996) for both conventional and renewable energy generation systems in the UK. Although IO analysis can effectively capture the environmental impacts of a specific product because of its economy-wide coverage, there are a number of limitations which may result in errors and uncertainties (e.g. sector aggregation, environmental indicator misalignment, neglect of post-consumption stages, etc.).

One of the other approaches that is widely used in examining environmental impact of power generation systems is process based life cycle analysis (PRO-LCA). Since the approach covers all stages of a product – from raw material extraction, goods production, transportation, consumption to disposal – it provides more detailed and comprehensive information than IO analysis. A number of studies used PRO-LCA to examine the environmental impacts of wind power (Jungbluth et al., 2005, Varun et al., 2010, Tremeac and Meunier, 2009). However, the results from PRO-LCA do not often effectively account for all the environmental impacts due to the arbitrary selection of system boundary (no scientific evidence basis) that has a significant impact on the reliability of the studies (Weber and Matthews, 2007, Suh et al., 2004).

Hybrid approaches combine the detail of PRO-LCA and the completeness of IO analysis, which has advantages in terms of accuracy and sophistication. Hybrid approaches have been used in a number of studies focusing on energy systems, e.g. Wiedmann et al. (2011) on wind power in the UK and Acquaye et al. (2011) on biomass in the UK.

This chapter starts with a brief introduction of IO analysis, including its applications and limitations. Following that, I introduce PRO-LCA and its applications and then proceed to an introduction of various hybrid approaches, including tiered base hybrid LCA, IO based hybrid LCA and integrated hybrid LCA. Then, I justify selected research methods of Chapter 5 (IO based hybrid life cycle analysis) and Chapter 6 (integrated hybrid life cycle analysis). This chapter ends with an introduction of choosing two environmental indicators – CO_2 emissions and water consumption.

3.2 Basics of input-output analysis

3.2.1 A brief history of input-output analysis

The original idea of IO analysis can be traced back to the 'Tableau Économique' (or Economic Table), which was developed by a French economist, François Quesnay, in 1758. One of the most significant contributions of Quesnay's work is that it provides an analytical foundation to product flows in an economy (Miller and Blair, 2009). In the late eighteenth century, another Frenchman, Léon Walras, developed a general equilibrium theory in economics. A set of production coefficients was introduced, which is similar to the technological coefficients in the later IO model. In 1936, Wassily Leontief simplified the Walras model and published the first article on IO analysis, entitled 'Quantitative Input-Output Relations in the Economic System of the United States' (Leontief, 1936). Later on, Leontief applied the IO model to assess the economic structure of the U.S. in his book 'Structure of American Economy: 1919 – 1939' and provided an IO model that was appropriate for empirical research (Leontief, 1951). During the past few decades, IO analysis has been further developed in numerous studies and applied in various research areas. For example, the oil crisis has stimulated the development of energy IO models in the 1970s. In recent years, one of the most significant contributions of the IO approach is applications on the quantification of environmental impacts in trade (Weber and Matthews, 2007). As addressed by Wyckoff and Roop (1994), national CO_2 emission reduction policies may be insufficient if imported products account for a significant proportion in a country's consumption. For instance, the US-China trade represented 720 million metric tonnes of CO_2 emission between 1997 and 2003 (Shui and Harriss, 2006). Furthermore, Peters and Hertwich (2006b) pointed out that over 70% of exports from developing countries are used to satisfy the needs in developed countries. In other words, whether the producers (mainly developing countries) or the consumers (mainly developed countries) should be responsible for these emissions are questionable (Munksgaard and Pedersen, 2001). Schaeffer and de Sá (1996) showed that developed countries are reducing their CO_2 emissions through importing products from developing countries. Shui and Harriss (2006) provided an empirical study in which they examined the CO_2 emission embodied in bi-lateral trade between China and the USA by using a multiregional IO model. This study involves the identification of CO_2 emissions avoided by importing Chinese goods in the USA, the increase of CO_2 emission in China due to product export activity to the USA and the contribution of CO_2 emissions embodied in US-China trade to global CO_2 emission. The authors conclude that 7% to 14% of Chinese CO_2 emissions were attributed to exports to the US while the US reduced 3% to 6% of their CO_2 emissions from the US-China trade. Consequently, the application of the IO framework on quantification of environmental impacts in trade is significant for planning national or global environmental policies.

3.2.2 Foundation of input-output analysis: input-output table and mathematical equations

The foundation of an IO analysis is the IO table, which is compiled from primary data collection or estimated by using partial survey or non-survey techniques. The IO table demonstrates the flow of goods and services from one industry to another in detail. The major components and their common notations of an IO table include:

- Intermediate transaction (x_{ij}): describes the intermediate deliveries of product from one sector to all sectors (including itself). For example, x_{ij} represents the delivery of product x from sector *i* to sector *j*.
- Final demand (y_i): shows the sales of product to end-users. Sales can be made to household purchases, government spending and foreign purchases and for inventory increase purposes.
- Value added (w_i): represents the other inputs to the production, including employees' compensation and tax.

The basic layout of an IO table is given in Table 3.1.

Table 3.1 An example of IO table

		Economic sectors 1 ⋯ j ⋯ n	Final demand	Total output
Economic sectors	1 ⋮ i ⋮ n	x_{ij}	y_i	x_i
Value added		w_i		
Total input		x_i		

IO analysis is based on several assumptions. The first assumption is that one sector produces a single product and any by-product is treated as the main product. It can be represented mathematically in the following equation, as

$$x_i = x_{i1} + \cdots + x_{ij} + \cdots + x_{in} + y_i \qquad \textbf{Equation 3.1}$$

x_i represents the total output of sector i; x_{ij} (where j = 1, 2, 3, …, n) depicts the flows of goods and services from sector i to the other sectors (sector 1, 2, 3, …, n); y_i represents the final demand of sector i.

The second assumption made in IO analysis is that the ratio of input to output remains constant within a specific time period in an economy. It is defined by Leontief as "technical coefficient" (a_{ij}). This coefficient states the requirement of sector i to produce one monetary unit of product of sector j which is calculated as dividing x_{ij} by x_j, where x_j means the total output of sector j (see Equation 3.2)

$$a_{ij} = \frac{x_{ij}}{x_j} \qquad \textbf{Equation 3.2}$$

Replacing x_{ij} by $a_{ij}\,x_j$, Equation 3.2 can be rewritten as Equation 3.3.

$$x_1 = a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n + y_1 \qquad \textbf{Equation 3.3}$$

Equation 3.3 can be written in matrix form as Equation 3.4.

$$(I - A)\,X = Y \qquad \textbf{Equation 3.4}$$

Whereas I represents the identify matrix

A represents $n \times n$ matrix of technical coefficients

X is the total output vector

Y is the final demand vector.

If $(I - A)$ is not equal to zero, then Equation 3.4 can be rewritten as Equation 3.5.

$$X = (I - A)^{-1}\, Y \qquad \textbf{Equation 3.5}$$

$(I - A)^{-1}$ is known as the Leontief inverse matrix. It describes that as $(I - A)^{-1}$ remain constant for a specific period of time, the changes in total output depend on the changes in final demand. The implication of this equation is that sector *i* needs to generate corresponding amount of products (additional products) to fulfil changes in final demand Y. Therefore, the outputs from other sectors to meet the additional requirements from sector *i* are also taken into account. In other words, this equation implies that the direct and indirect effects on different sectors in an economy accomplish the changes in final demand Y.

3.2.3 Applications of input-output analysis to energy studies

Energy IO analysis, which is one of the mainstreams in IO analysis, was extensively developed during the period of the oil crises in the early 1970s (Miller and Blair, 2009). A number of energy IO studies examine the energy impact of a specific economy, including net energy analysis (Bullard et al., 1978), energy cost of goods and services (Hendrickson et al., 2006, Crawford, 2009), energy and structural change (Lin and Polenske, 1995), and so on and so forth. The analytical approach started with adding a set of linear energy coefficients to the traditional Leontief framework to explain the energy use per unit of monetary value of economic sectors (Tiwari, 2000, Liang et al., 2007, Liu et al., 2009). Although this approach has been widely used in energy IO studies, limitations exist because of the assumption of uniform energy price, in which case energy consumption in physical units is not accurately reflected. A hybrid unit approach was introduced by Bullard and Herendeen (1975) and further developed by Blair (1980), Han and Lakshmanan (1994) and Dietzenbacher and Stage (2006) to deal with the limitations. By doing so, the IO table was extended by adding energy sectors in physical units (e.g. British thermal unit or tonnes of coal).

Besides, a number of studies used IO analysis to examine various energy production systems in terms of their socio-economic and environmental impacts. For example, using an IO analysis, Lenzen and Wachsmann (2004) estimated and compared the CO_2 emissions and energy consumption of wind power in Germany and Brazil. A few studies have used this approach to evaluate the economic and employment effects of promoting renewable energy development (Lehr et al., 2008, Caldes et al., 2009, Madlener and Koller, 2007).

For clarity, this research study is not about an application of energy IO analysis but the examination of environmental impacts of power generation systems. Below depicts how IO models are used to analyse electricity generation systems.

Power industry is usually known as Power Generation and Supply in most IO tables. It includes power generation from various sources, such as coal, hydro, natural gas and renewable energy, and electricity transmission and distribution, all of which have heterogeneous qualities of factor endowments in terms of input structure, costs and environmental impacts (Marriott, 2007). In order to examine the economic or environmental implications of one specific power generation technology, some studies disaggregate the electricity sector in the IO table. For example, owing to the reduction of electricity generation from nuclear and coal power plants and the increasing share of renewable energy sources, Allan et al. (2007) used IO analysis to examine the impact of eight electricity generation technologies on the Scottish economy. The study disaggregated the electricity generation sector into nine production sectors, including eight electricity generation sectors and one electricity transmission, distribution and supply sector. Vectors represent gross value added (GVA) coefficients and employment coefficients were added to the model to compute the GVA and employment effects of different power generation technologies. In the disaggregation of the electricity generation sector, the authors first estimated the turnover of each of the eight power generation technologies and then deducted these values from the original electricity sector. The residual values were regarded as the non-generation activities, including transmission, distribution and so forth. This two-step approach was adopted to generate the row entries of the newly built IO table firstly and the column entries subsequently. Data used in the estimation of total output for each generating technology were the total volumes of electricity generation multiplied by the corresponding sale price. With distinctive output multipliers from each electricity generation technology, the authors concluded that it is necessary to disaggregate the electricity sector when implementing electricity generation related studies as differences in economic impacts exist even within the conventional and renewable groups.

Besides discrepancies in economic impacts, one of the other significant discrepancies of different power generation technologies can be found by comparing the environmental impacts associated with one kilowatt-hour of power generation. For instance, Feng et al. (2010) summarized studies on CO_2 emissions of fourteen electricity generation technologies during their life cycles, including conventional power generation technologies such as coal and natural gas, and renewable energy sources such as solar and wind. In general, life cycle CO_2 emissions of fossil fuels are much higher than renewable energy and nuclear power, although the incorporation of carbon capture and storage (CCS) system reduces the CO_2 emissions significantly (See Table 3.2).

The significant varations in data range may come from a number of factors, including the methodology used in the research (process-based life cycle analysis or input-output based life cycle analysis), the location of case study (carbon intensive country would generate higher CO_2 emissions), the selection of power generation technology (a 800 kW wind turine might yield higher emissions per kWh generated than a 5 MW wind turbine) and so forth.

Table 3.2 Life cycle CO_2 emissions of power generation technologies

Electricity generation technologies	g-CO_2/kWh
Pulverized coal (PC)	847 - 879
PC with carbon capture and storage (CCS)	247 - 274
Natural gas combined cycle (NGCC)	488 - 499
NGCC with CCS	200 - 245
Integrated gasification combined cycle (IGCC)	861 - 872
IGCC with CCS	167 - 240
Combined cycle gas turbine (CCGT)	409
Nuclear power	10 - 130
Wind power	7.9 - 123.7
Solar PV	53.4 - 250
Biomass	35 - 178
Solar thermal	13.6 - 202
Hydropower	3.7 - 237

g-CO_2/kWh = grams of carbon dioxide equivalent per kilowatt hour

Source: Feng et al. (2010)

The indigenous divergences have resulted in studies on the environmental impacts of power generation technologies using the IO model. Some studies used existing models to examine CO_2 emissions of power generation technologies. For example, using The Carnegie Mellon's economic IO (EIO) based life cycle analysis (LCA) model, Zhang et al. (2007) examined the energy use and GHG emissions of hydropower plants in China. Two plants are considered in the study: a 44 MW plant with a 50-year lifespan and a 3,600 MW plant with a 100-year lifespan. The study concluded that life cycle GHG emissions of the two selected hydropower plants vary significantly. The 44 MW power plant yields 44 grams CO_2 equivalent/kWh, whilst the value for the 3,600 MW power plant is 6. Other studies applied the extensions of IO analysis. Proops et al. (1996) adopted an IO analysis to examine the CO_2, SO_2 and NO_X emissions in both clean coal and renewable energy generation systems in the UK. The authors decomposed the lifecycles of eight power generation systems to construction, operation and decommission phases and add a fuel-use coefficient matrix (*C*) and a pollution emission coefficient matrix (*E*) to extend the original input-output model. The construction and decommission phases of power stations were treated as changes in final demand vector (f) in each year. Hence, the total emission of these two phases can be calculated with the known *C, E* and f (final demand). In analyzing the operating phase of electricity generating stations, the authors constructed a new technical coefficient matrix and a new fuel-use coefficient matrix because the substitution of traditional power plants resulted in changes in electricity technology (input coefficients for electricity sector) and electricity mix (changes in *C*). Therefore, the total emissions of operating phases were examined by incorporating the new technical coefficient matrix and the new fuel-use coefficient matrix into the extended IO model. The study concluded that both clean coal and renewable energy technologies were significant in emission reduction compared to traditional power generating technologies; however renewable energy systems were more effective in cutting emissions.

Consequently, it is necessary to distinguish power generation technologies in terms of their environmental impacts. To differentiate power generation technologies, one could disaggregate the existing IO table as was introduced by Allan et al. (2007). The newly created electricity sector might allow for detailed economic and environmental analysis of each component in the electricity mix; make scenarios for the potential CO_2 reduction by substituting one technology with another technology. However, it should be noticed that a simple disaggregation as introduced by Allan and his colleagues could lead to uncertainty in result, since the technological coeffcients in the new sector is not representitive to the new technology, but an average value of the orginal sector.

In this study, the adopted research strategies are: (1) disaggregate the electricity sector to formulate a new wind power sector in order to examine its environmental impacts (see Chapter 5 for details), (2) use the integrated hybrid LCA (IHLCA) analysis to examine environmental impacts of different power generation technologies (e.g. pulverized coal, wind power, solar PV) without disaggregating the electricity sector in the IO table via a case study in China (see Chapter 6 for details). A justification of the disaggregation method used in this research is given in the following (see Chapter 3.3.6).

3.2.4 Dynamic input-output anlaysis

In a standard IO model, elements of the A matrix (a_{ij}) reflect the requirements of inputs from sector *i* to serve for per unit output of sector *j* at a particular time period. Thus, for a given output of sector *j* (x_j), flows from sector *i* to sectors *j* (z_{ij}) would remain constant for the time period, given that $z_{ij} = a_{ij}x_j$. The model is always referred to basic static IO model. The basic static input-output model focuses on one particular time period (usually one year), which has been used widely in input-output studies. However, it neglects stocks of capital goods that are not used up in the given time period, which can be used for production in the future (e.g. subsequent years). In order to describe time dimensions in economic models, Leontief introduced a dynamic version of the IO model in the late 1940s (Miller and Blair, 2009). Capital coefficients (b_{ij}) are used to represent capital stock of sector *i* that is used for the production of one dollar's worth of output in sector *j*.

Thus, with the inclusion of capital coefficients (b_{ij}), total output of sector *i* for a given year *t* would written as Equation 3.6

$$\boldsymbol{x_i^t = \sum_{j=1}^{n} a_{ij}x_j^t + \sum_{j=1}^{n} b_{ij}(x_j^{t+1} - x_j^t) + f_i^t} \qquad \textbf{Equation 3.6}$$

Where, a_{ij} represents the requirements of sector *i* to satisfy the unit of output of sector *j*; x_j^t represents the output of sector *j* in year *t;* x_j^{t+1} represents the output of sector *j* in year *t+1*, f_i^t is the final demand of sector *i* in year *t*. Thus,

$(x_j^{t+1} - x_j^t)$ gives the added demand of sector *j* between year *t+1* and year *t*; and $b_{ij}(x_j^{t+1} - x_j^t)$ denotes the sector *i*'s new production that is used as capital stocks to satisfy the increase of output in sector *j*. As a result, the output of sector *i* depends on technology, final demand as well as the rate of use of capital stock in a dynamic I-O model.

Equation 3.6 can be written in matrix form as,

$$\boldsymbol{x^t} = \boldsymbol{Ax^t} + \boldsymbol{B}(\boldsymbol{x^{t+1}} - \boldsymbol{x^t}) + \boldsymbol{f^t}$$ **Equation 3.7**

Whereas *A* represents matrix of technical coefficients,

x^t is the total output vector in year t,

B represents matrix of capital coefficients,

x^{t+1} is the total output vector in year t+1,

f^t is the final demand vector.

Solving for x^t as a function of x^{t+1}, equation 3.7 can be rewritten as,

$$\boldsymbol{x^t} = (\boldsymbol{I} - \boldsymbol{A} + \boldsymbol{B})^{-1} \times (\boldsymbol{Bx^{t+1}} + \boldsymbol{f^t})$$ **Equation 3.8**

Similarly, x^{t+1} can be also be represented by

$$\boldsymbol{x^{t+1}} = \boldsymbol{B^{-1}}\,((\boldsymbol{I} - \boldsymbol{A} + \boldsymbol{B})\boldsymbol{x^t} - \boldsymbol{f^t})$$ **Equation 3.9**

From Equation 3.8, outputs of year *t* would depend on outputs of year *t+1*; likewise, outputs of year *t+1* would depend on outputs of year *t* as shown in Equation 3.9. As a result, dynamic input-output model extends static input-output model by presenting changes in an economy between the target period (e.g. year *t*) and the preceding periods (e.g. year *t+1*), The dynamic input-output model has been introduced and applied in a number of studies (Duchin and Szyld, 1985, Leontief and Duchin, 1986). For example, Duchin and Steenge (2007) presented the mathematical representations of dynamic I-O model and its extensions. Based on a dynamic input-output model, Ten Raa (1986) developed and applied a dynamic I-O model to examine the temporally distributed activities, which production processes take time to complete. Hoekstra and Janssen (2006) Applied the dynamic I-O model with spatial consideration. The authors examined alternative tax schemes for products that are produced and consumed in different countries, using a dynamic multi-regional input-output model. Dobos and Tallos (2011) used the dynamic input-output analysis to investigate the linkages between economic activities and flows of regenerative natural resources.

However, there are a few limitations in the dynamic IO, including the data availability for the estimation of capital coefficients (Miller and Blair, 2009), the singularity of the capital coefficient matrix, the implausible results from the model (Duchin and Szyld, 1985), which constrains its application. Investments in wind power would last for years, in which case a dynamic I-O model would be appropriate in this research. However, the data for capital coefficients estimation are not available. Hence, I choose to use a static I-O model in this research.

3.2.5 Limitations of input-output analysis

Before going further on discussing details of the implementation of the selected research methods & models, it is important to acknowledge the limitations of IO analysis.

Firstly, the basic IO model assumes that each sector uses the same input structure (technology) to produce a single characteristic output. However, the linear relationship cannot reflect the technological improvement and changes in the production structure (Madlener and Koller, 2007). For some industries, input structure varies significantly in terms of cost and environmental impacts. For example, in China's IO table, Power Generation and Supply sector contains high CO_2 emissions technologies, such as coal-fired power generation, and low CO_2 emissions technologies, such as wind power as well as power transmission and distribution. In order to assess the impacts of alternative technologies in an industry, Duchin and Levine (2011) developed a rectangular choice-of-technology (ROCT) model, in which new columns are added to the traditional technical coefficient matrix A while rows remain unchanged. The model allows for choice of any number of alternative technologies in one sector, which is an improvement from previous studies that only allow for choice between two alternatives (normally two different years average technologies), such as (Duchin and Lange, 1995, Leontief, 1986). One of the other approaches that account for secondary products and by-products is the supply and use framework (also known as commodity-by-industry approach, which was introduced by Stone (1961). Inter-industry transactions in the original IO table are replaced by a Use matrix (also known as input matrix), in which each element denotes purchases of commodities by industries in monetary units. A Make matrix (also known as output matrix) represents commodities that are made by industries. Details of the supply-use framework can be found in Miller and Blair (2009).

Secondly, economic sectors in IO tables are highly aggregated. In fact, the most disaggregated published IO table, for example, the U.S. IO table, distinguishes the national economy into 424 economic sectors. As the basic IO model uses national average data, it may be inappropriate to represent a specific product by using the IO sector classification (Mo et al., 2010).The aggregated sector would limit examination of a specific power generation technology, such as coal or wind power generation, but only can be used to examine the sector as a whole (e.g. average CO_2 emissions from Power Generation and Supply).

In addition, the compilation of IO tables is very time and labour demanding.

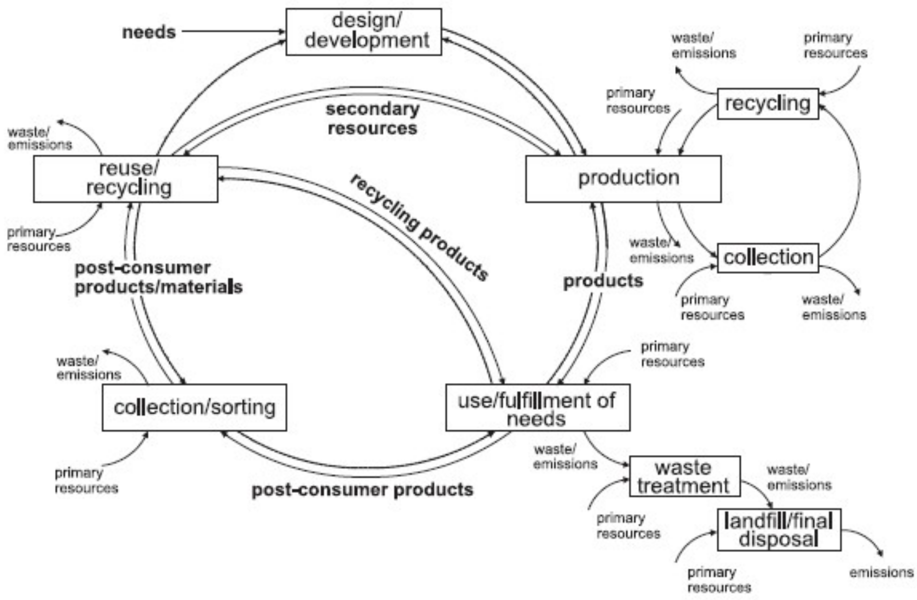
Most countries publish their IO table every five years (Miller and Blair, 2009). Since the IO table is not available instantly and annually, it limits the application of IO analysis on instant economic planning (Carter, 1974). Besides, with the growing concerns on environment, environmental IO analysis has been one of the mainstreams of IO analysis. However, environmental indicators may not be consistent with the IO table in terms of base year, which could lead to uncertainty in results.

Furthermore, the demand driven IO model assumes production capacity is infinite with which could fulfil the increased demand generated by economic activities (Suh and Nakamura, 2007). However, it is not always the case in reality. For example, Hubacek and Sun (2001) adopted the IO model to assess future land use in China, in which the authors pointed out that land is not always available when demand arises due to the restriction of land area and zoning regulations.

3.3 Input-output analysis and life cycle analysis

Although renewable energy is considered as nil emissions during its operation, the upstream environmental impacts are not negligible. These impacts including CO_2 emission, water consumption and energy consumption are usually better captured in life cycle analysis (LCA). LCA is used to assess the environmental impacts of a product during its lifecycle. Since the approach covers all stages of the product – from raw material extraction, goods production, transportation, consumption to disposal – it provides more detailed and comprehensive information than IO analysis. Rebitzer et al. (2004) provided a simplified schematic chart of a product's life cycle (See Figure 3.1). Starting from the design stage, the life cycle of a product also includes the manufacture, consumption and some post-consumer stages, such as recycling and waste management. Each of these life cycle stages involves inputs of materials, energy, and water and outputs such as emissions and waste.

Figure 3.1 A schematic representation of the life cycle of a product



Source: Rebitzer et al. (2004)

LCA captures the environmental impacts of a product from both upstream and downstream processes. The contribution of pollutions and resource uses at each process is explicit from the LCA results and thus, the associated environmental policy can be established to emphasize specific processes in order to minimize the overall environmental impacts of a product (Raadal et al., 2011). In addition, making choice of alternatives - e.g. a fluorescent type or an incandescent type light bulb - depends on a number of factors including cost, appearance, ease to use and so on. Owing to the growing awareness of environment, one of the criteria in making the choice is the environmental impact of the product. LCA is an effective tool to evaluate the environmental impacts of a specific product which could provide evidences to making choice of one product over the other with thorough consideration of the environment (Guinée et al., 2010).

Three approaches are used in LCA including a bottom-up approach, namely the process-based LCA (PRO-LCA), a top-down approach, namely the IO based LCA (IO-LCA) and a combination of PRO-LCA and IO-LCA, namely the hybrid analysis. In the following sections, the literature on PRO-LCA, IO-LCA and hybrid LCA and their applications are discussed.

3.3.1 Process-based life cycle analysis (PRO-LCA)

In PRO-LCA, two approaches have been adopted to assess the environmental impact of a product system, namely process flow diagram approach and matrix representation approach (Suh, 2004a). Process flow diagrams, which present the commodity flows in a product system by a diagram, are the most common practice in LCA studies (for a detailed description of process flow diagrams, see Suh et al. (2003) page 658). Matrix representation approach, which is introduced by Heijungs (1994), employs a number of linear equations to reflect the process of a product system. Here, a hypothetical system of kettle use is given to exemplify two approaches in PRO-LCA. Assuming the production of one 1-litre kettle needs 0.5 kg of steel and 2 kWh of electricity. The kettle is used to produce 3000 litres of boiled water during its life cycle and disposed of afterwards. The production of 1 kg of steel, 1 kWh of electricity, 1 unit of kettle and 1 litre of boiled water generates 2 kg, 1 kg, 3 kg, and 0.001 kg of CO_2 emission, respectively. The disposal of the kettle emits 1 kg of CO_2 emissions. Then a process flow diagram to represent the kettle's life cycle can be given as

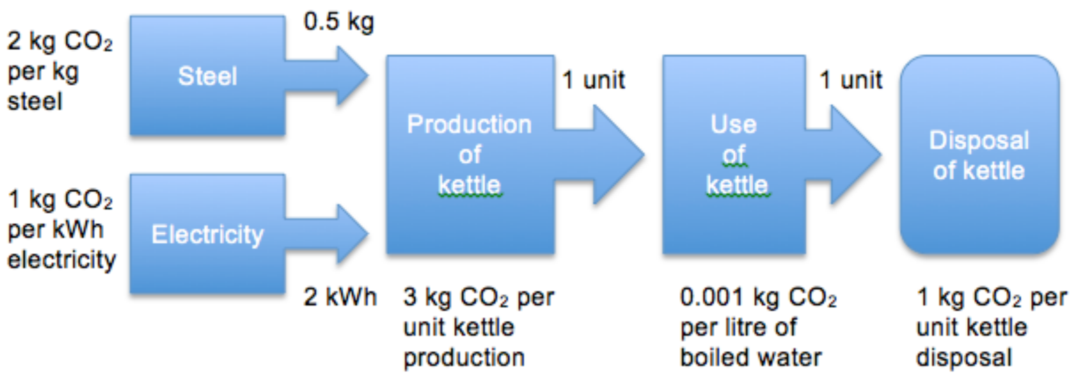


Figure 3.2 Process flow diagram of kettle use example

Hence, the environmental impact of kettle use can be calculated as:

2 x 0.5 (production of steel) + 1 x 2 (production of electricity) + 1 x 3 (production of kettle) + 0.001 x 3000 (use of kettle) + 1x 1 (disposal of kettle) = 10 kg CO_2.

The same product system can also be interpreted using the matrix representation approach. The inflows (+) and outflows (-) of the product system can be represented as Table 3.3.

Table 3.3 Inflows and outflows of the kettle use system

	Production of steel	Production of electricity	Production of kettle	Use of kettle	Disposal of kettle
Steel (kg)	1	0	- 0.5	0	0
Electricity (kWh)	0	1	- 2	0	0
Kettle (unit)	0	0	1	-1	0
Water (litre)	0	0	0	3000	0
Waste (kg waste)	0	0	0	1	-1

Table 3.3 can be shown in a matrix ($\tilde{A}$) as

$$\tilde{A} = \begin{bmatrix} 1 & 0 & -0.5 & 0 & 0 \\ 0 & 1 & -2 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 3000 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix}$$

The environmental intervention matrix $\tilde{B}$ can be given by

$$\tilde{B} = [2 \quad 1 \quad 3 \quad 3 \quad 1]$$

The outputs of the product system, $\tilde{f}$, can be given by

$$\tilde{f} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 3000 \\ 0 \end{bmatrix}$$

Then, using the matrix representation approach the environmental impact of the kettle use ($\tilde{E}$) can be calculated as

$$\tilde{E} = \tilde{B}\tilde{A}^{-1}\tilde{f} = 10 \text{ kg } CO_2$$

A number of studies have adopted PRO-LCA approach to evaluate the environmental impacts of various wind turbines in different countries (Jungbluth et al., 2005, Varun et al., 2010). For example, Weinzettel et al. (2009) evaluated the environmental burdens of 5MW floating offshore wind turbines in Norway. Ardente et al. (2008) analysed the energy and environmental performances of onshore wind farms in Italy. Tremeac and Meunier (2009) compared the energy consumptions and GHG emissions of a 4.5 MW and a 250 kW wind turbines in France and found that large-size wind turbines would require less energy and emit less CO_2 per unit of powered output. Martinez et al. (2009) estimated life-cycle effects of 2 MW wind turbines in Munilla of northern Spain, focusing on the environmental impacts of wind turbines from manufacturing to decommission phase. The authors concluded that the manufacturing of components such as rotors, foundations and nacelle of a wind turbine have significant impacts on the environment, whilst the impacts at the decommission stage of wind turbines is relatively low.

However, the results from PRO-LCA do not often effectively account for all the environmental impacts due to the arbitrary selection of system boundary (no scientific evidence basis) that has a significant impact on the reliability of the studies (Weber and Matthews, 2007, Suh, 2004a). A number of studies have pointed out that the environmental impacts of excluded processes could be even higher than the environmental impacts of included processes (Suh, 2004a, Lenzen, 2000). At present, the choice of system boundary would be determined by mass, energy and environmental relevance of the inputs/outputs to and from the system. However, it is difficult to justify the significance of such inputs and outputs. As stated by Suh and colleagues:

> *"there is no theoretical or empirical basis that guarantees that a small mass or energy contribution will always result in negligible environmental impacts; there are input flows – ancillary materials and process energy – that bypass the product system and do not contribute mass or energy content to the final product."*
>
> – Suh et al. (2003) page 658

3.3.2 Input-output based life cycle analysis (IO-LCA)

Using economic flow databases, the full supply chain of a product system could be examined in the IO framework (Rebitzer et al., 2004). The employment of economic IO analysis in LCA solves the boundary problems in PRO-LCA since IO framework captures the processes which are neglected in PRO-LCA. A number of studies have compared the traditional LCA approach to the IO-LCA approach in different industries (Udo de Haes et al., 2004, Suh, 2004a, Treloar et al., 2000). For example, Junnila (2006) evaluated the differences in research findings between PRO-LCA and IO-LCA during the one-year operation of a service company in Finland. Primary data were collected and merged in 251 processes for PRO-LCA and 78 processes in IO-LCA. In order to improve the reliability of IO-LCA results, secondary data from a US based IO LCA database is used in Junnila's study. The results show that total environmental impacts calculated by IO-LCA are 50% higher than the results from PRO-LCA. Furthermore, purchased services represent one fourth of the total CO_2 emissions in IO-LCA as compared to 3.8% in PRO-LCA. The author stated that the disparities in results were caused by the boundary definition and lack of information in PRO-LCA.

Although the IO-LCA is preferable because of its completeness of upstream system boundary, a number of limitations exist in IO-LCA approach which may result in errors and uncertainties. Firstly, one of the basic assumptions in IO analysis is that one economic sector uses a single technology to produce average goods, which could lead to uncertainty and errors in results. As discussed above, a number of studies tried to solve the problem by introducing alternative technologies in the IO table, such as a new RCOT model was introduced by Duchin and Levine (2011) and supply and use framework. Secondly, environmental indicators may not be consistent with the IO table in terms of industrial classification and base year, according to (Lenzen, 2011). The author suggested that a disaggregation of environmental indicators, even with less detailed information, would generate more precise results than the aggregation of industries in an IO table. Thirdly, the environmental impacts in consumption stages are neglected in IO-LCA since only pre-consumption stages are considered (Suh and Huppes, 2005). In addition, imported commodities are not taken into account in a single region analysis, which might result in the neglect of emissions from upstream processes (Rebitzer et al., 2004). Multiregional IO analysis is used to examine the displaced pollution based on single country technology assumption. As addressed by Wyckoff and Roop (1994), national CO_2 emission reduction policies may be insufficient if imported products account for a significant proportion in a country's consumption. Peters and Hertwich (2006b) pointed out that over 70% of exports from developing countries are used to satisfy the needs in developed countries. Lastly, data availability of IO may not be consistent with the time when IO-LCA is implemented (Suh and Nakamura, 2007).

As can be seen from the kettle use example in Chapter 3.3.1, the PRO-LCA approach includes processes that have direct linkage to kettle use, such as use of steel and electricity in kettle production. However, it neglects the linkages between processes that are not directly related to kettle use. For instance, the production of steel may need inflows from the production of electricity, and vice versa. Thus, the system boundary of PRO-LCA approach is considered as imcomplete. By contrast, the IO approach examines the direct linkages as well as the indirect linkages between all sectors in an economy. Hence, the system boundary of IO approach is considered as complete.

3.3.3 Tiered hybrid analysis

To take advantages of the accuracy of PRO-LCA and the completeness of IO-LCA, several hybrid approaches, including tiered hybrid analysis, IO based hybrid analysis and integrated hybrid life cycle analysis have been widely used in examining the environmental impacts of different products (Lenzen and Crawford, 2009).

Tiered hybrid analysis was introduced by Moriguchi and collaborates in 1993, in which the authors examine the life cycle CO_2 emissions of an automobile (Moriguchi et al., 1993). The authors separate the environmental impact analysis into two stages. The IO-LCA is used to estimate the environmental impacts at pre-use phases, which leaves the use and end-of-life stages being examined in PRO-LCA. Tiered hybrid approach has also been used in renewable energy studies (Hondo, 2005). For example, Lenzen and Wachsmann (2004) employed a tiered hybrid approach to examine the variability of energy and CO_2 emissions embodied in wind turbine manufacturing between Brazil and Germany. Direct energy requirements and CO_2 emissions from construction, operation and decommission phases were calculated in detail by using a PRO-LCA. At the same time, indirect environmental effects (such as material extraction) were assessed in an IO analysis. The overall environmental impacts of wind turbines were then evaluated by combining the results from PRO-LCA and EIO analysis. Crawford (2009) examined and compared the life cycle energy consumptions and GHG emissions of a 850kW and a 3.0MW wind turbines in Australia. The environmental impacts of important materials used in wind turbine manufacturing such as concrete, steel, aluminium, copper, glass fibre, epoxy and paint were obtained from PRO-LCA. In order to complete the system boundary, remaining processes were calculated using an IO model. To avoid double counting, the processes covered in PRO-LCA were deducted from the IO analysis. Findings of the research showed that PRO-LCA accounted for 22% of the total energy consumption of wind turbines, namely, the incompleteness of PRO-LCA might result in a 78% deficiency in the calculation of overall energy requirements of wind turbines. Nakamura and Kondo (2002) used a hybrid life cycle analysis to estimate the waste flows in the IO model, which is called the waste IO model (WIO). The model links background economy (represented by IO, in monetary units) with waste management processes (in physical units). One of the most distinctive characters of the WIO model is that it allows for any number of waste types (e.g. buildings waste, household waste and etc.) and any number of treatment methods (e.g. landfill, composting and incineration), which has to be equal in the conventional IO model. An application of the WIO model was introduced to estimate and compare the environmental impact of different waste management policies in Japan.

Tiered hybrid approach provides a complete system boundary compared to PRO-LCA and also takes the post-consumption stages into account comparing to IO-LCA. However, the selection of boundary between PRO-LCA and IO-LCA, namely, the allocation of processes to PRO-LCA and IO-LCA is arbitrary. Such boundary selection may induce two errors in results. Firstly, the interactions between processes in PRO-LCA and IO-LCA are neglected. Secondly, important processes may be neglected and analysed in the aggregated IO-LCA. Another limitation of tiered hybrid approach is the problem of double counting. In principle, all economic activities are included in the national IO framework. Hence, those processes adopted in a PRO-LCA are already included in the IO-LCA.

3.3.4 Input-output based hybrid life cycle analysis

The IO table is too aggregate to be used for detailed analysis focusing on a speicific sector. In most cases, the industry has already existed in the IO table. Thus, it is necessary to disaggregate an existing economic sector in order to generate a new economic sector. Sector disaggregation in input-output tables would require significant amount of data, which include the sales and purchases patterns of the new sector to and from other sectors in an economy. However, one of the most significant drawbacks in sector disaggregation is the lack of detailed data. The collection of detailed data is time consuming and sometimes the required data is not available to IO practitioner due to confidential reasons.

Since required data is not available, partial-survey and non-survey methods have been used in sector disaggregation. A simple approach to disaggregate economic sectors in an input-output table is to use the weighted factors, which the outputs of new sectors are known (Joshi, 1999). However the simple weighted disaggregation approach might lead to uncertainty in input-output analysis, since all the inputs to and the outputs from the new sector are in proportional to the original sectors. In other words, it assumes that production structure and sales patterns of the new sector are identical to the original sector, which is not always the case in reality. For example, electricity sector in an input-output table always includes various power generation technologies, which have distinctive characters in terms of production structure. Thermal power generation would require substantial amount of fossil fuels to produce its outputs. By contrast, wind power generation would require limited amount of fossil fuels for power outputs, but depend on the operation of wind turbines.

As a result, more sophisticated models for sector disaggregation has been introduced in a number of studies. For example, Wolsky (1984) advanced the simple weighted disaggregation by introducing an approach to disaggregate one sector into two sectors. Additional matrix is used in the disaggregation, including an augment matrix, which is formulated by the proportion of each of the subsector to the original sector, and a distinguishing matrix, which uses variables to adjust the differences between subsectors (e.g. the supply from machinery to coal-fired plant might be higher than to wind power plant). Later on, Lindner et al. (2012) extended Wolsky's approach by disaggregating IO tables into an arbitrary number of new sectors instead of two sectors in Wolsky's approach. And also, the study used a random walk algorithm to explore the potential full range of values for the coefficients of the inverse Leontief matrix in the disaggregated IO table, comparing to a single value in the simple weighted disaggregation. Using China's electricity sector as an example, the authors concluded that, even with limited information of the new sector, the approach would present a better estimation than the simple weighted disaggregation.

Besides, a number of studies use process information to disaggregate the input-output table. Depending on the availability of process information, Ferrao and Nhambiu (2009) suggested that the incorporation of process-based LCA tools into input-output framework could help to provide more accurate estimation in sector disaggregation. This approach is referred to as IO-based hybrid life cycle analysis. In the IO-base hybrid LCA, new economic sectors are created by disaggregating existing industry sectors with detailed process-based life cycle data. Joshi (1999) introduced steps in the disaggregation (in Model III and Model IV)[8]. The newly created sector is separated from the existing economic sector by incorporating the share of the new sector in the original sector. Then, detailed process data are used to adjust the average values generated by using the share and to formulate the new economic sector eventually. IO based hybrid analysis is considered as an updated version of IO-LCA because the newly created sector is considered as a representative to the targeted product exclusively.

The disaggregation starts with a known share (represented by *s*) of the new economic sector to the existing economic sector. Hence, a new row and a new column are created through multiplying the values in the existing sector with the share (s) to represent the new sector (i.e. the wind energy sector in my case). The remaining values (those have a share of *1-s* in the existing economic sector *n*. The original technical coefficient matrix A', which has *n* × *n* dimension, is replaced by a new technical coefficient matrix A, which has *(n+1)* × *(n+1)* dimensions. The first *n-1* sectors in both models remain unchanged, and thus Equation 3.10 is derived.

$$\mathbf{A}'_{i,n-1} = \mathbf{A}_{i,n-1}$$ **Equation 3.10**

Where $\mathrm{A}'_{i,n-1}$ represents the original technical coeffient of the first *n -1* sectors; $\mathrm{A}_{i,n-1}$ represents the new technical coefficient of the first *n -1* sectors.

For the original sector *n*, I have

[8] Model III refers to the disaggregation of an existing economic sector by using the share of new economic sector in the total output of original economic sector. Model IV refers to iterative disaggregation, which uses detailed information from life cycle analysis to approximate the inputs to newly created economic sector.

$$\mathbf{A}'_{in} = (\mathbf{1} - \mathbf{s})\mathbf{A}_{in} + \mathbf{s}\mathbf{A}_{i,n+1}$$ **Equation 3.11**

Whereas *s* represents the proportion of the new sector to the existing sector; A'_{in} represents the original technical coeffient of sector *n;* A_{in} represents the new technical coeffient of sector *n;* $\mathrm{A}_{i,n+1}$ represents the new technical coeffient of sector *n+1.*

The input to sector *j* from the original sector *n* (A'_{nj}) in the new IO model is calculated by

$$\mathbf{A}'_{nj} = \mathbf{A}_{nj} + \mathbf{A}_{n+1,j}$$ **Equation 3.12**

Whereas A_{nj} and $\mathrm{A}_{n+1,j}$ represents the inputs from the new sector *n* and sector *n+1* to original sector *j.*

The input to sector *n* from the original sector *n* (A'_{nn}) in the new IO model and is calculated by

$$\mathbf{A}'_{nn} = (\mathbf{1} - \mathbf{s})(\mathbf{A}_{nn} + \mathbf{A}_{n,n+1}) + \mathbf{s}(\mathbf{A}_{n+1,n} + \mathbf{A}_{n+1,n+1})$$ **Equation 3.13**

Whereas *s* represents the proportion of the new sector to the existing sector; A_{nn}, $\mathrm{A}_{n,n+1}$, $\mathrm{A}_{n+1,n}$ and $\mathrm{A}_{n+1,n+1}$ gives the technical coefficients of the new sector *n* and sector *n+1*, respectively.

To formulate a new economic sector that represents a specific industry, iterative disaggregation is needed by incorporating detailed process information (Joshi, 1999). Here I use an example to describe the steps of sector disaggregation in this thesis.

Assuming an economy has four sectors, the technical coefficient matrix can be shown as Table 3.4.

Table 3.4 An example of sector disaggregation

		Economic sectors			
		1	2	3	4
Economic sectors	1	A_{11}	A_{12}	A_{13}	A_{14}
	2	A_{21}	A_{22}	A_{23}	A_{24}
	3	A_{31}	A_{32}	A_{33}	A_{34}
	4	A_{41}	A_{42}	A_{43}	A_{44}

Sector 4 needs to be disaggregated into two new sectors for a detailed analysis, with the new sector 4 accounts for 20% of the original sector 4 and the new sector 5 accounts for the remaining 80%. Hence, the new techinical coefficient matrix can be shown as

Table 3.5 Sector disaggregation with simple weighted factors

		Economic sectors				
		1	2	3	4_{new}	5_{new}
Economic sectors	1	A_{11}	A_{12}	A_{13}	A_{14} x 20%	A_{15} x 80%
	2	A_{21}	A_{22}	A_{23}	A_{24} x 20%	A_{25} x 80%
	3	A_{31}	A_{32}	A_{33}	A_{34} x 20%	A_{35} x 80%
	4_{new}	A_{41} x 20%	A_{42} x 20%	A_{43} x 20%	A_{44} x 20%	A_{45} x 80%
	5_{new}	A_{51} x 80%	A_{52} x 80%	A_{53} x 80%	A_{54} x 20%	A_{55} x 80%

As was discussed above, simple weighted disaggregation might lead to uncertainty in results as it assumes that the new sector (sector 5 in this case) has same production structure and sales pattern to the original sector. Hence, process information is used for an iterative disaggregation. For example, inputs from sector 2 to sector 5 represents 40% (rather than 80% in the initial guess) of the original sector 4, the value A_{25} x 80% should be adjusted to A_{25} x 40%; the remaining values are added back to the original sector 4 as A_{24} x 60%. And also, there is no input from the original sector 4 to the new sector 5. Then the value (A_{45} x 80%) should adjusted to 0; the remaining values are added back to the original sector 5 as A_{44} x 100%.

Likewise, all other sectors are adjusted manually correspondingly. As a result, a new technical coefficient matrix can be given as Table 3.6.

Table 3.6 Sector disaggregation with process information

		Economic sectors				
		1	2	3	4_{new}	5_{new}
Economic sectors	1	A_{11}	A_{12}	A_{13}	A_{14} x 20%	A_{15} x 80%
	2	A_{21}	A_{22}	A_{23}	A_{24} x 60%	A_{25} x 40%
	3	A_{31}	A_{32}	A_{33}	A_{34} x 40%	A_{35} x 60%
	4_{new}	A_{41} x 20%	A_{42} x 20%	A_{43} x 20%	A_{44} x 100%	0
	5_{new}	A_{51} x 80%	A_{52} x 80%	A_{53} x 80%	A_{54} x 15%	A_{55} x 85%

Using IO based LCA, environmental interventions can be calculated by

$$\boldsymbol{m} = \boldsymbol{B}(\boldsymbol{I} - \boldsymbol{A})^{-1}\,\boldsymbol{k}$$ **Equation 3.14**

Whereas *m* is the environmental impacts vector,

B is the environmental impacts matrix of size $q \times (n+1)$,

I is an identity matrix with $(n+1) \times (n+1)$ dimension,

A is the IO technical coefficient matrix with $(n+1) \times (n+1)$ dimension,

k is a vector that shows the functional unit (yuan/kWh).

3.3.5 Integrated hybrid life cycle analysis

Integrated hybrid analysis is an integration of matrix representation approach in PRO-LCA and IO-LCA. It is recognized as the most precise approach in assessing environmental impact of a product system (Suh and Huppes, 2005).

A general framework of the integrated hybrid life cycle analysis is given in Table 3.7. Two matrices are introduced to link IO analysis (represented by *A*) and conventional life cycle analysis (represented by $\tilde{A}$) in the integrated hybrid life cycle analysis. One matrix (represented by *U*) presents the upstream cut-off flows from the economic sectors in the IO system to the process system. The downstream cut-off flows from the process system to the IO system is represented by another matrix (represented by *D*).

Table 3.7 A general framework of integrated hybrid life cycle analysis

	Processes	Industries	Functional unit
Products	Physical flow matrix ($\tilde{A}$)	Downstream cut-off (*D*)	Functional unit of process system
Industries	Upstream cut-off (*U*)	Input-output matrix (*A*)	Functional unit of IO
Environmental intervention	Environmental intervention of LCA	Environmental intervention of IO	

The mathematical formulation of the integrated hybrid life cycle analysis approach is depicted in Equation 3.15.

$$\boldsymbol{G_{IH}} = \begin{bmatrix} \widetilde{\boldsymbol{B}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{B} \end{bmatrix} \begin{bmatrix} \widetilde{\boldsymbol{A}} & \boldsymbol{D} \\ \boldsymbol{U} & \boldsymbol{I} - \boldsymbol{A} \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{0} \end{bmatrix}$$ **Equation 3.15**

Where G_{IH} is the total environmental intervention matrix; $\tilde{B}$ and *B* are the environmental intervention matrix for the conventional LCA system and the IO system, respectively; $\tilde{A}$ represents inflows and outflows of products to processes in the conventional LCA system; *A* is the flows among economic sectors in the IO system; *U* is the upstream cut-off matrix, which represents the information that are neglected in the process-based LCA[9]; *D* is the

---

[9] Recall the hypothetical example of kettle use in Chapter 3.3.1. Processes that are directly linked to kettle production is included. However, the indirect processes, such as the use of electricity in steel production is neglected. Here, matrix *U* is used to represents these processes that are left out.

downstream cut-off matrix, which represents the use of inputs from the process system to the IO system[10]; *f* represents the functional unit of the LCA system, which is one kilowatt hour in this study.

Wiedmann et al. (2011) employed both IO based hybrid analysis and integrated hybrid analysis to examine the CO_2 emissions of wind power in the UK. The study found that total CO_2 emissions per unit of power output are similar between integrated hybrid LCA (28.7 g/kWh) and IO based hybrid LCA (29.7 g/kWh), but both these figures are much higher than the result derived from PRO-LCA (13.4 g/kWh), which implies that integrated hybrid LCA and IO based hybrid LCA includes upstream emissions that is neglected in PRO-LCA. The authors concluded that IO based hybrid LCA approach required less effort in model compilation and thus, it is considered as a simplified and efficient alternative to integrated hybrid approach. However, data requirement of this approach may incur higher costs. Acquaye et al. (2011) demonstrated the application of the integrated hybrid life cycle analysis in the estimation of GHG emissions of rape methyl ester (RME) biodiesel, which is considered as a promising alternative to fossil fuels in the UK. The authors concluded that upstream emissions account for 23% of total life cycle emissions of RME biodiesel.

3.3.6 Justification of methodology – IO based hybrid LCA and integrated hybrid LCA

As was discussed above, there are various approaches to examine environmental impacts of wind power, including IO analysis, PRO-LCA and tiered hybrid analysis, IO based hybrid LCA and integrated hybrid LCA.

---

[10] For example, the product system in process-based LCA might use inputs, such as machinery or electricity as inputs for the production. The contribution of downstream cut-offs on total environmental impacts is minor, especially if a demand on the functional unit is used. Chapter 6.3.4 provides a discussion of the inclusion of downstream matrix D.

For PRO-LCA, the most significant drawback is its inevitable truncation of the system boundary (Lenzen and Munksgaard, 2002), which could lead to significant uncertainty in interpreting the result. Thus, PRO-LCA is not used in this research study. IO-LCA solves the problems of system boundary selection. However, the electricity sector in China's IO table is too aggregate to represent specific power generation technologies (see Chapter 5 the electricity sector of China's IO table for details). Due to this, IO-LCA is not selected for use in this research.

Hybrid approaches combine the detail of PRO-LCA and the completeness of IO-LCA, which has advantages in terms of accuracy and sophistication. As was argued in Chapter 3.3.3, tiered hybrid approach neglect the interactions between PRO-LCA and IO-LCA. In addition, the selection of which processes should be covered in the PRO-LCA and IO-LCA is lack of scientific evidences.

Consequently, the IO based hybrid LCA and integrated hybrid LCA are chosen as the most appropriate research methodologies for this study.

3.4 The selected environmental indicators: CO_2 emissions and water consumption

Wang et al. (2010) considered renewable energy as an ideal solution to safeguard energy supply and to mitigate GHG emissions in China. The author pointed out that *'… renewable energy neither depletes natural resources, nor causes CO_2 or other gaseous emission into air or generates liquid or solid waste products'.* However, the argument is not appropriate since it neglects the environmental impacts of renewable energy during their life cycles.

A range of indicators are used in assessing the environmental impacts of renewable energy technologies, such as greenhouse gas (GHG) emissions and energy pay-back time (Varun et al., 2009). As one of the most promising renewable energy sources, the environmental impacts of wind power is also examined in a number of studies. For example, Fthenakis and Kim (2009) compared renewable energy sources (including wind, solar, hydro and biomass) to conventional energy sources (including coal, natural gas and nuclear) in terms of life-cycle land use. Two indicators are introduced: land transformation, which refers to the area of land altered; and land occupation, which refers to the area of land occupied and the duration of the occupation. The authors pointed out that the area of land altered by wind power is larger than most of the power generation technologies, except for hydropower and biomass. However, the conclusion disregarded the fact that 1) wind farms can be constructed on low quality land (e.g. brownfields); and 2) land occupied by wind turbines can also be used for other purposes, such as grazing. Others centred on the energy analysis of wind power. For instance, Schleisner (2000) examined the energy payback time of onshore and offshore wind farms in Denmark, using process-based life cycle analysis. The energy payback time for onshore and offshore wind farms were 0.26 and 0.39 years, respectively, due to significant differences in annual power generation (19,800 Megawatt hour (MWh) for onshore wind farm and 12,500 MWh for offshore wind farm).

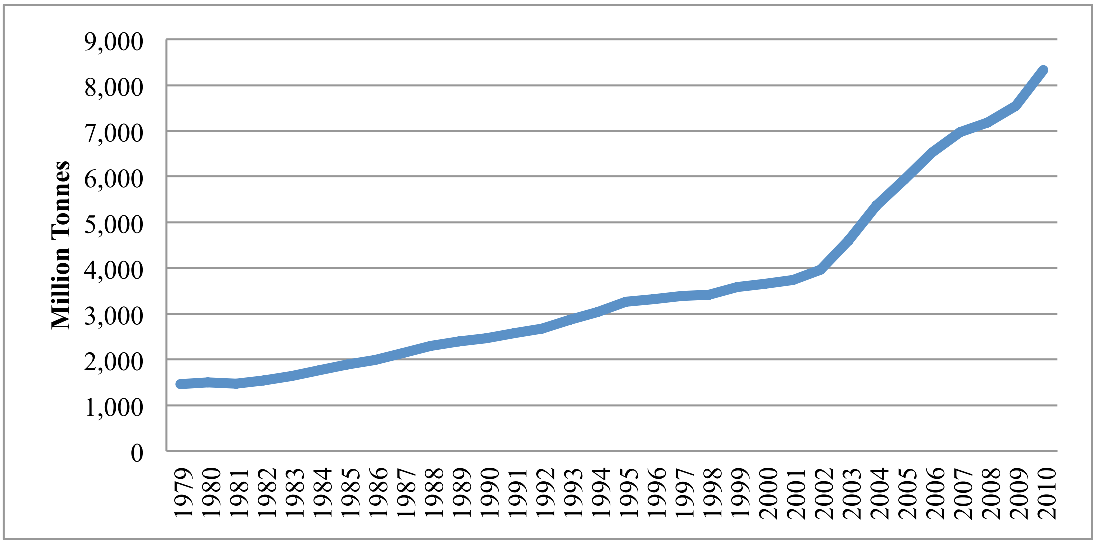
Among all the environmental indicators, two of them are of particular interest in this research study – CO_2 emissions and water quantity-quality impacts. In this section, rationales for choosing CO_2 emissions and water quantity-quality impacts as the environmental indicators in this study are explained.

3.4.1 China's soaring CO_2 emissions

China has been the largest CO_2 emitter around the globe since 2007, followed by the United States. In 2010, over one quarter of the global emissions happened in China (BP, 2011). It can be seen from Figure 3.2 that CO_2 emissions in China had experienced a steady growth between 1979 and

2001, with an annual growth rate of 11.1%[11]. The rate further accelerated in the last decade. Total emissions increased from 3969.8 MT in 2002 to 8332.5 MT in 2010 with an annual growth rate of 23.3%.

Figure 3.3 China's CO_2 emissions growth between 1979 and 2010



Source: BP (2011)

The United Nations Framework for Convention on Climate Change (UNFCCC) states the significance of mitigating greenhouse gas (GHG) emissions, the majority of which are energy-related CO_2 emissions, in order to avoid extreme weather conditions (UN, 1992). As the largest CO_2 emitter, China's contribution to CO_2 emission reduction would be vital to meet the target of limiting the global temperature rise to 2^{o}C.

3.4.1.1 CO_2 emissions reduction: Can wind power face up to the challenge?

In China, one of the alternatives in achieving carbon emissions reduction targets is to diversify the existing fossil fuel-based energy system with

---

[11] Own calculation. Figures are from BP (2011).

carbon-saving technologies such as renewable energy, hydropower and nuclear power (Chen et al., 2011, Wang and Watson, 2010, Zhang, 2010). The assessment of CO_2 emissions from different carbon-saving technologies needs to be implemented in order to assure the target of carbon mitigation can be achieved.

The assessment of CO_2 emissions of wind power can be categorised into two groups. The first group focuses on the life-cycle CO_2 emissions of wind power generation, which includes wind turbine manufacturing, transportation, operation and disposal (Martínez et al., 2009, Crawford, 2008, Wiedmann et al., 2011, Raadal et al., 2011, Wang and Sun, 2012). Lenzen and Munksgaard (2002) presented the first comprehensive review of life cycle CO_2 analyses concerning wind power. There are considerable variations in the 72 studies examined in terms of methodology (e.g. process analysis, IO analysis, or hybrid approaches), scope (e.g. the inclusion of wind turbine manufacturing, wind farm construction, decommission and grid connection, and etc.), selected wind turbine (from 1 kW to 5,000 kW), capacity factor (from 7.6% to 50.4%), and country of manufacture. The variations contributed to a wide range in CO_2 emissions, which is from 7.9 to 123.7 grams per kWh. The other group focuses on system-wide CO_2 emissions induced by the incorporation of fluctuated wind power to the entire power system (Valentino et al., 2012, Sioshansi, 2011, Denholm et al., 2005, Holttinen and Tuhkanen, 2004). There is no doubt that a combination of these two types of studies would comprehend the understandings of CO_2 emissions from the entire power system. However, the latter group is beyond the scope of this thesis because of the lack of data on power system operation, which are strictly confidential in China at the moment.

As presented in Chapter 2, China is the largest CO_2 emitter and its power generation system has been dominated by coal. It was also shown that wind power is expected to play a significant role in China’s power system in the future. However, regardless of the significance of wind power in CO_2 emission mitigation, life-cycle CO_2 emissions of wind power are rarely examined in China. Chapters 5 and 6 of this thesis exemplify two approaches to examine life-cycle CO_2 emissions of wind power in China.

3.4.2 China's water crisis

China's water resources are scarce and unevenly distributed (Xie et al., 2009). Water resource availability per capita in China is only one-fourth of the world average (Hubacek and Sun, 2007). A fast growing water use in China is expected in the coming decades. According to the China Ministry of Water Resources (2011), water use is projected to increase from 599 billion m^3 in 2010 to 670 billion m^3 in 2020. Contrary to the increase in demand, the overall water availability has fallen 13% since 2000 because of the shortage of snowfall and precipitation (Schneider, 2011b). The uneven distribution of water resources exacerbates the water shortage in the northern regions. In 2010, northern regions accounts for 19.6% of China's water resources, but approximately 40% of the total population (MWR, 2011). Two-thirds of the Chinese cities are facing water shortage, especially in the northern part of China (Dore et al., 2010). Hence, a large-scale water project aiming at diverting freshwater from the water-rich south to the water-poor north, has been under construction in China. Besides, water pollution is one of the most serious environmental challenges to China. In 2010, 38.6 % of rivers did not meet Grade III water quality standard (water is not safe for human consumption), 17.7% of which failed to meet Grade V water quality standard that are not suitable to use for any purposes (MWR, 2011). Over 300 million people do not have access to safe drinking water (Gleick, 2009).

The water crisis posed a significant challenge to the sustainable growth of Chinese economy. According to the World Bank (2007), economic costs of China's water scarcity and water pollution are equivalent to about 2.3% of GDP in 2003.

3.4.2.1 The energy-water nexus: rationales for including water uses in evaluating energy generation technologies

The linkage between energy and water is inextricable. On one hand, all types of power generation systems consume water either directly from the evaporation in the cooling system or indirectly from the incorporation into the manufacturing processes of power generation facilities. On the other hand, water needs energy to extract and deliver freshwater to end-users and also to treat wastewater that comes from water discharge. Besides the direct linkage, the indirect linkage of water and energy cannot be ignored. For instance, the increase of atmospheric greenhouse gas (GHG) emissions, which are mainly from the combustion of traditional energy sources such as coal, oil and natural gas has caused an increase of global average temperature, which in turn leads to climate change (IPCC, 2011). One of the wide-ranging consequences of climate change is the significant impact on freshwater resources. Those impacts include a decrease in water quality from raising water temperature, a reduction of water supply from glaciers and snows, the increase of floods and droughts, etc. (IPCC, 2008b).

The significant connection between energy and water has called for an integration of water issues in the energy system planning as well as an integration of the energy issues in the water system planning (Siddiqi and Anadon, 2011). However, energy and water are always treated independently, especially in energy-related discussions. The reduction of CO_2 emissions has been overwhelmingly addressed in government agenda, academic research and public debates since the accumulation of CO_2 in the atmosphere is considered as the major cause of climate change.

The energy sector not only contributes to CO_2 emissions increase but also shares a significant proportion of water uses in the world. For instance, in the U.S., water withdrawal of thermoelectric power plants amounts to 190,000 million of gallons per day which accounts for 48% of the total water withdrawal of the nation (Huston et al., 2005). Most water is used in the cooling systems of power generators through evaporation. At the same time, indirect water consumption in coal mining (0.034 litres per kilowatt hour) and coal washing (0.01 litres per kilowatt hour)[12] is also substantial (Mielke et al., 2010). Not only conventional thermal power plants, new power generation plants which are regarded as carbon-saving alternatives also have significant water consumption implications. For example, according to the United States Department of Energy (USDoE) (2006), the application of carbon capture and storage power plants would lead to 50% - 90% increase in water consumption. Concentrated solar energy (CSP) consumes 3.16 litre/kWh, which is twice as much as traditional coal-fired power plants 1.48 litre/kWh[13] (Glassman et al., 2011).

The choice of water-intensive power generation plants either exacerbates the problem of water supply in water scarcity regions or constrains operations efficiency of water-intensive power plants during water-shortage periods (Mo et al., 2010). As argued by Cooper and Sehlke (2012):

> *'If mitigation efforts become too focused on GHG emission reductions at the expense of other considerations, then such efforts run the risk of creating new problems that may have a greater negative impact on sustainability.'*

- Cooper and Sehlke (2012)

Hence, in addition to carbon emissions it is vital to evaluate water consumption in different types of power generation in order to achieve climate change mitigation objectives and to meet environmental targets such

---

12 The figures given in Mikele's study are 2.6 gallons per MMBtu and 0.8 gallons per MMBtu, respectively. I have converted the unit to litre per kWh using 1 MMBtu = 293 kWh, 1 gallon = 3.79 litre.

13 The figures given in Glassman's study are 835 gallon per MWh and 390 gallon per MWh, respectively. I have converted the unit to litre per kWh using 1 MWh = 1,000 kWh, 1 gallon = 3.79 litre.

as use of water resources. Failure to do so may simply shift the problem to other places.

Water and energy issues are not well-linked in China. In a recent interview conducted by Asia Water Project China of World Resources Institute (WRI), the China Water Team stated that:

> *'National energy policies often do not fully consider or reflect their implications on freshwater consumption. Likewise, policies for improving freshwater availability often do not consider their implications on energy use.'*
>
> – Asia Water Project China (2011)

Very few studies are found in the existing literature examining the connection of energy and water issues with a specific issue in China. Kahrl and Roland-Holst (2008) presented one of the first studies on the energy-water nexus in China. Using an IO analysis, the authors focused on the energy consumption of water use and they concluded that energy requirements in non-agriculture water provision were insignificant – representing less than 0.5% of China's total energy consumption. Furthermore, changes in energy price would not have a significant impact on water prices in China. Most of other existing studies that examine the connection of energy and water are related to potentials of power generation using water resources (Chang et al., 2010a).

The life cycle CO_2 emissions, water consumption and water quality impact of wind power in China will be examined in Chapters 5 and 6 in great detail at national and regional level, respectively.

3.5 Chapter three summary

Chapter 3 discusses the research design and chosen methodology used for this study. There are three approaches frequently used to assess the environmental impact of wind power, including IO analysis, process-based LCA and hybrid analysis such as tiered hybrid LCA, IO based hybrid LCA and integrated hybrid LCA. The foundation and application of these approaches are discussed in great detail and justifications for selecting the research methods (i.e. IO based hybrid LCA and integrated hybrid LCA) for this research are given too. In sum, the chosen methods take advantages from the completeness of the IO analysis and the detail of LCA analysis to provide more accurate results than IO or LCA on its own.

Besides, two environmental indicators (i.e. CO_2 emissions and water uses in terms of quantity and quality) are also selected for this study to demonstrate the impacts of energy power on the environment. Rationales for choosing these two environmental indicators and adopting a case study approach have been explained in great detail.

Chapter 5 and Chapter 6 presented applications of the chosen models on evaluating CO_2 emissions and water impacts of wind power in China.

Chapter 4 Wind Power in China – Dream or Reality?

An overview of the growth of wind power in China during the past decade and the significance of wind power in the future power mix of China has been given in Chapter 2. Despite the recent growth rates and promises of a bright future, two important issues - the capability of power grid infrastructure and the availability of backup systems - must be critically discussed and tackled in the medium term. This chapter aims to examine these two issues and suggest solutions to face up to the challenges. It starts with a brief introduction of wind power development in China and provide a review of the existing literature to identify the gaps which this research is focused on bridging. It is followed by examining China's power grid system and back-up system to which wind power is to be integrated and identifying the potential and barriers of doing so. The chapter is concluded with a discussion of the possible solutions to tackle the problems.

4.1 Introduction

As explained in Chapters 1 and 2, China's wind energy industry has experienced a rapid growth over the last decade. In addition, the wind energy potential in China is also considerable.

The existing literature of wind energy development in China focuses on several discussion themes. The majority of the studies emphasize the importance of government policy on the promotion of wind energy industry in China (Wang and Chen, 2010, Yu and Qu, 2010, Liu et al., 2002, Zhang et al., 2009). For instance, Lema and Ruby (2007) compared the growth of wind generation capacity between 1986 and 2006, and addressed the importance of a coordinated government policy and corresponding incentives. Several studies assessed other issues such as the current status of wind energy development in China (Xu et al., 2010); the potential of wind power (Liu and Kokko, 2010); the significance of wind turbine manufacturing (He and Chen, 2009); wind resource assessment (Yu and Qu, 2010); the application of small-scale wind power in rural areas (Lew, 2000); clean development mechanism in the promotion of wind energy in China (Wang and Chen, 2010), social, economic and technical performance of wind turbines (Han et al., 2009) etc.

There are few studies which assess the challenge of grid infrastructure in the integration of wind power. For instance, Wang (2010) studied grid investment, grid security, long-distance transmission and the difficulties of wind power integration at present. Liao et al. (2010) criticised the inadequacy of transmission lines in the wind energy development. However, I believe that there is a need to further investigate these issues since they are critical to the development of wind power in China. Furthermore, wind power is not a stand-alone energy source; it needs to be complemented by other energy sources when wind does not blow. Although the viability and feasibility of the combination of wind power with other power generation technologies have been discussed widely in other countries, none of the papers reviewed the situation in the Chinese context. In this chapter, I discuss and clarify two major issues in light of the Chinese wind energy distribution process: 1) the capability of the grid infrastructure to absorb and transmit large amounts of wind powered electricity, especially when these wind farms are built in remote areas; 2) the choices and viability of the backup systems to cope with the fluctuations of wind electricity output.

4.2 Is the existing power grid infrastructure sufficient?

Wind power has to be generated at specific locations with sufficient wind speed and other favourable conditions. In China, most of the wind energy potential is located in remote areas with sparse populations and less developed economies. It means that less wind powered electricity would be consumed close to the source. A large amount of electricity has to be transmitted between supply and demand centres leading to several problems associated with the integration with the national power grid system, including grid investment, grid safety and grid interconnection.

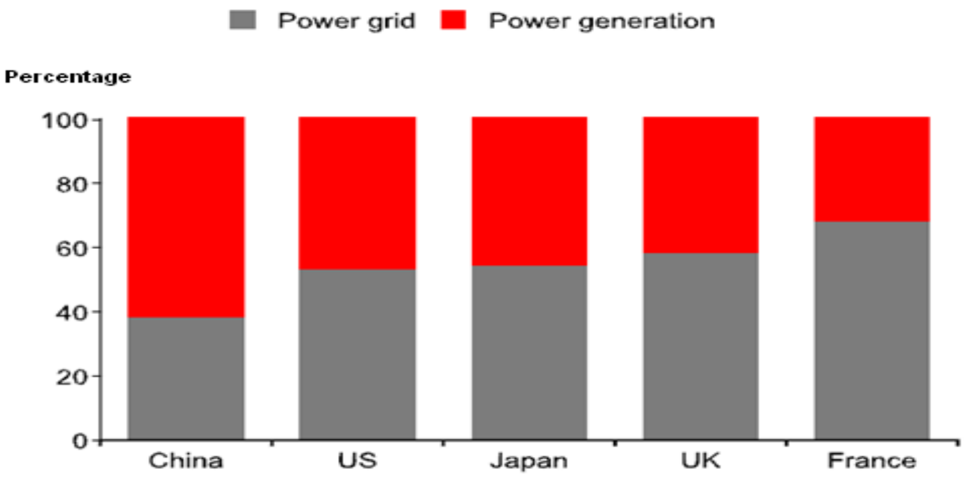
4.2.1 Power grid investment

Although the two state grid companies - State Grid Corporation of China (SGCC) and China Southern Grid (CSG) - have invested heavily in grid construction, China's power grid is still insufficient to cope with increasing demand. For example, some coal-fired plants in Jiangsu, which is one of the largest electricity consumers in China, had to drop the load ratio to 60 percent against the international standard of 80 percent due to the limited transmission capacity (Fenby and Qu, 2008). This situation is a result of an imbalanced investment between power grid construction and power generation capacity. For example, during the Eighth Five-Year Plan, Ninth Five-Year Plan and Tenth Five Year Plan[14], power grid investments accounted for 13.7%, 37.3% and 30% of total investment in the electricity sector, respectively. The ratio further increased from 31.1% in 2005 to 45.94% in 2008, the cumulative investment in the power grid is still significantly lower than the investments in power generation (SERC, 2009). Figure 4.1 gives a comparison of the ratios of accumulative investments in power grid and power generation in China, the US, Japan, the UK and France since 1978. In most of these countries, more than half of the electric power investment has been made on grid construction. By contrast, the ratio is less than 40% in China.

---

[14] The Five-Year Plan is the strategic planning of five consecutive years of the economic development in China. For example, the Eighth Five-Year Plan is from 1991 to 1995, the Ninth Five-Year Plan is from 1996 to 2000 and the Tenth Five -Year Plan is from 2001 to 2005, and so on and so forth.

Figure 4.1 A comparative study of national accumulated investment in power grid and power generation since 1978

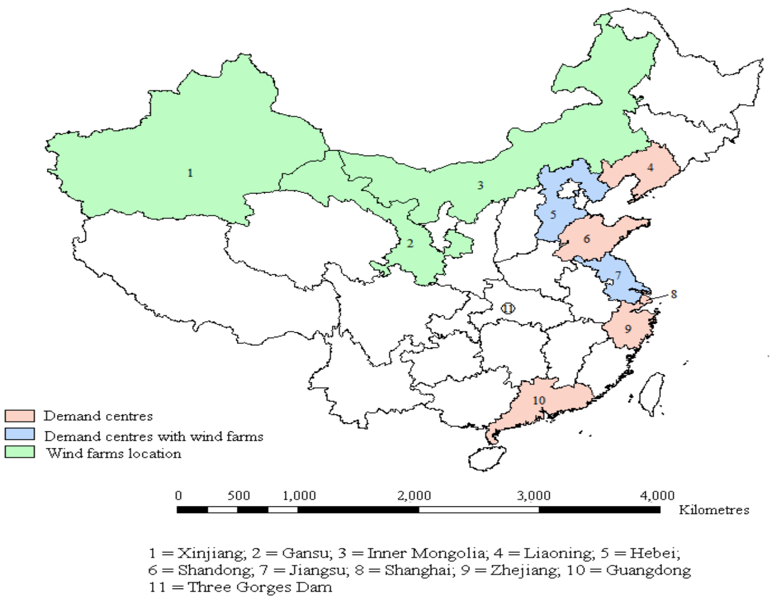


Source: Fenby and Qu (2008)

According to the Articles 14 and 21 of the Chinese Renewable Energy Law, the power grid operators are responsible for the grid connection of renewable energy projects. Subsidies are given subject to the length of the grid extension with standard rates. However, Mo (2009) found that the subsidies were only sufficient to compensate for capital investment and corresponding interest but excluding operational and maintenance costs.

Again, similar to grid connection, grid reinforcement requires significant amounts of capital investment. The Three Gorges power plant has provided an example of large-scale and long-distance electricity transmission in China. Similar to wind power, hydropower is usually situated in less developed areas. As a result, electricity transmission lines are necessary to deliver the electricity to the demand centres where the majority are located; these are the eastern coastal areas and southern part of China. According to SGCC (2007), the grid reinforcement investment of the Three Gorges power plants amounted to 34.4 billion yuan (about 5 billion US dollars). This could be a lot higher in the case of wind power due to a number of reasons. First, the total generating capacity of Three Gorges project is approximately 18.2 GW at this moment and will reach 22.4 GW when fully operating (Lenzen, 2009), whilst the total generating capacity of the massive wind farms amount to over 100 GW. Hence, more transmission capacities are absolutely necessary. Second, the Three Gorges hydro-power plant is located in central China. A number of transmission paths are available, such as the 500 kV DC transmission lines to Shanghai (with a length of 1,100 km), Guangzhou (located in Guangdong province, with a length of 1,000 km) and Changzhou (located in Jiangsu province, with a length of 1,000 km) with a transmission capacity of 3 GW each and the 500 kV AC transmission lines to central China with transmission capacity of 12 GW. By contrast, the majority of wind farm bases, which are located in the northern part of China, are far away from the load centres. For example, Jiuquan located in Gansu has a planned generation capacity of 20 GW. The distances from Jiuquan to the demand centres of the Central China grid and the Eastern China grid are 1,500 km and 2,500 km, respectively. For Xinjiang, the distances are even longer at 2,500 km and 4,000 km, respectively. As a result, longer transmission lines are required. Figure 4.2 depicts the demand centres and wind farms in detail.

Figure 4.2 Locations of wind farms and electricity demand centres in China



Source: Figures for wind farms from (Xinhua, 2009); Figures for demand centres from (CEPY, 2009)

4.2.2 Grid safety

The second problem is related to grid safety. The large scale penetration of wind electricity leads to voltage instability, flickers and voltage asymmetry which are likely to cause severe damage to the stability of the power grid (Chen and Blaabjerg, 2009). For example, voltage stability is a key issue in the grid impact studies of wind power integration. During the continuous operation of wind turbines, a large amount of reactive power is absorbed, which lead to voltage stability deterioration (Chi et al., 2006). Furthermore, the significant changes in power supply from wind might damage the power quality (Holttinen, 2009). Hence, additional regulation capacity would be needed. However, in a power system with the majority of its power from baseload provider, the requirements cannot be met easily (Ipakchi and Albuyeh, 2009). In addition, the possible expansion of existing transmission lines would be necessary since integration of large-scale wind would cause congestion and other grid safety problems in the existing transmission system. For example, Holttinen (2009) summarized the major impacts of wind power integration on the power grid at the temporal level (the impacts of power outputs at second, minute to year level on the power grid operation) and the spatial level (the impact on local, regional and national power grid). Besides the impacts mentioned above, the authors highlight other impacts such as distribution efficiency, voltage management and adequacy of power on the integration of wind power (Holttinen, 2009).

One of the grid safety problems caused by wind power is reported by the State Electricity Regulatory Commission (SERC, 2011b). In February and April of 2011, three large-scale wind power drop-off accidents in Gansu (twice) and Hebei caused power losses of 840.43 MW, 1006.223 MW and 854 MW, respectively, which accounted for 54.4%, 54.17% and 48.5% of the total wind powered outputs. The massive shutdown of wind turbines resulted in serious operational difficulties as frequency dropped to 49.854Hz, 49.815Hz and 49.95Hz in the corresponding regional power grids.

The Chinese Renewable Energy Law requires the power grid operators to coordinate the integration of windmills and accept all of the wind powered electricity. However, the power grid companies have been reluctant to do so due to the above mentioned problems as well as technical and economic reasons. For instance, more than one third of the wind turbines in China, amounting to 4 GW capacity, were not connected to the power grid by the end of 2008 (SERC, 2009). Given that the national grid in China is exclusively controlled by the power companies – SGCC and CSG - the willingness of these companies to integrate wind energy into the electricity generation systems is critical.

4.2.3 The interconnection of provincial and regional power grids

The interconnection of trans-regional power grids started at the end of 1980s. A high voltage direct current (HVDC) transmission line was established to link the Gezhouba[15] dam with Shanghai which signifies the beginning of regional power grids interconnection. In 2001, two regional power grids, the North China Power Grid and Northeast China Power Grid were interconnected. This was followed by the interconnection of the Central China Power Grid and the North China Power Grid in 2003. In 2005, two other interconnection agreements were made between the South China Power Grid with North, Northeast and Central China Power Grid, and the Northwest China Power Grid and the Central China Power Grid. Finally, in 2009, the interconnection of Central China Power Grid and the East China Power Grid was made. In today's China, the Chinese power transmission systems are composed of 330kV and 500kV transmission lines as the backbone and six interconnected regional power grids and one Tibet power grid (Fu et al., 2010).

It seems that the interconnectivity of regional power grids would help the

---

[15] Gezhouba – the first dam on the Yangtze River – is located in northwest of Yichang City with a total length of 2,561 meters. It is 38 kilometres away from the Three Gorges Dam and 1,000 kilometres away from Shanghai.

delivery of wind powered outputs from wind-rich regions to demand centres. However, administrative and technical barriers still exist. First, the interconnectivity among regions is always considered as a back-up to contingencies, and could not support the large-scale, long-distance electricity transmission (Li et al., 2010). In addition, the construction of transmission systems is far behind the expansion of wind power. The delivery of large amounts of wind power would be difficult due to limited transmission capacity. Furthermore, the quantity of interregional electricity transmission is fixed (Li et al., 2010). Additional wind power in the interregional transmission might have to go through complex administrative procedures and may result in profit reductions of conventional power plants.

4.3 Are the backup systems geographically available and technically feasible?

Power system operators maintain the security of power supply by holding power reserve capacities in operation. Although terminologies used in the classification of power reserves vary among countries (Rebours et al., 2007), power reserves are always used to keep the production and consumption in balance under a range of circumstances, including power plant outages, uncertain variations in load and fluctuations in power generations (such as wind) (Holttinen, 2005). As wind speed varies on all timescales (e.g. from seconds to minutes and from months to years), the integration of fluctuating wind power generation induces additional system balancing requirements on the operational timescale (Holttinen, 2005).

A number of studies have examined the approaches to stabilize the electricity output from wind power plants. For example, Belanger and Gagnon (2002) conducted a study on the compensation of wind power fluctuations by using hydropower in Canada. Nema et al. (2009) discussed the application of wind combined solar PV power generation systems and concluded that the hybrid energy system was a viable alternative to current power supply systems in remote areas. In China, He et al. (2008)

investigated the choices of combined power generation systems. The combinations of wind-hydro, wind-diesel, wind-solar and wind-gas power were evaluated respectively. They found that, for instance, the wind-diesel hybrid systems were used at remote areas and isolated islands. This is because the wind-diesel hybrid systems have lower generation efficiency and higher generation costs compared to other generation systems. Currently, the wind-solar hybrid systems are not economically viable for large-scale application; thus, these systems have either been used at remote areas with limited electricity demand (e.g. Gansu Subei and Qinghai Tiansuo) or for lighting in some coastal cities (He et al., 2008). Liu et al. (2011a) adopted the EnergyPLAN model to investigate the maximum wind power penetration level in the Chinese power system. The authors derived a conclusion that approximately 26% of national power demand could be supplied by wind power by the end of 2007. However, the authors fail to explain the provision of power reserves at different timescales due to wind power integration.

Because of the smoothing effects of dispersing wind turbines at different locations (as exemplified by Drake and Hubacek (2007) for the U.K., Roques et al. (2010) for the E.U. and Kempton et al. (2010) for the U.S.), the integration of wind power has a very small impact on the primary reserves which are available from seconds to minutes (Dany, 2001). However, the increased reserve requirements are considerable on secondary reserves (available within 10 – 15 minutes) which mainly consist of hydropower plants and gas turbine power plants (Holttinen, 2005). Besides, the long-term reserves, which are used to restore secondary reserves after a major power deficit, will be in operation to keep power production and consumption in balance for a longer timescale (from several minutes to several hours). In the following subsection, I examine the availability of power plants providing secondary and long-term reserves and investigate the viability of energy storage system in China.

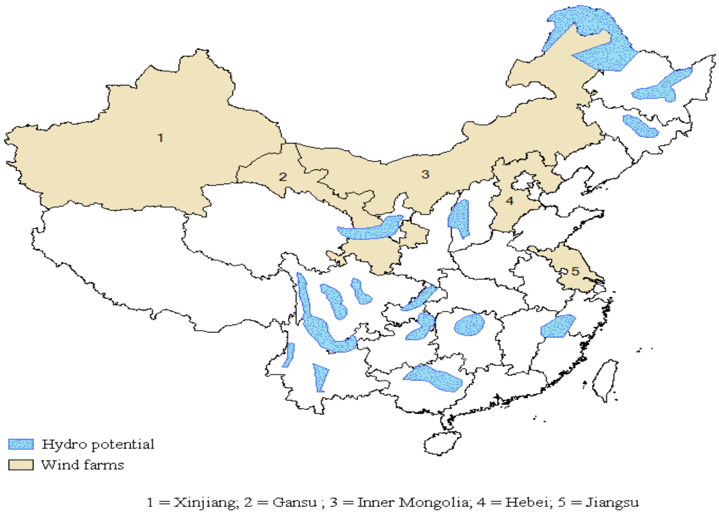
4.3.1 The availability of secondary reserve capacity

4.3.1.1 Hydropower system

There are two types of wind-hydro hybrid systems. The first type of hybrid system is the combination of wind power generation systems and hydropower generation systems. When electricity output from wind farms fluctuates, the hydropower plants could be used to provide the auxiliary supply to the electricity output. The rationale of using hydropower plants as a backup system is based on their quick response to electricity demand. The other type of combined hydro-wind power systems uses hydro storage systems. The foundation of this combined system, which is discussed in detail in chapter 4.3.3, is to store excessive energy by pumping water from the lower reservoirs to the higher reservoirs and to release the power when electricity output from wind farms is decreasing.

China has one of the largest hydropower resources in the world and its total exploitable capacity amounts to 542 GW (Li and Shi, 2006). As one of the major sources in the electricity mix, hydropower has contributed to approximately 16% of the total electricity consumption in China for the year 2010. However, the choice of the wind-hydro power generation system is dependent on the locations of the available energy sources. Given that most of the hydropower resources are located in south-west China, (He et al., 2008) suggested that wind-hydropower generation systems might not be appropriate in specific areas such as Inner Mongolia, Hebei and Jiangsu, as the spatial distributions between the wind energy potentials and the hydropower potentials are not matched (see Figure 4.3).

Figure 4.3 The distribution of hydropower potential and the locations of wind farms in China



Source: Figures for hydropower potential from (Wang and Chen, 2010); Figures for wind farm locations from (Xinhua, 2009)

Table 4.1 shows the comparison between proposed wind farm generation capacity and hydropower resources in the five wind farm regions. In some locations such as Gansu and Xinjiang, the synergy of the wind-hydro hybrid system is possible because of the regional advantage of areas with both high hydropower and wind power potential. However, most wind farm locations do not have sufficient hydropower potential. Consequently, the combination of wind-hydro systems is not without problems given the spatial mismatch of the two energy potentials.

Table 4.1 A comparison of the Chinese proposed wind turbine installed capacity and hydropower potentials in five wind farm provinces by 2020

Provinces	Proposed wind turbine installed capacity	Hydropower potential
Inner Mongolia	50 GW	2.6 GW
Gansu	20 GW	9.0 GW
Xinjiang	20 GW	15.6 GW
Jiangsu	10 GW	0.02 GW
Hebei	10 GW	1.3 GW

Source: Figures for hydropower potential from (Li and Shi, 2006); Figures for proposed wind generation capacity from (Xinhua, 2009)

4.3.1.2 Natural gas power system

The other solution to balance the power outputs from wind power is the application of wind and natural gas combined generation system. Compared to other thermal power generation systems, the natural gas power generation system has the advantages of less pollution, higher efficiency and quicker response (He et al., 2008).

The China Academy of Engineering (CAE) has carried out a feasibility study of the combined power generation system in Xinjiang (He et al., 2008). In this analysis, a number of factors were examined such as the generation capacity of the wind farm, capacity factor of the wind turbine and the generation capacity of the natural gas power plant. The CAE study concluded that with capital cost at 7,500 yuan/kW for wind farms, natural gas price at 1.2 yuan/m^3 and wind turbine capacity factors at 30%, the cost of wind-gas combined power generation system is 0.5 yuan/kWh. Although the cost of hybrid generation systems per unit of electricity output is higher than the cost of wind powered output alone (0.42 yuan/kWh), it is economically viable if the stability of the power grid is taken into consideration (He et al., 2008).

However, these findings might be misleading due to a number of reasons. First, the capital costs of wind farms are higher than 7,500 yuan/kW. According to Liu and Yang (2008), the capital investments of windmills are approximately 10,000 yuan/kW for MW-level wind turbines in 2008.

Second, the end-user prices of natural gas vary significantly amongst regions in China due to the lengths of transportation from the supply centres to the demand centres. The price for industrial use gas in Inner Mongolia, Gansu, Xinjiang, Hebei and Jiangsu are 1.67 yuan/m^3, 1.25 yuan/m^3, 1.25 yuan/m^3, 2.00 yuan/m^3 and 2.75 yuan/m^3, respectively (Higashi, 2009).

Third, China had been self-sufficient in natural gas supply up until 2006. The increasing demand and limited domestic supply have resulted in gas imports in recent years. Although several agreements have been made between China and Russia, Turkmenistan and other supply countries to guarantee natural gas supply, the prices of imported natural gas are twice as much as from domestic supply. Since increasing amounts of natural gas have to be imported, the current natural gas price regime is likely to change. Hence, power generation companies have been reluctant to use natural gas as a major electricity supply source. By the end of 2006, gas-fired power plants accounted for only 2.5% of total generation capacity (Higashi, 2009).

Fourth, the capacity factors of wind farms in China are far below the expected level. The State Electricity Regulatory Commission (2009) found that six out of seven wind farms, which were randomly selected in seven provinces, had fewer operating hours (1,864 hours on average) than the designed operating hours (2,305 hours on average). The capacity factor of these six wind farms is 21.3% which is considerably below the expected 26.3%.

Last but not least, there is no doubt that the hybrid generation system would help to reduce the variation of the electricity output from wind farms.

However, the total electricity output from the hybrid generation system might double the electricity output from wind farms alone. For example, in the CAE study, the total electricity generation amounts to 1.3 TWh from the hybrid system per year, with 0.52 TWh from the wind farm and 0.78 TWh from the natural gas power plant (He et al., 2008). Considering most of the electricity needs to be transmitted to the demand centres, which are around 3,000 km away, it will require more lines and capacities in electricity transmission. As a result, none of the assumptions, which have been made in the CAE study to justify the economics of wind-gas generation systems, have been met. Application of the wind-natural gas hybrid electricity generation system remains doubtful in the future.

4.3.2 The availability of long-term reserve capacity

4.3.2.1 Nuclear power system

Nuclear power is considered as one of the important technologies in diversifying the future power generation mix in China. According to the Mid-Long Term Plan for Nuclear Power in China (2005 – 2020), total generation capacity would increase from 7 GW in 2005 to 40 GW in 2020. Total power output would reach 260 - 280 TWh (NDRC, 2007a). Currently, there are six nuclear power stations with total generation capacity amounted to 9 GW built in Zhejiang and Guangdong. Another 7.9 GW of nuclear power generation facilities are under construction (NDRC, 2007a). The development of nuclear power has been controversial in China especially since the nuclear crisis after Japan's devastating earthquake in March 2011. Although the Chinese authorities temporarily suspended nuclear power projects approval and stated the government would prioritise safety issues regarding nuclear power development in the future, the suspension would only be considered as a temporary order taking into account the needs of energy system diversification (Biello, 2011).

In addition, most of the nuclear power stations are built or planned around the coastlines in order to fulfil the electricity demand in the developed coastal areas. Hence, it is less possible to use nuclear power as compensation to the variable wind power due to the mismatch in spatial location. More importantly, as a base-load provider, nuclear power plants always deliver stable and continuous power outputs. For example, in 2007, existing nuclear power plants in China operates 7,793 hours on average, which is significantly higher than coal-fired power plants (5,466 hours)[16]. The continuous operation mode of nuclear power generation units made them incapable in ramping ups and downs quickly (Chalmers and Gibbins, 2006). Consequently, nuclear power is not appropriate to compensate for the variation of wind powered outputs.

4.3.2.2 Coal power system

In China, coal is dominating the energy system. 74% of primary energy consumption was provided by coal in 2009 (NBS, 2010). In addition, coal-fired power plants accounted for approximately 76% of electricity generation and over 97% of thermal power plants (Chen and Xu, 2010). The current electricity mix is not likely to change any time soon due to the relatively abundant Chinese coal reserves compared to oil and natural gas reserves and the growth in energy demand caused by changes in lifestyles and increasing urbanization (Guan et al., 2008, Hubacek et al., 2007). Table 4.2 gives the composition of the electricity mix for six planned wind farms.

---

[16] Own calculation, figures from CEPY (2008)

Table 4.2 The share of power generation capacity in the Chinese case study provinces in 2008

	Hydropower	Thermal	Nuclear	Wind
National	21.77%	76.05%	1.12%	1.06%
Hebei	4.80%	93.02%	0.00%	2.18%
Inner Mongolia	2.68%	92.61%	0.00%	4.71%
Jiangsu	2.09%	93.13%	3.68%	1.12%
Gansu	36.07%	59.55%	0.00%	3.98%
Xinjiang	20.09%	75.23%	0.00%	4.68%

Source: own calculation, figures from (CEPY, 2009)

As stated by Goggin (2008), the integration of wind power is likely to result in a decrease of energy efficiency for thermal power plants. The loss of energy efficiency comes from the frequent start-up and shut-down of these plants in order to balance the fluctuating electricity output of windmills. For example, White (2004) found that a 2% energy efficiency loss would result in a 150 grams CO_2 emission growth per kWh electricity output for a coal-fired boiler. Consequently, the loss of energy efficiency might have significant impacts on the overall CO_2 emission from coal power plants. In addition, the design and operation of these base load providers fit a stable and continuous power output mode. The frequent ramping ups and downs might cause more frequent and higher costs of maintenance (White, 2004). Another issue of using coal as a backup is that, as mentioned in Chapter 4.3.1.2, the total power output from the combined system might be significant. To sum up, the use of coal-fired plants as the backup system is unavoidable because of the coal-dominated electricity mix. Although the distribution of coal is consistent with the wind energy potential, several problems such as loss of efficiency and requirements of grid reinforcement are significant.

4.3.3 Energy storage systems

As mentioned above, the integration of large-scale wind farms to the insufficient grid infrastructure might result in instability of the power grid. In addition, the feasibility of hybrid power generation systems remains doubtful due to geographical and economic reasons. Another option in wind energy integration is the application of an energy storage system.

There are two types of energy storage systems available at present. First, physical energy storage systems such as wind powered pumped hydro storage systems (Bueno and Carta, 2006) and compressed-air systems (Enis et al., 2003) are used. However, the applications of the physical energy storage systems are constrained by geographic conditions and capital costs. For instance, wind powered pumped hydro storage system requires large areas and sufficient water resources for the upper and lower reservoirs. By the end of 2007, there have been 18 pumped hydro storage plants operated in China. Another 11 plants are under construction. However, only one pumped hydro storage plant was built in the most important three wind farm bases (Inner Mongolia, Gansu and Xinjiang) (Network, 2010). In addition, a number of electrochemical energy storage systems are available, such as lead-acid battery energy storage systems, redox flow cell energy storage systems and sodium-sulphur battery energy storage system. Compared to the physical energy storage systems, the maximum energy storage capacity could only reach 10 MW (He et al., 2008). Since the majority of the wind farms have a generation capacity of 50 MW, electrochemical batteries are not appropriate to be used as energy storage systems in China. Consequently, hybrid generation systems and energy storage systems are likely to solve the wind-powered electricity fluctuations in some areas. However, such systems will only serve a limited proportion of proposed wind farms in the future. The majority of the wind generation capacities still require considerable efforts for the integration into the regional or national power grid systems.

The back-up system to wind power should be considered as part of the wind power generation. Regardless of the selected back-up technology, it can be represented in the IO framework either by disaggregating existing economic sectors or by formulating a new sector using new data. However, both approaches would require substantial amount of data, such as the production structure of the back-up system and its linkages to wind power generation system. Collaborations with people from the field of engineering might be able to help to gather the information. Nevertheless, the inclusion of back-up systems in wind power analysis presents significant potentials in I-O modelling in the future.

4.3.4 The asymmetrical relationship between wind power and other power generation technologies

In addition to the above mentioned issues, a number of factors such as resource availability, load characteristics and safety standards need to be prioritised from the beginning of the construction of conventional power plants rather than the hybridizing with wind power. For example, combined heat and power (CHP) plants in the northern part of China are important because they provide both electricity and heat to the end-users in winter. A significantly higher proportion of the CHP plants are found in northern China (e.g. 72% in Jilin). It is not possible to adjust the peak and light load by using these CHP plants. Since the strongest wind also blows in winter, power system operators have to curtail the wind power outputs during the light load period in order to provide sufficient heat supply (Li, 2009). Thus, it is naturally hard to make the combination of wind power with those possible options match each other well in reality.

4.4 Future prospects of wind energy development in China

4.4.1 The construction of ultra-high voltage transmission system

The power grid system is of good quality in China since the majority of the grid infrastructure has been constructed during the past decades (KPMG, 2010). However, even when operated with modern and efficient power grids, transmission losses are still significant and amount to more than 6% of the electricity produced (Li, 2009). In addition, due to the uneven distribution of energy sources and the huge territory, excessive amounts of wind electricity need to be delivered to the load centres requiring long-distance, large-capacity electricity transmission lines.

The transmission system can be classified by different voltage levels[17]. An ultra-high voltage (UHV) transmission system has been planned by SGCC as the primary electricity carrier in China's future transmission system (Liu et al., 2011b). Several factors are taken into consideration in the choice of transmission lines. The application of UHV transmission lines would reduce power losses significantly. For example, Li (2009) pointed out that the use of UHV transmission system would save up to 100 TWh electricity per year, which equals the annual power generation from 20 GW equivalent coal-fired plants. Furthermore, the costs and land use of an UHV transmission lines are lower than the other high voltage transmission systems for long-distance power transmission (Zhang et al., 2006). Although the feasibility of UHV transmission lines and related grid safety issues have been very controversial, over 600 billion yuan (88 billion US dollar) of investments have been initiated by SGCC for the next decade to extend and enhance grid infrastructure with a special focus on UHV transmission system (Li, 2009). Of this, 42.8 billion yuan (6.3 billion US dollar) would be directly invested in wind integration related grid construction (SGCC, 2011). The future UHV transmission system would consist of ±800kV DC lines for large capacity electricity transmission from the west and north to the east and south and 800 – 1,000kV AC lines for building an interconnected regional network in China[18]. With the completion of the UHV transmission system, the capability of power grids in wind power integration would be doubled and could

---

[17] High voltage levels consist of: 100(110) kV, 138 kV, 161 kV, 230 (220) kV; Extra high voltage levels are: 345(330) kV, 400 kV, 500 kV, 765(750) kV; Ultra high voltage is alternating current larger than 765kV and direct current larger than 600 kV (Zhang, et al. 2012).

[18] For the choice of transmission system (different voltage levels, and AC or DC), see Zhang et al. (2012).

accommodate up to 90 and 150 GW of wind power by 2015 and 2020, respectively (SGCC, 2011).

4.4.2 The applications of non-grid connected wind power

Besides the large-scale grid-connected wind farms, other applications of wind power such as the direct use of wind power could also provide opportunities for future wind power development in China (Xu et al., 2010). Non-grid wind power has attracted a lot of attention in the international power system research (Hensel and Uhl, 2004, Pavlak, 2008). The direct application of wind energy in these end-use devices is due to two major factors. First, the operation of these end-use devices would not be affected by the variable output of wind. For example, water heating and hybrid vehicle battery charging do not require a consistent power supply. Second, load period is matched to wind power supply period. For example, wind power outputs reach their highest level when space heating is needed (Kempton et al., 2007). Zhou and Min (2009) proposed a non-grid wind power application at less developed area in China. The principle of non-grid wind power application is to harness the wind energy when wind blows and to use the power supply from power grid when wind power output is insufficient. This type of non-grid wind power application guarantees the full usage of wind power and ensures the power quality for the consumers through the complementary supply from the power grid. Taking into account the power supply requirements of the cement industry and the characteristics of wind power, Miller et al. (2008) proposed a hybrid wind-gas power system to provide reliable and cleaner electric power to energy intensive industries. Other off-grid applications, such as small-scale wind power (less than 100kW) in the remote areas (Zhang and Qi, 2011), and the applications in desalination and aluminium smelting are also discussed in the literature (Hensel and Uhl, 2004).

During the past 15 years, energy-intensive industries such as chemical, mineral and cement industries have been growing quickly. For example, the ratio of light and heavy industry decreased from 50:50 between 1987 and 1997 to 30:70 between 1997 and 2007 (Li, 2009). There are several advantages of non-grid-connecting wind power, including avoidance of grid safety issues induced by wind power integration, effective harnessing of wind source, reduction in equipment required in grid-connection and cutting costs for intensive-energy consumers by using low-cost wind sources (Zhou and Min, 2009). The development of clean energy direct application would be addressed in the national grid connection standard, which has been proposed by the Chinese government (Liu et al., 2011b).

4.4.3 The development of offshore wind power in China

In addition to the inland areas, the wind power potentials around the coastal areas and islands in east and southeast China are also significant. For example, Jiangsu province is one of the six large-scale wind farms, which has total wind generation capacity of 10 GW to be installed by the end of 2020. Shandong, Shanghai and Guangdong also have significant offshore wind power potential (Xu et al., 2010). The locations of these wind farms are considered superior to the inland wind farms, since they are nearer to the demand centres. Hence, long-distance transmission is not necessary to offshore wind farms. In addition, offshore wind power outputs are less variable than the onshore wind power outputs due to the consistent wind resources around the coastlines. Since the first offshore wind farm was constructed at Shanghai Dongda bridge in 2009, many offshore wind farms have been planned for the next decades in provinces such as Zhejiang and Shandong. For example, total proposed offshore wind capacity would be 3.7 GW for Zhejiang and 7 GW for Shandong at the end of 2020. Total offshore wind capacity would reach 15.1 GW and 32.8 GW by the end of 2015 and 2020, respectively (Li et al., 2010). Hence, development of offshore wind power would be significant in China in the next decades.

4.5 Policy implications

4.5.1 Power transmission planning and operation

To facilitate network planning and operation and to exploit economies of scale, many countries have proposed replacing multiple power grid operators with single horizontally-integrated operators in recent years (OECD, 2007). For example, the United Kingdom consolidated its transmission and distribution system into one single company during its power system restructure in 1990. Meanwhile, China's power system has undergone a profound institutional reform since 1985, including the dismantling of business operations from the government power industry department, encouragement of private and foreign investment in power generation, unbundling of transmission and distribution from generation, and so on (Xu and Chen, 2006). As part of the reform, two state-owned grid companies (SGCC and CSG) were established by the end of 2002 and are responsible for the power transmission and distribution in 26 provinces and 5 provinces, respectively. The monopoly in transmission and distribution has provided a foundation to facilitate the grid planning and operation in China. However, provincial governments and agencies are not always compliant with the command by the central government and agencies, which make the inter-provincial and inter-regional transmission planning and operation fragile. Williams and Kahrl (2008) pointed out that the divergence of central and local authorities' interests and the ineffective policy implementation has resulted in such non-compliance in the Chinese power system. It seems paradoxical for a top-down economy such as China but such conflict was rooted in China's other industries and history (Williams and Kahrl, 2008). Hence, it is important to implement a national co-ordination policy which should define the responsibility of central, regional and provincial authorities in the grid planning and operation. Corresponding governance at central, regional and provincial level should be addressed to guarantee the effective implementation of such policy. In addition, economic incentives and penalties need to be created to encourage the participation of provinces in inter-provincial and inter-regional power trade.

In addition to harmonizing the operations among regions, a policy focusing on the responsibility of the monopoly grid companies, such as whether the power transmission and distribution companies should invest in power generation assets, is critical and necessary. SGCC has invested in offshore wind farms in Shanghai (Yang, 2010). Because of the monopoly of SGCC and CSG, the participation of power grid owners in wind energy development might induce unfair competition, such as giving priorities to their own wind farms during integration and electricity purchase. Such policy should also emphasize the construction of smart grid and UHV transmission lines in accordance with the future development of wind power (such as transmission capacity and transmission paths), which are necessary to the large-scale integration of wind energy into the existing electricity mix.

4.5.2 From capacity growth incentives to performance improvement incentives

Current Chinese policies focus on installed capacity in the pursuit of a sustainable electricity mix. For instance, the Medium-Long Term Renewable Energy Development Plan has stipulated the responsibility of power generation companies which have more than 5,000 MW generation capacities to contribute 3% and 8% of their generation capacity to non-hydro renewable energy sources by 2010 and 2020, respectively. The mandatory timelines and proportion commitments have induced the large power generation companies to increase capacity growth, thus contributing to the actual operating hours of wind turbines being much lower than the expected operating hours. According to (Liu and Yang, 2008), more than 70% of the windmills were owned by these large power generation companies by the end of 2007. Installing large numbers of wind turbines alone, although creating workplaces in several industrial sectors such as manufacturing, transportation and finance is not a sufficient reason by itself unless they are being used for electricity generation. Thus, the tremendous growth in generation capacity is exciting but not convincing. Most countries addressed the proportion of total electricity supply from wind power at a target year.

Similar measurements should be adopted in China. Such policy might encourage the wind farm developers, especially the state-owned power generation companies, to focus on the actual performance of wind turbines, which in turn would stimulate the technology improvement of wind turbine manufacturers.

4.5.3 Compensation mechanism

It is important to establish a compensation mechanism for the partial loading of conventional power generation systems resulting from wind power integration. Renewable energy, such as wind, is given priority in the power grid operation at present according to the Renewable Energy Law. Hence, during the full-load operation of wind power, there will inevitably be restrictions on the operation of conventional power plants, especially coal-fired ones which have already been operating under significant profit losses due to the centrally planned electricity prices[19]. The restrictions on conventional power plants operations would induce further profit losses and further damage their willingness to provide power generation.

4.5.4 Demand side management

Previous regulations regarding power planning in China often emphasize the supply side. As an alternative to altering the power supply, encouraging demand response to changes in power supply would also help in the integration of wind power. China's national demand-side management regulations went into effect at the beginning of 2011, in which power grid

---

[19] One recent large-scale electricity shortage happened in April and May 2011, which are not the normal peak load season, in a number of provinces. A large number of thermal power plants were shut down for maintenance. However, it is believed that the cause of such large-scale power plants maintenance is because the centrally planned electricity price could not cover the generation cost. Consequently, thermal power plants are reluctant to operate as usual.

companies are required to reduce power sales by 0.3% and of maximum power load by 0.3% by implementing demand side management. The regulation highlights the improvement of energy efficiency but it does not address the planning and management from an end-user perspective. Currently, the application of wind power to some specific industries, especially those energy-intensive industries, is not supported by the SGCC which would see a significant decline in profit since energy-intensive industries are the primary consumers of electricity (Liu et al., 2011b). Hence, it is necessary to legislate the demand-side activities such as the deployment of distributed wind power by introducing a comprehensive government policy.

4.5.5 Coal as backup: one step forward two steps back

A number of studies have examined the impact of large-scale wind energy on the power generation systems in various countries, such as Denmark, Germany and the U.S. (Holttinen, 2009). It is noticeable that these countries have either significant proportions of flexible power generation units or a well-connected power grid, or both. With limited power grid infrastructure, it remains worrisome when large-scale wind energy is integrated into the coal-dominated generation system in China. The Chinese government should notice that capacity displacement is a necessary but not sufficient condition in the measurement of CO_2 emission reduction in the power system. In other words, the displacement of traditional thermal power plants with more sustainable energy sources is necessary to reduce the overall CO_2 emissions in the power system. However, the loss of energy efficiency in coal-fired plants due to compensating fluctuations in the wind powered output will result in higher CO_2 emissions (Pehnt et al., 2008), which might cancel out part of the emission savings of wind energy. For example, Lenzen (2009) concluded that between 35g and 75g of CO_2 emissions would be emitted from the altered operation in conventional power plants due to the integration of wind, and this would outweigh the emissions from the wind turbine lifecycle. The author also pointed out that the technology mix would be vital to these values. Consequently, a comprehensive investigation of wind energy-related emissions, including the emissions from wind turbine production and abnormal operations of conventional power systems, should be carried out.

4.6 Conclusions

This chapter shows that the existing power grid system is insufficient to cope with the extensive growth of wind energy in recent years. Furthermore, the backup systems at different time scales are either geographically too remote from the potential wind power sites or currently financially infeasible. The construction of a UHV transmission system with an integrated national power grid would help the integration of wind power in the future. In addition, the development of offshore wind power would be significant in the next decade. Sustained efforts need to be made to accommodate wind energy in the coming decades because the overall power generation system is only as strong as its weakest link. Hence, emphasising the whole system and focusing on the bottlenecks are the foundations of building a robust and sophisticated electric system.

Chapter 5 Energy-Water nexus of wind power in China: The balancing act between CO_2 emissions and water consumption

At the end of 2010, China's contribution to global CO_2 emissions reached 25.1%. Estimates show that power generation accounts for 37.2% of the Chinese CO_2 emissions. Even though there is an increasing number of studies using life cycle analysis (LCA) to examine energy consumption and CO_2 emissions required by different types of power generation technologies, there are very few studies focusing on China. Furthermore, the nexus between water consumption and energy production has largely been ignored. In this chapter, input-output based hybrid life cycle analysis is adopted to evaluate water consumption and CO_2 emissions of wind power in China. It starts with a discussion of linkages between energy and CO_2 emissions and water consumption at the beginning. It is followed by introducing the research method (input-output based hybrid life cycle analysis), data source and compilation for the national research case study in this chapter. Results on CO_2 emissions and water consumption are given. This chapter is concluded with a discussion of implementing a scenario analysis on projecting China's CO_2 emissions reduction and water consumption reduction by 2020. Implications of the projections and the recommended solutions are elaborated and explained.

5.1 Introduction

Water and energy are inextricably linked. On the one hand, all types of power generation systems consume water either directly through evaporation or indirectly when water is consumed along the supply chains for manufacturing and construction of power generation facilities and technologies. On the other hand, water supply requires energy to extract and deliver freshwater to end-users or to treat wastewater.

The significant connection between energy and water has called for an integration of water issues in energy planning and an integration of energy issues in water planning and management (Siddiqi and Anadon, 2011). The energy sector not only contributes to an increase in CO_2 emissions, but also consumes a lot of water. A number of studies have been carried out to analyse the connection of energy and water focusing on the water requirements of energy production (Fthenakis and Kim, 2010, Sovacool and Sovacool, 2009). For instance, in the U.S., water withdrawal of thermoelectric power plants amounted to 190,000 million gallons per day which accounted for 39% of all freshwater withdrawal of the nation in 2000 (Huston et al., 2005). Installed with wet-cooled systems, nuclear, coal and natural gas combined cycle power plants consume 2.9 litre, 2.6 litre and 1.4 litre per kilowatt hour (kWh) power output, respectively (Burkhardt et al., 2011). Furthermore, some of the carbon-saving energy production alternatives are water intensive. For example, the water consumption of concentrated solar power (CSP)[20] can be substantial (Glassman et al., 2011). According to Burkhardt et al. (2011), CSP consumes more water (up to 4.7 litres/kWh) than most thermoelectric power plants, although the application of dry-cooling systems can reduce the total water consumption by 77% during their life cycle. In addition, the application of a carbon capture and storage (CCS) system in retrofitting fossil fuel based power plants would lead to an estimated 50% - 90% increase in water consumption when compared with coal power plants without CCS (Gerdes and Nichols, 2009).

---

[20]CSP system is one of the applications of solar power which uses mirrors and lenses to concentrate sunlight from a large area to a small target area. The concentrated sunlight is converted to heat which could drive a steam turbine to produce electric power.

The choice of water-intensive power generation plants either exacerbates the problem of water supply in water scarce regions or constrains operations of water-intensive power plants during periods of water-shortages (Mo et al., 2010). Hence, in addition to curbing carbon emissions, it is vital to evaluate water consumption in different types of power generation in order to achieve climate change mitigation objectives and meet environmental targets such as sustainable management of water resources. To date, little research has been done looking at the intersection of energy and water issues in China. Kahrl and Roland-Holst (2008) presented one of the first studies on the energy-water nexus in China, using IO analysis. The authors focused on the energy consumption of water use and they found that energy requirements in non-agriculture water provision were insignificant – representing less than 0.5% of China's total energy consumption. The percentage share of water use might increase by one to two percent if the energy consumption for irrigation is taken into account.

At the end of 2010, China's contribution to global CO_2 emissions reached 25.1% (BP, 2011). In China, the power generation industry accounted for 37.18% of the total CO_2 emissions (CCChina, 2011b). As one of the most promising low carbon energy sources in the future energy system, China's wind energy has been experiencing a significant growth in recent years. Since the promulgation of the Renewable Energy Law in 2006, the wind power generation capacity has increased from 1.26 GW to 44.7 GW by the end of 2010 (GWEC, 2011). In 2010, approximately half of the newly installed wind turbines in the world were deployed in China. At present, China has the largest installed capacity of wind power, followed by the U.S. (GWEC, 2011). Although issues such as power grid infrastructure and back-up systems pose significant problems for wind energy diffusion, the future growth of wind generation capacity would still be substantial (Li et al., 2012b). The U.S. Energy Information Administration (2010) estimated that wind powered electricity production would increase from 6,000 GWh in 2007 to 374,000 GWh in 2035. Since 90% of carbon emissions from wind power are from upstream processes such as turbine manufacturing and transportation (Weisser, 2007), the amount of water consumed by upstream processes should not be ignored. Thus, there is a need for an integrated approach to analyse water consumption and CO_2 emissions of the supply chain for wind energy in China. In this chapter, I adopt an input-output (IO) based hybrid life cycle analysis (LCA) to examine the energy-water nexus for the wind power sector in China.

5.2 Methodology

Although most renewable energy, such as wind, solar and hydro, is considered as nil emissions during operation, the upstream environmental impacts are not negligible (Weisser, 2007) although frequently ignored. The impacts such as CO_2 emissions and energy consumption can effectively be captured using LCA. Broadly speaking, three approaches are found in LCA, namely a bottom-up approach (also known as the process-based LCA (PRO-LCA)), a top-down approach (also known as the environmental IO based LCA (IO-LCA)) and a combination of PRO-LCA and IO-LCA (also known as hybrid analysis).

A number of studies have adopted the PRO-LCA approach to evaluate the environmental impacts of various wind turbines in different countries (Ardente et al., 2008, Jungbluth et al., 2005, Tremeac and Meunier, 2009, Varun et al., 2010). However, the results from PRO-LCA do not often effectively account for all the environmental impacts of wind power due to the problem of boundary definition which has a significant impact on the reliability of the studies (Weber and Matthews, 2007). The adoption of IO-LCA solves the boundary problems in PRO-LCA. A number of studies have compared the PRO-LCA approach to the IO-LCA approach in different industries (Suh et al., 2003, Treloar et al., 2000, Udo de Haes et al., 2004). Although the IO-LCA approach can effectively capture the environmental impacts of a specific product because of its completeness of upstream system boundary, there are a number of limitations which may result in errors and uncertainties (e.g. sector aggregation, environmental indicator misalignment, neglect of post-consumption stages, etc.). To take advantages of the accuracy of PRO-LCA and the completeness of IO-LCA, several hybrid approaches have widely been used in examining the environmental impacts of different products, including tiered hybrid analysis, IO based hybrid analysis and integrated hybrid analysis (Lenzen and Crawford, 2009, Wiedmann et al., 2011).

The choice of research method (PRO-LCA, IO-LCA or the hybrid approaches) often largely depends on the goal and scope, the geographical coverage, and the availability of time and resources of the research (Hertwich, 2005).

The PRO-LCA approach is not a suitable choice for this study because the definition of system boundary may cause significant truncation errors (Hertwich, 2005). In addition, the IO-LCA model is not chosen for use in this study. According to Joshi (1999), the IO-LCA model can be adopted if the technical coefficients and the environmental impact coefficients are representative to the economic sector of interest. Since the electricity sector of the 2007 national IO table is confined to electricity generation, transmission, distribution, and heat generation and distribution, it is not appropriate to represent wind energy. Furthermore, the border selection of PRO-LCA and IO-LCA in tiered hybrid analysis is arbitrary. It may result in double counting due to the fact that the IO table already includes all the commodity flows. Although the integrated hybrid LCA generates more accurate results than the IO based hybrid analysis, the resources (in terms of time and financial cost) required for gathering data in integrated hybrid LCA are substantial. Hence, I adopt an IO based hybrid analysis in this study.

5.2.1 Input-output based hybrid life cycle analysis

IO based hybrid LCA is an extension of the basic IO-LCA methods, in which new economic sector(s) are introduced through disaggregating the existing IO table[21]. In this study, the 'electricity sector' in China's IO table is disaggregated into 'wind energy sector' and 'all other electricity generation sector'. The disaggregation starts with a known share (represented by *s*) of the new economic sector to the existing economic sector. Hence, a new row and a new column are created through multiplying the values in the existing sector with the share (s) to represent the new sector (i.e. the wind energy sector in my case). The remaining values (those have a share of *1-s* in the existing economic sector *n*. The original technical coefficient matrix A', which has *n* × *n* dimension, is replaced by a new technical coefficient matrix A, which has *(n+1)* × *(n+1)* dimensions. The first *n-1* sectors in both models remain unchanged, thus I have

$$\mathbf{A}'_{i,n-1} = \mathbf{A}_{i,n-1} \qquad \textbf{Equation 5.1}$$

For the original sector *n*, I have

$$\mathbf{A}'_{in} = (\mathbf{1} - \mathbf{s})\mathbf{A}_{in} + \mathbf{s}\mathbf{A}_{i,n+1} \qquad \textbf{Equation 5.2}$$

The input to sector *j* from the original sector *n* in the new IO model is calculated by

$$\mathbf{A}'_{nj} = \mathbf{A}_{nj} + \mathbf{A}_{n+1,j} \qquad \textbf{Equation 5.3}$$

---

[21] It refers to Model III and Model IV in Joshi (1999). Model III depicts the disaggregation of an existing industry sector using percentage values. Model IV extends the disaggregation in Model III by incorporating the conventional LCA data.

The input to sector *n* from the original sector *n* in the new IO model is calculated by

$$\mathbf{A}'_{nn} = (\mathbf{1} - \mathbf{s})(\mathbf{A}_{nn} + \mathbf{A}_{n,n+1}) + \mathbf{s}(\mathbf{A}_{n+1,n} + \mathbf{A}_{n+1,n+1}) \qquad \textbf{Equation 5.4}$$

To formulate a new economic sector that represents a specific industry, iterative disaggregation is needed by incorporating detailed process information (Joshi, 1999).

Using IO based LCA, environmental interventions can be calculated by

$$\boldsymbol{m} = \boldsymbol{B}(\boldsymbol{I} - \boldsymbol{A})^{-1}\,\boldsymbol{k} \qquad \textbf{Equation 5.5}$$

Whereas *m* is the environmental impacts vector,

B is the environmental impacts matrix of size *q* × *(n+1)*,

I is an identity matrix with *(n +1)* × *(n+1)* dimension,

A is the IO technical coefficient matrix with *(n +1)* × *(n+1)* dimension,

k is a functional unit vector (yuan/kWh).

5.2.2 Data source and data compilation

The primary dataset of this study is based on the most recent 2007 national IO table for China. The electricity sector in IO table is frequently considered as a homogenous entity, although its components have distinctive character (Weber et al., 2010). In the IO tables of China, aggregated data is found in the electricity sector, which includes electricity generation, transmission, distribution, and heat generation and distribution. The quantification of CO_2

emissions and water consumption of wind energy under the IO framework calls for a disaggregation of the existing electricity sector to formulate an additional sector that only represents wind energy.

To achieve this, I use the feasibility reports of 50 Chinese wind farms, which qualified for the clean development mechanism (CDM) requirements by the end of 2007. The total generation capacity of these 50 wind farms is 2,603 megawatt (MW), accounting for 44.3% of China's cumulative generation capacity in 2007. The computed average generation capacity for each wind farm is 52.06 MW. The computed procedure of total turnover of wind energy sector is given in Appendix One.

I also obtain the data on total outputs of electricity sector (which is 3,148.6 billion yuan) from the national IO table to compute the percentage share of wind power in China, which is 1.7% (in terms of monetary value). It is followed by disaggregating the electricity sector using the calculated percentage (1.7%) to form the new wind energy sector.

The newly created wind energy sector is not representative since only percentage value is used in the disaggregation. Due to this, I incorporate an 800kW wind turbine life cycle inventory (LCI) data which is extracted from Ecoinvent Centre[22] in this analysis. There are a number of reasons of so doing. First, Chinese wind turbines are produced with purchased licenses from or in cooperation with other wind turbine manufacturers, especially European wind turbine manufacturers. Based on that, I assume that the materials used in wind turbine manufacturing in China are identical to those used in the Europe. Second, 6,469 wind turbines were installed in China by the end of 2007, with the total generation capacity of 5.9 GW and an average

---

[22] Ecoinvent Centre provides international life cycle inventory data on areas of agriculture, energy supply, transport, waste treatment and so on and so forth. See www.ecoinvent.ch for detailed information.

wind turbine size of 912 kW (Shi, 2008), which is not too far off from my chosen 800kW wind turbine life cycle inventory (LCI) data extracted from Ecoinvent. Since LCI data are in physical units, I convert the LCI data into monetary units using the 2007 China Price Yearbook (NDRC, 2008). I adopt the method used in Wiedmann et al. (2011) to make the adjustment of the newly created wind energy sector. The adopted conversion method is described below.

First, the converted monetary values, such as values of steel and copper, are used to replace the values calculated using the percentage. Second, I manually adjust the sectors that I consider not relevant to wind energy, such as the non-alcoholic beverage and tobacco products, in which I set the value to zero in the newly formulated wind energy sector and add the value back to the original electricity sector. Finally, I use the bi-proportional matrix balancing technique (also called RAS technique[23]) to balance the IO table, which has the original 135 sectors plus 1 wind energy sector.

I construct the CO_2 emission inventory based on the method used by Peters et al. (2006). Energy data is drawn from China Energy Statistical Yearbook (NBS, 2008a), which has physical consumption of 20 types of energy sources in 44 economic sectors. As there is a mismatch of classification of sectors between the energy statistical yearbook and the national IO table, there is a need for either disaggregating the energy data or aggregating the IO data. According to Lenzen (2011), the disaggregation of IO data is preferred to the aggregation of environmental data, even with limited data on the sectoral disaggregation. However, Lenzen's suggestion is based on a higher level of detail of available environmental data than the given sectoral detail of the IO tables. In China, detailed sectoral environmental data is not

[23] The RAS technique - also known as bi-proportional matrix balancing technique - is a methodology widely used to evaluate, balance or update matrices. For detailed description, refer to Miller and Blair (2009), Chapter 7, p313 - 335.

widely available. For example, China Energy Statistics Yearbook provides energy consumption for 44 economic sectors while China IO table contains 135 economic sectors. Due to this, in this study, I aggregate my 136 economic sectors (135 original classification plus 1 wind energy sector) into 44 economic sectors according to the sectoral classification from the Energy Statistical Yearbook. I then divide CO_2 intensity by total monetary outputs for each of the 44 economic sectors to generate CO_2 emission coefficient, assuming identical direct CO_2 coefficients in each sector.

In existing studies on energy-related water requirements, two terms are often mentioned - water withdrawal and water consumption. Water withdrawal is referred to as the volume of freshwater abstracted for a specific purpose (WFN, 2011). Water consumption refers to the volume of freshwater used and then being evaporated during production or incorporated into a product (WFN, 2011). It is important to clarify the terms used in this study because water withdrawal and water consumption in power generation are very different. For example, the U.S. power generation withdraws 24.5 gallon and consumes 0.5 gallon of freshwater per kWh power output on average (USDoE, 2006). Besides, according to Shuster and Hoffmann (2009), the daily water withdrawal for thermoelectric generation was 136 billion gallon when compared to 4 billion gallon for water consumption in 2000[24]. In this study, my focus is on water consumption of wind power. I obtain sectoral water consumption data from the Ministry of Water Resources (MWR, 2006). The approach and method that I used to calculate CO_2 emission coefficients is applied here to generate the water consumption coefficients.

---

[24] The figures are inconsistent between these two studies - the ratio between water withdrawal and water consumption per kWh is 59 in USDoE (2006), whereas the ratio is 34 for total water withdrawal and water consumption in Shuster and Hoffmann (2009). It may be due to methodological inconsistency and gaps in the federal datasets (Macknick et al. 2011). However, this investigation is beyond the scope of this study.

5.2.3 Limitations and constraints

This Chapter has several limitations.

1) Since detailed environmental data for China is unavailable, I assume that similar industries have the same CO_2 emission coefficients and water consumption coefficients. For example, I aggregate the 136 IO sectors in accordance with the 44 economic sectors classification given in China Energy Statistical Yearbook in order to generate the CO_2 emission coefficients.

2) The LCA data is based on 800kW-wind turbines which can cause overestimation of CO_2 emissions of wind power. By the end of 2009, the average turbine size is 912kW in China, which is larger and more efficient than my selected 50 Chinese wind farms. According to Lenzen and Munksgaard (2002), a bigger turbine would generate lower CO_2 emissions per kWh electricity output.

3) My focus is on the national level of water consumption and CO_2 emissions of wind power in China disregarding the regional situation in terms of water availability, wind supply and energy consumption.

4) The requirements of backup systems and grid extensions are not included in this chapter. Also, it is necessary to point out that the comparison of greenhouse gas (GHG) emissions and water consumption among power generation sources might be inappropriate since the one-to-one replacement of electricity produced with different sources might not be a valid assumption. A number of studies have expressed concerns on the appropriateness of one-to-one kWh based replacement. For example, Weisser (2007) deemed the comparison of GHG emissions between traditional power generation technologies and variable renewable energy technologies (RET) as inappropriate due to the fact that variable RETs are not capable to provide consistent power supply. The variable output of wind energy would require either energy storage or additional balancing reserves to deliver consistent outputs. The supplement of such necessary backup is not always considered as part of wind power generation. The incorporation of large-scale wind power would induce partial loading of traditional power plants, which results

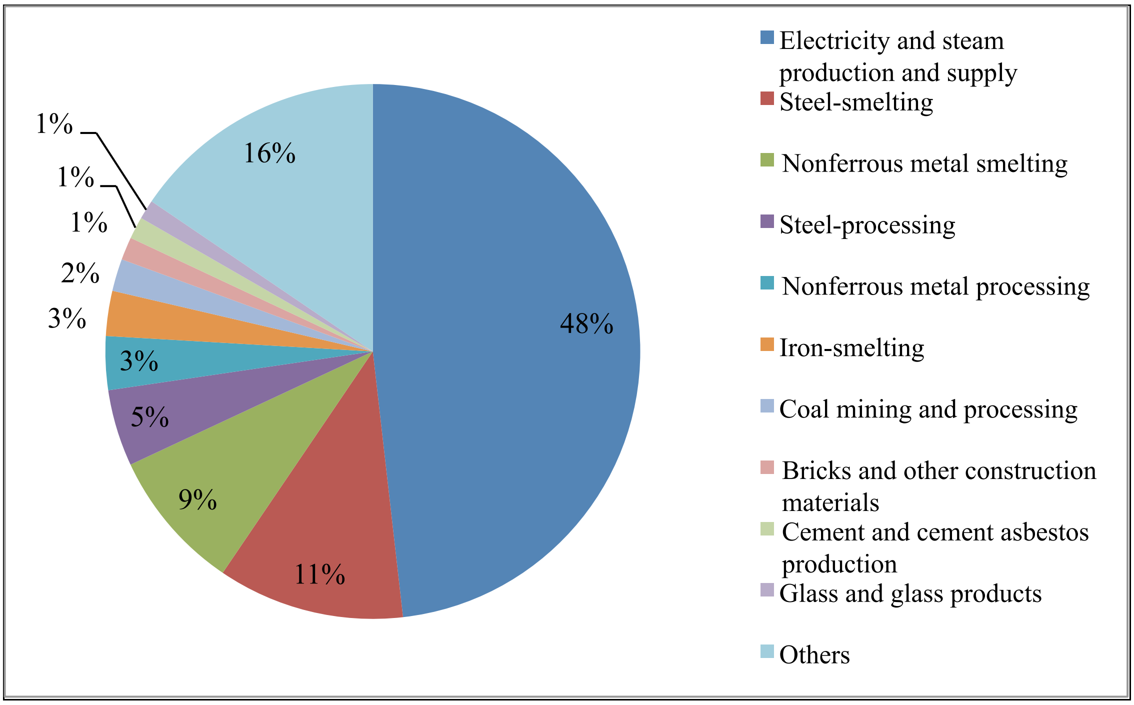
in lower energy efficiency and higher emissions (Pehnt et al., 2008). Hence, the inclusion of backup systems into the study of renewable energy technologies with variable outputs would be required for a fair comparison of carbon emissions across different energy production technologies.

5.3 Results and Discussions

5.3.1 CO_2 emissions

Life cycle emissions of electricity generated by wind power in China are 69.9 grams per kilowatt hour (g/kWh). The electricity sector contributes the largest share of the total CO_2 emissions, accounting for 48% or 33.7 g/kWh. This is due to the large amount of indirect electricity inputs required in manufacturing wind turbines and a coal dominated fuel mix. Steel-smelting is the second largest CO_2 contributor with 7.89 g/kWh, which represents 11% of the total carbon emissions, due to the fact that steel is the main component of wind turbines. Nonferrous metal smelting (9%), steel-processing (5%), nonferrous metal processing (3%), iron-smelting (3%), which are related to the manufacturing of steel, copper, iron and so on, account for a significant proportion of CO_2 emissions of wind power. Other sectors, such as highway freight, crude petroleum products and natural gas products, and petroleum and nuclear fuel refining, account for 16% of total carbon emissions. Figure 5.1 shows the percentage share of carbon emissions of the top 10 economic sectors in producing wind turbines in China.

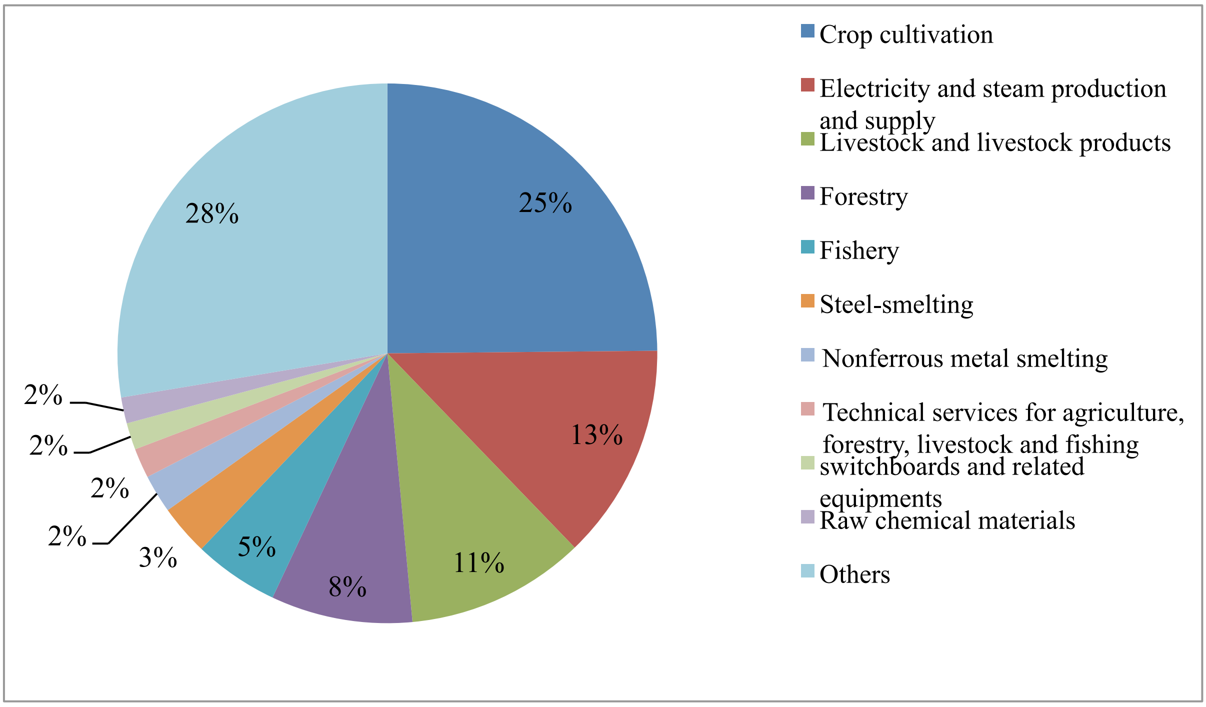
Figure 5.1 CO_2 emissions of the top 10 economic sectors in producing wind turbines in China (in %)



5.3.2 Water consumption

Although the direct water consumption from wind energy is nil, my findings show that life cycle water consumption of wind power (both direct and indirect consumption) is 0.64 litres per kWh (l/kWh). Primary industries account for most of the water consumption. For example, agriculture accounts for 0.159 l/kWh or 25% of total water consumption. Agricultural services, forestry, livestock and fishery account for 11%, 8%, 5% and 2% of total water consumption of wind energy, respectively. In total, primary industries account for 51% of water consumption of wind energy. Although the direct links between wind energy sector and agricultural sectors are negligible, the indirect links could be significant. It may come from, for instance, the inputs of electricity that are generated from biomass or the inputs of cast iron which requires wood during the construction of the cast iron manufacturing bases. Furthermore, primary industries are very water intensive. For example, 87% of water is directly consumed in primary industries according to China's Ministry of Water Resource (MWR, 2006). At the same time, the total outputs of primary industries only account for 5.97% of the total outputs[25]. Hence, the indirect link between the primary sector and wind energy sector result in a significant amount of water consumption. In addition to primary industrial sectors, electricity and steam production and supply, which is the second largest water consumption sector in China, accounts for 13% of total water consumption or 0.082 l/kWh. For all other sectors, they contribute to a significant proportion of water consumption - 28% in total. Figure 5.2 shows the percentage share of water consumption of the top 10 economic sectors in producing windmills in China (For a full list figures of water consumption, see Appendix Two).

Figure 5.2 Water consumption of the top 10 economic sectors in producing wind turbines in China (in %)



[25] Own calculation. Figures used are given in the 2007 national IO table supplied by the National Statistics Bureau.

5.3.3 Comparison with other studies

I compare my findings on the wind energy CO_2 emissions to other studies with regards to two aspects: total CO_2 emissions of wind energy and sectoral breakdown of wind energy CO_2 emissions. In terms of total CO_2 emissions, the figure derived from my study (i.e. 69.9 grams per kWh) is a bit on the high side but within the range of existing studies. For example, Lenzen and Munksgaard (2002) presented a survey of 72 studies on energy consumption and CO_2 emissions of wind power. They found that CO_2 intensities of wind energy varied from 9.7 g/kWh to 123.7 g/kWh. Raadal et al. (2011) conducted a similar review and found that CO_2 emissions of wind energy were ranging from 4.6 g/kWh to 55.4 g/kWh. The wide range of data estimates is due to the choice of research methods, turbine manufacturing locations and turbine operation hours.

The higher carbon intensity of wind energy in China is due to a number of factors. First, the IO based hybrid approach might generate higher values in CO_2 emissions than PRO-LCA because of the completeness of system boundary. Wiedmann et al. (2011) compared the results of wind energy CO_2 emissions using PRO-LCA, IO-based hybrid LCA and integrated hybrid LCA. They found that the latter two approaches generated similar results (29.7 g/kWh for IO-based hybrid LCA and 28.7 g/kWh for integrated hybrid LCA), but these two values were significantly higher than the results derived from PRO-LCA (18.77 g/kWh). Second, China is one of the most carbon-intensive economies because of the overwhelming dependence on coal for energy supply. According to International Energy Agency (2010a), China's CO_2 intensity per unit of GDP is higher than most other countries, except the Middle East and Annex I economies-in-transition (EIT)[26] countries. Goods produced in China have a higher carbon intensity than goods produced in

[26] Annex I EIT countries including Belarus, Bulgaria, Croatia, Estonia, Latvia, Lithuania, Romania, Russian Federation, Slovenia and Ukraine, which are undergoing transitions to market economy.

most of the countries in the world. Furthermore, the performance of Chinese wind turbine is not as efficient as those wind turbines in the other countries. According to Lenzen and Munksgaard (2002), the capacity factor of wind turbine varies between 7.6% to 50.4%. Higher capacity factor means longer operating hours that would yield more power output and hence, lower emissions per unit of electricity output. The capacity factor of Chinese wind turbines is 25.8%[27], which is similar to wind turbines in other countries.

In terms of sectoral breakdown, this chapter also gives different results when compared to the existing studies in the literature. In my study, the largest share of CO_2 emissions in producing wind energy is the electricity sector while steel and cement production is the dominant sector as shown in other studies (Wiedmann et al., 2011). My finding is similar to the conclusion derived from Chang et al.'s study (2010b). The authors used an IO-LCA to examine CO_2 emissions of construction projects in China and found that the electricity sector was the largest contributor to CO_2 emissions, although the direct inputs from electricity sector to construction sector was insignificant. Since approximately 80% of China's electricity is generated by coal (CEC, 2009), 37.18% of the direct CO_2 emissions are from electricity generation in China. The manufacturing of steel, non-ferrous metal products and so on are among the most energy-intensive industries requiring substantial amounts of electricity. Hence, although direct emissions from the electricity sector are small, the contribution from indirect emissions is substantial.

With regards to water consumption, there are very few existing studies that have examined the life cycle water consumption of wind energy. Hence, I compare my results with existing studies focusing on a number of power generation systems, such as coal and nuclear. It is necessary to point out that life cycle emissions of power generation systems are not always taken

[27] Own calculation. Figures are derived from the 50 wind farm feasibility reports and an average value is calculated from the capacity factor provided in each report.

into account in previous studies. Only direct water consumption such as evaporation in cooling effects is examined, although coal mining and processing and power plant construction also consumes water. Thus, in this chapter, only direct water consumptions from various power plants are taken into account for comparison. Table 5.1 gives a summary of water consumption of different power generation sources from two existing studies.

Table 5.1 A breakdown of water consumption by different power generation systems in China

Power generation technologies	Water consumption* (litre/kWh)		
	Vestas (2011)	Saidur et al. (2011)	Burkhardt et al. (2011)
Wind	0	0.004	NA
Solar PV	0	0.11	NA
NGCC CT	0.7	0.95	1.4
NGCC CT + CCS	1.3	NA	NA
Oil	NA	1.6	NA
Super-critical PC CT	1.7	NA	NA
Coal	NA	1.9	2.6
Nuclear CT	2.7	2.3	2.9
CSP through CT	3	NA	4.7
CSP with dry-cooling	NA	NA	1.1
Super-critical PC CT+CCS	3.2	NA	NA

Source: Vestas (2011); Saidur et al. (2011); Burkhardt et al. (2011)

NGCC: Natural gas combined cycle; CT: Cooling tower; CCS: Carbon capture and storage; PC: Pulverized coal; CSP: Concentrated solar power; NA: data not available

*Only direct water consumption is taken into account.

In this chapter, it shows that, even equipped with its full life cycle, wind energy consumes less water (0.64 l/kWh) than the most water-efficient conventional power generation system natural gas combined cycle (NGCC) (0.7 l/kWh). It is also necessary to point out that some of the new power generation technologies, such as concentrated solar power (CSP) and carbon capture and storage (CCS), which are considered as carbon-saving solutions, induce higher water consumption per unit of power output. For example, the installation of CCS system in super-critical pulverized coal power plant would consume 1.5 litres more of water per kWh than power plants without CCS. Furthermore, since the Chinese water consumption per unit of GDP is five times the world average and eight times the U.S. average (Kiang et al., 2009), water consumption of wind power in other countries might be lower.

5.4 Scenarios of water and carbon savings from wind power in China

Wind energy plays an important role in the future electricity mix in China. In this section, I make projections of water and carbon savings from wind power in the coming decades based on the proposed wind power generation capacity by the Chinese government. The National Development and Reform Commission (NDRC) together with the International Energy Agency (IEA) have proposed a wind energy roadmap in China until 2050 (IEA/NDRC, 2011). The projected wind power generation capacity and corresponding electricity generation are depicted in Table 5.2.

Table 5.2 Targeted installed capacity, electricity generation and share of total electricity generation of wind power in China, 2020 - 2050

Year	Generation capacity (GW)	Electricity generation (TWh)	Share of total electricity generation (%)
2020	200	400	5
2030	400	840	8.4
2050	1000	2200	17

Source: IEA/NDRC (2011)

Di et al. (2007) used a process-based LCA model to assess the environmental impacts of fossil-fuel based power generation and nuclear power generation in China. The study examined life cycle emissions of CO_2, SO_2, NO_x, CO in fuel production (mining and processing), transportation and combustion, excluding the construction and operation of power generation infrastructure. The authors concluded that CO_2 emissions of Chinese power generation are 761 g/kWh if transmission loss and power plant consumption are excluded. The Ecoinvent database has provided the average water consumption per kWh of power generation for China. Table 5.3 gives a comparison of my research findings of water consumption and CO_2 emissions of wind power with national average power generation levels obtained from other studies. Here, I do not take the variable output of wind power into account and assume that one-to-one kWh replacement of conventional power generation by wind power is valid.

Table 5.3 A comparison of water consumption and CO2 emissions of wind energy with national average figures

	Water consumption (l/kWh)	CO_2 emissions (g/kWh)
Wind energy	0.64	69.9
National average	2.64	761
Savings	2	691.1

Source: wind energy figures are my research findings. National average water consumption is extracted from Ecoinvent database; CO_2 emissions are drawn on Di et al., (2007)

Assuming the current conditions remain unchanged (i.e. the wind turbine size, the power mix and the production structure remain constant until 2050), the projection of total water and CO_2 emission savings in China for 2020, 2030 and 2050 are depicted in Table 5.4.

Table 5.4 Water and CO_2 savings from the integration of wind energy in China in 2020, 2030 and 2050.

Year	Water savings (million cubic metre)	CO_2 emission savings (million tonne)
2020	800	276.4
2030	1,640	580.5
2050	4,400	1,520.4

During the 11th Five-Year Plan period (2006-2010), China had fulfilled a target of 20% reduction in energy intensity per unit of GDP, which has resulted in a saving of 1,500 million tonnes of CO_2 emissions (Wang et al., 2011). A new carbon intensity target has been set by the Chinese government at the Copenhagen Summit in 2009, which aims to reduce the carbon intensity per unit of GDP by 40% to 45% over the period between 2006 and 2020. According to Zhang (2011), the fulfilment of the carbon intensity target would induce CO_2 emission savings by up to 1.2 billion tonnes by 2020. Based on the results from this chapter, wind power could contribute 23% of the total carbon emission savings in 2020. Furthermore, according to Dore et al. (2010), urban household water consumption is 195 litres per day or 71.2 cubic metres per year in China. In the United States, most of the water used for power generation at operational phases is freshwater (Macknick et al., 2011). If I apply the same situation to China, then total water savings from wind power would be sufficient to provide water supply to 11.2 million households by 2020. Carbon emission savings and water savings would be even more substantial with a higher share of wind power in the power generation mix in 2030 and 2050.

5.5 Conclusions

In this Chapter, I examine water consumption and CO_2 emissions of wind power in China. Compared to other power generation technologies, wind energy is a more advantageous energy source in reducing carbon emissions and water consumption. Thus, given the often postulated water crisis, China's energy policy could reap double benefits through a progressive energy policy increasing the share of wind power as part of overall efforts to diversify its generation fuel mix.

My study provides quantitative evidence for the benefits of wind energy in terms of reduced water consumption and CO_2 emissions. First, the CO_2 emissions of wind energy per kWh are much lower than from other energy technologies. The deployment of wind turbines could help reduce carbon emissions from the power generation industry significantly. Given that the electricity sector accounts for most of wind power's life cycle CO_2 emissions, the diversification of electricity mix with more low-carbon energy sources such as wind are necessary to reduce the carbon content of goods made in China.

Second, the deployment of wind turbines would reduce water consumption of power generation systems in China, especially for the northern part of China, which is short of freshwater and endowed with plenty of wind resources. For example, Inner Mongolia suffered the most serious drought in China with 2.33 million people facing water shortage and 660 thousand hectares of farmland providing no harvest in mid-2011 (MWR, 2011). At the same time, Inner Mongolia is one of the seven planned wind farm locations with total generation capacity of 50 GW to be installed by 2020. The installation of these planned wind turbines would save up to 210 million m^3 of water.

In addition, China's interior areas are endowed with plenty of natural resources, whilst the demand centres are thousands of kilometres away around the coastlines. According to the State Grid Corporation of China (SGCC, 2010), which owns the majority of China's power grid assets, electricity transmission is cheaper compared to raw energy source transportation. Thus the ratio of electricity transmission to coal transportation would increase from 1:20 in 2006 to 1:4 to 2020 (SGCC, 2010). A reason for that is a number of new coal-fired power plants will be constructed near the coal mines in water-scarce northern China since they are rich in coal reserves and their electricity outputs will be transmitted to the demand centres. Local residents would have to bear the environment repercussions that come from power generation, whilst the demand centres would benefit from the 'emission-free' electricity within their provincial territory. Although new technologies such as air-cooling system[28], which could reduce water

---

[28] Two types of cooling systems are used to cool the turbine blades and vanes: wet cooled (e.g. the circulating system/once through system) and dry cooled (e.g. air-cooling system). In air-cooling system, cold air is bled from the compression system for cooling purposes, which uses less water than wet cooling system.

consumption, and carbon capture and storage system, and as a result of a reduction of CO_2 emissions, have been installed or are under experimentation in the newly constructed coal fired power plants in northern China (Dore et al., 2010), they would induce higher energy consumption per unit of electricity and higher capital cost in power plant construction (AWPC, 2011).

Chapter 6 CO_2 and water implications of power generation in Inner Mongolia, China

Most energy-water nexus studies focus on the amount of water needed during the life-cycle phases of power generation. Limited studies have looked at water quantity-quality impacts of electricity production. Using the integrated hybrid life cycle analysis, this Chapter adopts a case study approach to conduct a regional study to assess life cycle environmental impacts of pulverized coal, wind power and solar power on CO_2 emissions, water consumption and water quality. Inner Mongolia Autonomous Region is chosen as the regional case study in China. Rationales for the selection, the procedures and the implementation of the regional case study are given below.

6.1 Introduction

Greenhouse gas emissions that result from energy production are considered as one of the major causes of climate change, which can have significant impacts on hydrological systems such as changes of precipitation, increase of sea level and flooding (IPCC, 2008a). Energy production requires substantial amounts of water during its production life-cycle including processes ranging from mining of fuels to cooling of power generators (Mielke et al., 2010).

A number of studies have been carried out to examine and compare the water intensity of energy production (Nicot and Scanlon, 2012, King and Webber, 2008, Li et al., 2011). Water requirements for conventional energy production can be substantial. For instance, thermo-electric water withdrawal for cooling purposes accounts for approximately 50% of total water withdrawal in the U.S. (Hutson et al., 2004). These considerable water requirements in energy production have caused water shortages. For example, Averyt et al. (2011) estimated for the U.S. in 2008 that the amount of freshwater withdrawal was 60 – 170 billion gallons and consumption for power generation was 2.8 – 5.9 billion gallons. The authors pointed out that water requirements of power generation contributed to water supply stress in approximately 80 watersheds across the U.S.

In recent years, transitions to a low carbon future have increased employment of renewable energy technologies around the globe. Some renewable energy sources require less water in energy production than conventional power generation technologies. For instance, in the U.S., water consumption of photovoltaic power generation is only one eighth of water consumption for fossil fuel-based power generation (Evans et al., 2009). However, some renewable energy technologies are also high water consumers. Burkhardt et al. (2011) pointed out that concentrated solar power systems with wet-cooling can consume up to 4.7 litres of water per kilowatt hour of electricity (kWh). Therefore, it is important to conduct a detailed assessment on the water requirements (both water quantity and quality) of different electricity generation technologies to better aid local (and regional) energy strategies and plans.

China is only second to the U.S. in terms of electricity demand, globally. Owing to the inextricable linkages between energy and water, China's power generation accounts for a significant proportion of the country's total water withdrawal. For instance, in 2010, coal power generation accounted for 20% of China's total water withdrawal (or 112 billion m^3) (Schneider, 2011a). However, there have been very few studies investigating water requirements in energy production in China. Li et al. (2012a), one of the first energy-water nexus studies focusing on China, investigated the life cycle CO_2 emissions and water consumption of wind power in China. The authors concluded that wind power could be seen as carbon and water saving solutions to the coal-dominated power generation system in China. However, there are a few shortcomings of the existing literature: 1) Regions in China have very distinctive characters in terms of geographic condition, natural resource distribution and economic development. A nation-wide analysis might be too coarse to pinpoint and highlight the regional water situation in China. 2) Owing to the significant differences in the regional power mix, the extent to which the application of renewable energy sources could contribute to CO_2 emission reduction in China's regions is unknown. 3) The focus of the existing literature is largely on the amount of water needed during the life-cycle phases of power generation (Cooper and Sehlke, 2012, Chandel et al., 2011, Cooley et al., 2011). To the best of my knowledge, no study has addressed the problem of water quality impacts of electricity production. These shortcomings are addressed in this chapter.

Based on integrated hybrid life cycle analysis, this chapter aims to examine and compare three electricity generation systems, namely coal power, wind power and solar power, with regards to their impacts on CO_2 emissions, water consumption and water quality in Inner Mongolia, China. Inner Mongolia is selected because 1) the growth of energy intensive industries, such as coal mining and processing, raw chemical materials and products and nonferrous smelting and processing, has stimulated power demand in Inner Mongolia (IMARBS, 2010). At the end of 2010, Inner Mongolia had the third largest power generation capacity (64.6 gigawatt) (GW) of all regions in China with coal contributing 92.6% of total power generation (SERC, 2011a). 2) As of 2010, Inner Mongolia has the largest wind power generation capacity in China (13.9 GW), which is estimated to increase to 31.2 GW by 2015 and 58.1 GW by 2020 (Li et al., 2010). 3) Inner Mongolia has one of the largest potentials for solar power in China (Calvin, 2010). Since the Chinese government has committed to promoting renewable energy sources, the percentage share of renewable energy to total energy supply will be considerable in the future. In particular, the region like Inner Mongolia has a large potential for renewable energy sources.

6.2 Inner Mongolia – a future energy hub facing water challenges

Located in the north of China (See Figure 6.1), Inner Mongolia has a total area of 1.18 million square kilometres, which covers 12.3% of the territory of China (IMG, 2012). Inner Mongolia is endowed with various natural resources, including rare earth elements (76% of the total reserves in the world), wind power (one fifth of total wind power potential in China) and coal (top of China with 701.6 billion tonnes of reserves), according to the Inner Mongolia Government (IMG, 2012). In the past years, GDP growth of Inner Mongolia, which is renowned for the leading position in China, has an average annual growth rate over 20% between 2003 and 2007 and over 15% between 2008 and 2010 (NBS, 2011).

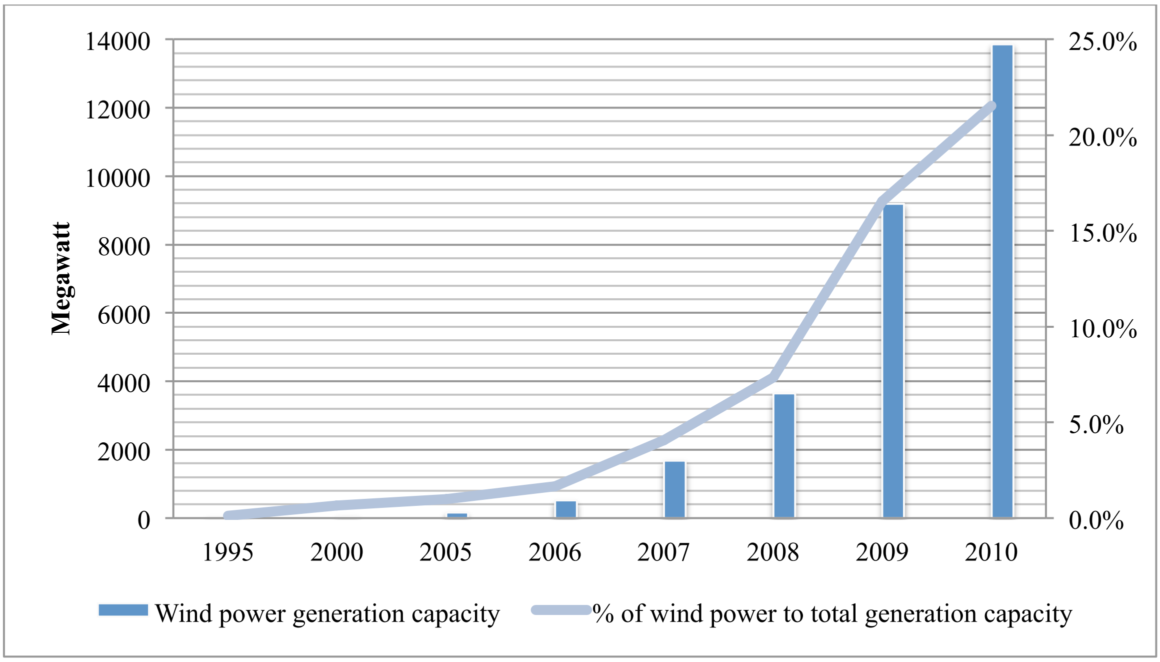
Figure 6.1 Location of Inner Mongolia Autonomous Region in China

6.2.1 Energy Production in Inner Mongolia

Inner Mongolia is the largest coal producer in China. In 2011, total coal production in Inner Mongolia amounted to 979 million tonnes, which accounted for 27.8% of the total coal production in China (CEC, 2012b, NDRC, 2012). Owing to the substantial coal reserves, coal power dominates electricity generation. In 2010, coal power generation amounted to 240.7 billion kWh. 61.3% of the electricity generated were consumed within Inner Mongolia while the remaining electricity was exported to other regions in China (CEPY, 2011). At present, Inner Mongolia has outpaced all the other regions in China in terms of growth in newly installed power generation capacity, power generation per capita and domestic power exports (IMG, 2012).

Also, Inner Mongolia is one of the first regions to use wind power in China, which can be traced back to the 1970s (Ling and Cai, 2012). Decentralized wind power was mainly used for providing electricity supply for herdsmen in remote areas during the early stage of wind power development. Centralized wind power was not introduced until 1989, in which a wind farm with total generation capacity of 1 megawatt (MW) was deployed with financial support from the United States (Li and Gao, 2007). Wind power generation capacity increased from 8.2 MW in 1995 to 13,858 MW in 2010 (see Figure 6.2).

Figure 6.2 The growth in installed wind power capacity and share of wind power to total power generation in Inner Mongolia of China from 1995 to 2010.



Source: for wind power (IMG, 2012); share of wind power to total power generation capacity: own calculation, total generation capacity figures from various China Electric Power Yearbook (CEPY, 1996, CEPY, 2001, CEPY, 2006, CEPY, 2008, CEPY, 2010).

6.2.2 Water resources and consumption in Inner Mongolia

Total water availability in Inner Mongolia amounts to 38.9 billion cubic metres, of which 52.7 % is surface water and 47.3 % is ground water (IMMWR, 2010). Compared to other arid northern regions, Inner Mongolia has higher water availability on a per capita basis. For example, in 2010, water availability per person was 1576.1 m^3 in Inner Mongolia compared to 124.2 m^3 in Beijing and 195.3 m^3 in Hebei (NBS, 2011). But it is lower than the national average, which was 2310.4 m^3 in 2010. Another important aspect is that water resources are unevenly distributed in Inner Mongolia. East Inner Mongolia, which covers 27% of the territory and accounts for 18% of the total population and 20% of the farmland is endowed with 65% of water resources; whilst west Inner Mongolia, which covers 26% of the territory and has 66% of the total population and 30% of farmland, accounts for 25% of the water resources (IMG, 2012). Total water shortage is expected to increase from 1 billion m^3 in 2011 to 3 billion m^3 in 2020 (Xinhua, 2011). Furthermore, water pollution compounds the pressing issues of freshwater availability and distribution. For example, the concentration of chemical oxygen demand (COD) is higher than the Class IV water quality standard[29] in Songhua River, Liao River and Yellow River that flows through Inner Mongolia. By the end of 2010, 54.6% of the watersheds in Inner Mongolia were severely polluted (IMMWR, 2010).

Orszag (2011) estimated that coal power generation would account for almost 40% of the increase in China's water consumption over the coming decade. Inner Mongolia has the third largest power generation capacity in China with majority of them are coal-fired power plants and yet this region is not rich in water resources. Thus, it is necessary to examine the impacts of different power generation technologies on water (both quantity and quality) in Inner Mongolia.

6.3 Methods and Data

6.3.1 Integrated hybrid life cycle analysis

Integrated hybrid life cycle analysis is a combination of conventional process-based life cycle analysis (LCA) and input-output analysis. Conventional process-based LCA often underestimates the environmental impacts of a

[29] In China, water quality grading is based on two standards: the water quality standard, which refers to the quality of watershed such as river and lake; the wastewater discharge standard, such as COD concentration. To clarify, the Class IV water quality standard is for the quality of water bodies in watersheds such as rivers and lakes, which is different from the industrial wastewater discharge standard. Water quality level higher than Grade IV is considered not suitable for direct human contact.

product due to the arbitrary selection of the system boundary, which refers to processes that are included or excluded in the analysis (Suh, 2004a). Upstream impacts beyond the selected system boundary are often neglected (Suh, 2004a).

Integrating LCA with input-output analysis (IO) has provided a viable means to complementing the system boundary of conventional LCA approaches. The early application of IO in LCA can be traced back to the early 1990s from the estimation of life cycle CO_2 emissions of an automobile in Japan by Moriguchi et al. (1993). Later on, Lave et al. (1995) presented an environmental input-output based life cycle analysis (IO-LCA) to assess the environmental repercussions of five products in the U.S., including automobiles, refrigerators, computer purchases, paper cups and plastic cups. However, IO-LCA is suffering from an aggregation problem due to the representation of data at sectoral level rather than individual process level. The IO and LCA systems have been treated individually until Suh (2004b) postulated a linkage between LCA and IOA, which is now often known as the integrated hybrid life cycle analysis.

Integrated hybrid LCA has been used in a number of LCA studies (Mattila et al., 2010, Suh and Huppes, 2005, Peters and Hertwich, 2004, Crawford, 2009). Suh and Huppes (2005) provided a review of methods in life cycle analysis. The authors compared the computational structure of both conventional and hybrid LCA and concluded that results generated by integrated hybrid LCA are more reliable compared to its counterparts. A couple of studies applied integrated hybrid life cycle analysis to examine the environmental impacts of energy systems. For example, Acquaye et al. (2011) demonstrated the application of the integrated hybrid life cycle analysis in the estimation of GHG emissions of rape methyl ester (RME) biodiesel in the U.K. Wiedmann et al. (2011) compared three LCA techniques (i.e. process-based LCA, input-output based hybrid LCA and integrated hybrid LCA) in assessing greenhouse gas (GHG) emissions of wind energy in the U.K.

6.3.2 A general framework of integrated hybrid life cycle analysis

A general framework of the integrated hybrid LCA, which is developed by Suh (2004b), is given in Table 6.1. Two matrices are introduced to link input-output analysis (represented by *A*) and conventional life cycle analysis (represented by $\tilde{A}$) in the integrated hybrid life cycle analysis. One matrix (represented by *U*) presents the upstream cut-off flows from the economic sectors in the input-output system to the process system. The downstream cut-off flows from the process system to the IO system is represented by another matrix (represented by *D*).

Table 6.1 A general framework of integrated hybrid life cycle analysis

	Processes	Industries	Functional unit
Products	Physical flow matrix ($\tilde{A}$)	Downstream cut-off (*D*)	Functional unit of process analysis
Industries	Upstream cut-off (*U*)	Input-output matrix (*A*)	Functional unit of IO
Environmental Impacts	Environmental impacts of LCA	Environmental impacts of IO	

The mathematical formulation of the integrated hybrid LCA approach is depicted in Equation 6.1.

$$G_{IH} = \begin{bmatrix} \tilde{B} & 0 \\ 0 & B \end{bmatrix} \begin{bmatrix} \tilde{A} & -D \\ -U & I-A \end{bmatrix}^{-1} \begin{bmatrix} f \\ 0 \end{bmatrix} \qquad \textbf{Equation 6.1}$$

Where G_{IH} is the total environmental intervention matrix, which describes total direct and indirect environmental impacts of the product system examined; $\tilde{B}$ and B are the environmental intervention matrices for the conventional LCA system and the IO system, respectively; $\tilde{A}$ represents inflows and outflows of products to processes in the conventional LCA system; A represents the flows among economic sectors in the input-output system; U is the upstream cut-off matrix; D is the downstream cut-off matrix; f represents the functional unit of the LCA system, which is one kilowatt hour.

6.3.3 Data

This research uses several types of data, including process-based life cycle data of selected power generation technologies, the input-output table of Inner Mongolia, and sectoral CO_2 emissions, water consumption and COD discharge data. Data source and compilation methods are introduced in the following subsections.

6.3.3.1 Process-based life cycle data

The process-based life cycle datasets are taken from Ecoinvent Database[30], from which I obtained data on 300 MW pulverized coal power from china, 800 kilowatt (kW) wind power and 3 kW solar photovoltaic (PV) systems.

Data on coal power plants (with total generation capacity over 1 GW) are extracted from China Electric Power Yearbook (CEPY, 2008). For Inner Mongolia, 11 coal power plants with a total of 23.7 GW generation capacity (57% of the total power generation capacity in Inner Mongolia) are listed. Each coal power plant has a combination of different power generation units, ranging from 100 MW to 600 MW. 300 MW power generation units represent 21 out of 58 power generation units. Although 600 MW power generation

---

[30] 2010 Ecoinvent database v2.2 from the Ecoinvent Centre at http://www.ecoinvent.ch/. The Ecoinvent process database provides a process matrix, which includes almost 4000 goods and processes.

units accounts for 23 out of 58 power generation units, process-based data of 600 MW coal power system is not available in China. Thus I have chosen the 300 MW power generators in this chapter instead.

Estimation of impacts from 800 kW wind power system is based on wind power generation in Switzerland. The decision of using 800 kW wind turbine in this chapter is based on two reasons: 1) By the end of 2007, Inner Mongolia has 1,736 wind turbines deployed with a total generation capacity of 1.56 GW[31], which yields a turbine size of 898.6 kW on average (Shi, 2008). 2) Wind turbines produced in China are with licences from European partners and thus, I assume the material used and the manufacturing processes of wind turbines in China are similar to the ones described in the database for European countries.

3kW Solar PV is based on electricity production with grid-connected photovoltaic power plants mounted on buildings with slanted roof in Switzerland.

6.3.3.2 Input-output table

Following the standard compilation scheme established by the National Bureau of Statistics, regional IO tables have been complied to represent 30

---

[31] There is a disparity in the statistical figures given by Shi (2008) and Li et al. (2010) on the 2007 total generation capacity. The disparity may be due to the differences in the statistical method used. The China Electricity Council only takes the wind farms in operation into account in calculating wind power generation capacity. The manufacturers of wind turbine use the sales figures instead to derive wind power generation capacity. It is beyond the scope of this study to investigate the statistical method used in these two studies. Since Shi's study contains data on the number of wind turbines and the total generation capacity, I have opted for these figures for use in this study.

regions[32] in China since 1987. In this chapter, the most recent Inner Mongolia input-output table for the year 2007 is used.

6.3.3.3 Upstream and downstream cut-off matrix

I adopted the methods used by Acquaye et al. (2011) and Wiedmann et al. (2011) to compile of upstream cut-off matrix (matrix *U*). First, physical inputs of the examined product system (e.g. coal-fired power, wind power and solar power in my study) are extracted from the physical flow matrix. Then, monetary value of the product system is estimated by multiplying physical inputs with cost of the product system. The cost data are extracted from China Price Yearbook (NDRC, 2008). Since all physical inputs are covered in the IO system, the estimated monetary value of the physical inputs is deducted in order to avoid double counting. The remaining values represent elements of the upstream cut-off matrix. I assume that all the power outputs are consumed by the electricity sector in the input-output table. Thus, downstream cut-off matrix *D* is set to zero, which means the goods inputs from process system to the IO system are negligible. The uncertainty and limitation of setting matrix *D* as zero will be discussed in section 6.3.4.

6.3.3.4 CO_2 emission data

Following the compilation method introduced by Peters et al. (2006), I estimate the sectoral CO_2 emission data for Inner Mongolia by using the sectoral energy consumption data from the Inner Mongolia Statistical Yearbook (IMARBS, 2008).

[32] It includes 22 provinces, 4 municipalities and 4 autonomous regions. Hong Kong, Macao, Taiwan and Tibet are not included.

6.3.3.5 Water consumption data

The water consumption data of Inner Mongolia is extracted from China Statistical Yearbook (2008b). However, only seven sectors are given, which are agriculture, forestry and fishing, industry, services, households, and ecological compensation. As suggested by Yang and Suh (2011), the incorporation of environmental impact indicators from other sources could help to improve the results. Hence, in this chapter, I incorporate the sectoral wastewater discharge data, which is extracted from Inner Mongolia Bureau of Statistics (2008), and the water recycling rate, from the Industries Water Requirement Quota and Standards of Inner Mongolia (2003), to compile the sectoral water consumption data. The compilation of sectoral water consumption follows two steps. First, sectoral water withdrawal data is estimated using sectoral wastewater discharge data and water recycling rates. Sectoral wastewater discharge data has 38 industries included, which provides more detail than the water consumption data from China Statistical Yearbook, which has only seven sectors included. Second, the results are multiplied by water consumption rates for industry, which are obtained from Inner Mongolia Water Bulletin (IMMWR, 2008), to generate the sectoral water consumption data.

The water recycling rate presents the percentage of water that is available for reuse. For example, for coal mining and processing, the water recycle rate is 90%, which means 90% of the water withdrawal can be reused in coal mining and processing industry. For other industries such as manufacturing of food, there is a large variation of water recycle rate, ranging from 35% to 70% dependent on the food product. Equation 6.2 depicts the calculation of the recycling rate.

$$\boldsymbol{R} = \frac{\boldsymbol{V_r}}{\boldsymbol{V_i}+\boldsymbol{V_r}} \times \mathbf{100}\% \qquad \textbf{Equation 6.2}$$

Whereas R represents recycling rate in percentage; V_r represents total amount of reuse water at a given time period; V_i represents new water intake at a given time period.

The denominator of Equation 6.2 represents total water withdrawal of the industry (V); thus, I have,

$$V_i + V_r = V$$ **Equation 6.3**

In this chapter, I assume that water losses from evaporation are negligible. Consequently, new water intake V_i is equivalent to wastewater discharge for each economic sector, which can be obtained from Inner Mongolia Statistical Yearbook (IMARBS, 2008). Since the water recycle rate included almost 400 products, I aggregate them in accordance with the sectoral classification of wastewater discharge data. A list of water recycle rate for industries[33] are given in Appendix Three. Then, sectoral water withdrawal is calculated using Equation 6.4 which is derived from Equations 6.2 and 6.3.

$$V = \frac{V_i}{1-R}$$ **Equation 6.4**

The calculated total water withdrawal with lower recycle rate is 17.2 billion m^3, which is not far from the total water withdrawal (17.5 billion m^3) from Inner Mongolia Water Bulletin (2008). Then, the sectoral water withdrawal

---

[33] Using the input-output table requires the assumption that industries have homogeneous products within each sector. However, the classification of industries for water recycle rate is provided in much detail. For example, manufacturing of food has a wide range of water recycle rates - from 35% for manufacturing of canned meat to 70% for manufacturing of milk. Thus, I list the lower recycle rate and higher recycle rate and estimate the lowest and highest water withdrawal for each industry.

data are multiplied by the water consumption rate, which is generated from Inner Mongolia Water Bulletin (2008). Based on the bulletin, industrial water consumption rate is 61.4% of total water withdrawal. The sectoral water consumption data can be found in Appendix Four.

6.3.3.6 Chemical oxygen demand (COD) discharge data

Guan and Hubacek (2008) presented a hydrological model to investigate the relationship between COD and water availability in North China. The authors calculated the water requirements to dilute COD discharges so that the mixed water (wastewater contains COD plus dilution water) can be used for other purposes. However, the model is not feasible in this chapter, as wastewater discharge is not separated into surface water and ground water in the Inner Mongolia Statistical Yearbook (2008). Instead, I incorporate the general principle of mass balancing in Guan and Hubacek's model, which is the quantity of COD in wastewater (m_1) equals to the quantity of COD after dilution (m_2).

$$\boldsymbol{m_1 = m_2} \qquad \textbf{Equation 6.5}$$

The quantity of COD in wastewater (m_1) equals the total volume of wastewater (v_1) multiplied by the concentration of COD in the wastewater (ρ_1). Furthermore, the quantity of COD after dilution (m_2) equals the total volume of water needed to dilute the COD content in wastewater (v_2) multiplied by the standard concentration of COD[34] (ρ_2). Thus, I have,

---

[34] Standard concentrations of COD follow the stipulation of industrial wastewater discharge standards by the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China in 1996. Details of the standard are discussed later in this subsection.

$$\boldsymbol{m_1 = v_1 \times \rho_1} \qquad \textbf{Equation 6.6}$$

$$\boldsymbol{m_2 = v_2 \times \rho_2} \qquad \textbf{Equation 6.7}$$

Since $m_1 = m_2$ in Equation 6.5, I have

$$\boldsymbol{v_1 \rho_1 = v_2 \rho_2} \qquad \textbf{Equation 6.8}$$

The sectoral COD discharge data (m_1) and wastewater discharge data (v_1) for 37 industries are given by the Inner Mongolia Statistical Yearbook (2008). Then, I calculate the concentration of COD in the wastewater (ρ_1), which can be found in Appendix Five. COD discharge data is not given for agriculture in the Inner Mongolia Statistical Yearbook (2008); so, I adopt the COD discharge coefficients from Guan and Hubacek (2008).

The General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (GAQSIQ) (1996) has promulgated industrial wastewater discharge standards (referred to as the standard thereafter), which classify the contents of COD into three grades (See Appendix Six). The concentration of COD in wastewater needs to achieve the concentration shown in Grade I industrial wastewater discharge standard (regarded as the standard concentration of COD, ρ_2, in this chapter) in Appendix Five.

As can be seen from Appendix Five, the concentration of COD in wastewater for most industries are higher than the Grade I industrial wastewater discharge standard. Grade I industrial wastewater discharge standard is adopted due to following reasons:

1) Industries that fulfil the requirements of Grade II are only allowed to discharge wastewater to Class IV[35] or Class V watershed. Water quality of Class IV and Class V watershed is considered as poor quality of water resources, which are only available for agricultural purposes. Thus, higher standard should be used.

2) The Inner Mongolia Statistical Yearbook (2008) provides COD discharge data as COD removal and COD discharge. I assume that the COD discharge data are derived after the removal of COD content in secondary wastewater treatment plants. My assumption is based on two reasons: First, the COD removal figures are an order of magnitude higher than COD discharge figures; second, primary wastewater treatment plants use physical methods to remove tangible waste in the water body, which cannot remove COD content. Hence, Grade III in the wastewater standard is not considered in this chapter.

3) The standard is stipulated in 1996, which needs to be revised because of the improvement of wastewater treatment technology in the past decade.

Hence, in order to achieve the Grade I standard, additional water (estimated by $v_2 - v_1$) are required to dilute the COD concentration.

6.3.4 Limitations

First, since the detailed sectoral water withdrawal data is not available in most regions, the use of wastewater discharge data in the compilation of sectoral water withdrawal data has been adopted by a couple of studies (Feng et al., 2012, Zhang et al., 2011). The inherent assumption of using

---

[35] Water quality grading has several standards, including water quality standard, which refers to the quality of watershed such as river and lake; the wastewater discharge standard, such as COD concentration. To clarify, the Class IV water quality standard is for the quality of watershed such as river and lake, which is different from the industrial wastewater discharge standard.

wastewater discharge in this chapter is that water loss in production and from evaporation is negligible. Since a minor fraction of water is consumed in industries at present, such an assumption is valid. However, the study can further be improved by incorporating detailed water data when they are made available in the near future.

Second, I neglect the use of inputs from the process system to the IO system by setting downstream cut-off matrix to zero ($D = 0$). The compilation of downstream cut-off matrix requires sales information (e.g. the distribution structure) of the product that is not always accessible to an LCA practitioner using commercial databases (Suh, 2006). In fact, the contribution of downstream cut-offs on total environmental impacts is minor, especially if a demand on the functional unit is used (Peters and Hertwich, 2006a). Thus, for simplicity, I do not take into account the downstream cut-offs in this chapter. However, I acknowledge that the results can be improved if relevant information for the compilation of downstream cut-offs is available.

Third, the choice of representative power generation technologies might lead to uncertainty in the estimation of their environmental impacts. That is due to the following reasons: 1) the selected power generation technologies (i.e. 300 MW coal power, 800 kW wind power and 3 kW solar PV) may not fully represent the power generation system; 2) In general, process-based life cycle emissions of power generation technologies in European countries are lower than those produced in China. Hence, the use of PRO-LCA data based on European countries (in this case study, I use 800kW wind turbine and 3kW solar PV manufactured in Switzerland) could underestimate the environmental impacts of the power generation technologies in China. However, since the Chinese data is not available, I consider it as the most viable means to estimate the life cycle environmental impacts of China’s power generation system at the moment.

Fourth, I assume that selected power generation technologies are produced in Inner Mongolia, which neglect the environmental impacts of imports from and exports to other regions. Multiregional input-output analysis that links Inner Mongolia with other regions could help to improve the results of my study. However, multiregional input-output analysis requires data on trade at sectoral level between Inner Mongolia and other regions, which are not available.

6.4 Research Findings

6.4.1 CO_2 emissions

Figure 6.3 Life cycle CO_2 emissions of pulverized coal, wind power and solar PV systems per kWh in Inner Mongolia, China.

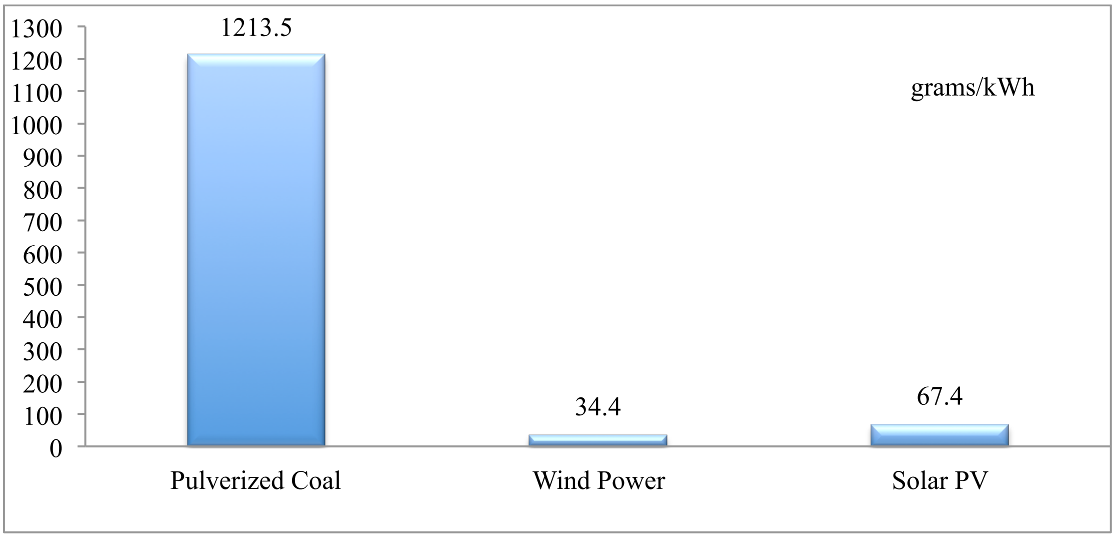
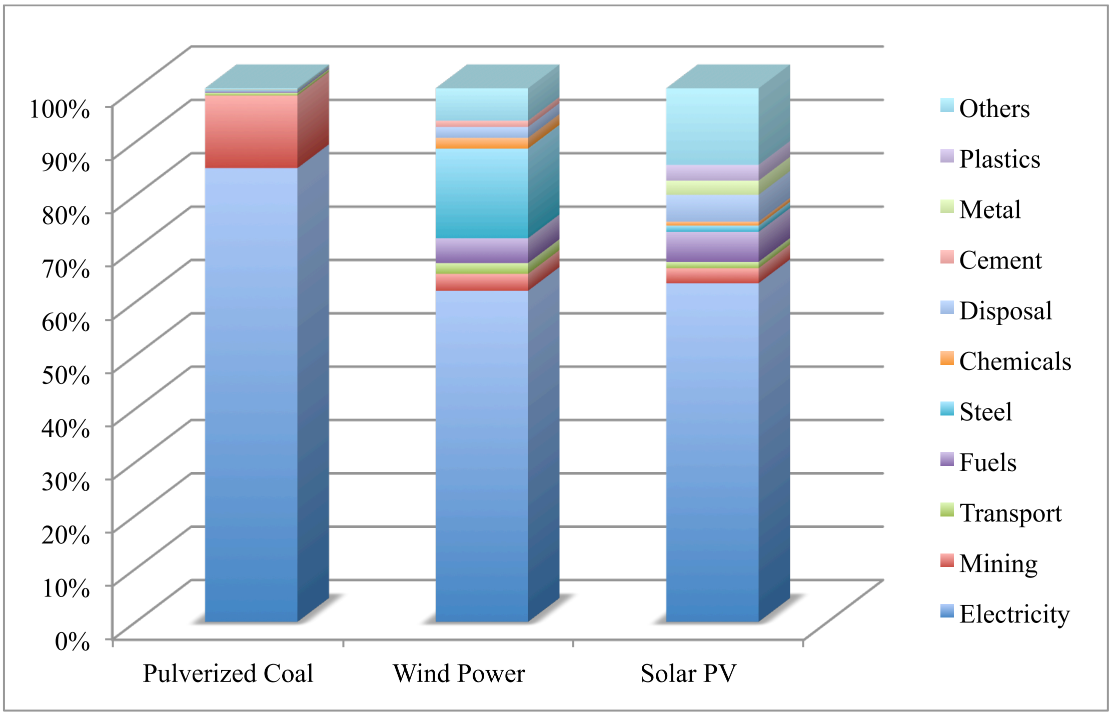


Figure 6.3 compares the life cycle CO_2 emissions of pulverized coal, wind power and solar PV systems. Pulverized coal emits 1,213.5 grams of CO_2 per kilowatt-hour of electricity output, compared with 34.4 g/kWh and 67.4 g/kWh for wind power and solar PV systems, respectively. The significant differences in CO_2 emissions between different energy production systems reveal that substantial reduction in CO_2 emissions can be attained if the

existing coal-dominated power generation technology were substituted by renewable energy technologies.

Figure 6.4 A breakdown of sectoral CO_2 emissions generated from pulverized coal, wind power and solar PV systems in Inner Mongolia, China.



In Figure 6.4, a breakdown of the CO_2 emissions by sectors shows that the electricity sector contributes most to the life cycle emissions of all power generation technologies in Inner Mongolia. For pulverized coal power generation, coal combustion at plant accounts for most of the emissions (1031.8 g/kWh), followed by the coal mining (165.2 g/kWh) and transportation (6.3 g/kWh). Activities related to power plant construction, such as steel production (2.1 g/kWh), account for a minor proportion of the total emissions. For wind power and solar PV, electricity generation accounts for more than 50% of the total CO_2 emissions. Similar results are found in Li et al. (2012a), which provides a national level analysis on CO_2 emissions of wind power in China.

6.4.2 Water consumption

Figure 6.5 A comparison of life-cycle water consumption of pulverized coal, wind power and solar PV systems in electricity generation in Inner Mongolia, China.

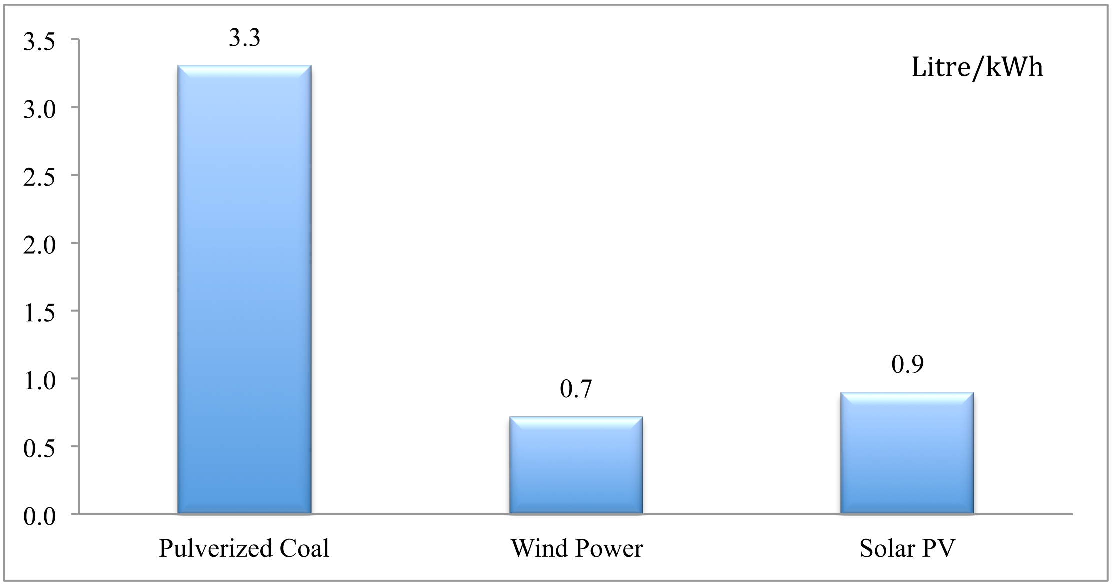
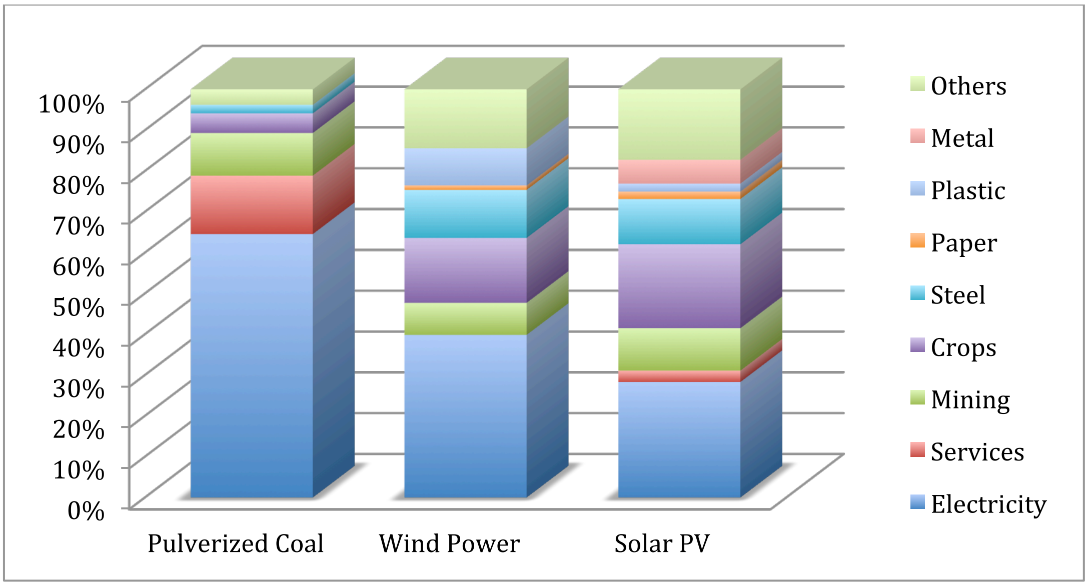


Figure 6.5 presents the life cycle water consumption required by pulverized coal, wind power and solar PV systems to generate electricity in Inner Mongolia. Pulverized coal consumes 3.3 litres of water per kilowatt-hour of electricity output compared to 0.7 litres/kWh and 0.9 litres/kWh for wind power and solar PV systems, respectively. It is concluded that a switch from a pulverized coal power generation to wind power and solar PV can reduce water consumption per kilowatt-hour of power output significantly, a similar finding as in CO_2 emissions.

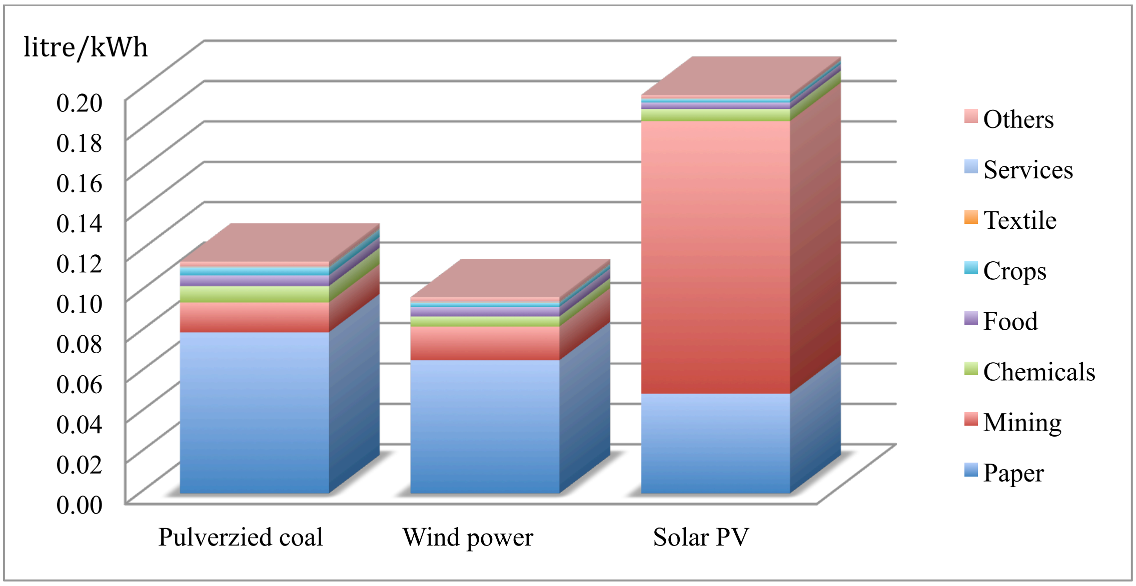
Figure 6.6 A breakdown of sectoral water consumption of pulverized coal, wind power and solar PV systems in electricity generation in Inner Mongolia, China.



As shown in Figure 6.6, the electricity sector accounts for approximately 60% (or 2.13 l/kWh) of the water consumption for pulverized coal. Most water sources are consumed for cooling purposes. Electricity accounts for most significant share in water consumption for wind power (0.28 l/kWh out of 0.71 l/kWh in total) and solar PV (0.27 l/kWh out of 0.90 l/Kwh).

6.4.3 COD discharge

Figure 6.7 Dilution water required for electricity generation in pulverized coal, wind power and solar PV systems in Inner Mongolia, China.



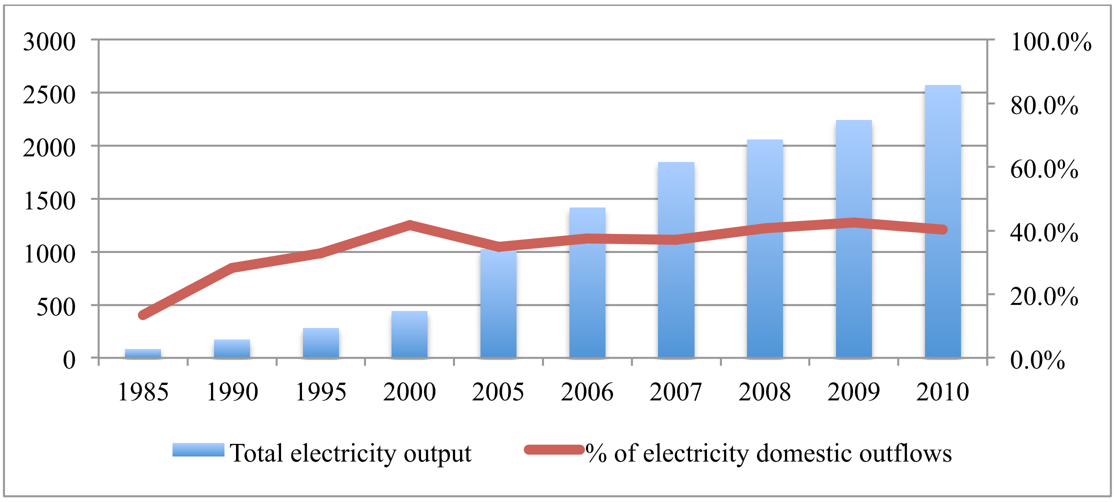
COD discharge is estimated as additional water consumption since the discharge with excessive COD contents needs to be diluted in order to achieve the water quality standard. From Figure 7, dilution water to purify the discharged wastewater from pulverized coal, wind power and solar PV amounted to 0.11, 0.09 and 0.19 litres per kWh, respectively. COD discharge from paper production uses most of the dilution water for pulverized coal (0.08 l/kWh) and wind power (0.07 l/kWh) due to the concentration of COD in paper industry's wastewater (1659.9 g/m^3), which is higher than all the other industries in Inner Mongolia (See a full list of sectoral COD concentration in Appendix Five). By contrast, mining of metals accounts for the highest proportion of dilution water for solar PV (0.13 l/kWh), and it is followed by paper, chemicals and food production.

6.5 A scenario analysis of CO_2 emissions and water impacts of power generation in Inner Mongolia by 2020

Presently, Inner Mongolia is the largest coal producer in China which is located in considerable distance from the demand centres on the east coast. The uneven distribution of energy sources in China has called for the construction of a long-distance power transmission system, which has been initiated by the State Grid Corporation of China (SGCC). One of the primary targets of Inner Mongolia is to increase power generation capacities that provide power supply to regions outside Inner Mongolia to 120 GW by 2020. Since the changes in outflow power generation capacity would have significant impact on carbon emissions, water availability and water quality in Inner Mongolia, I adopt the scenario analysis technique to project the total amount of CO_2 emissions and water requirements in 2020 based on the projection from SGCC.

Figure 6.8 gives the total electricity outputs and shares of domestic outflows to total outputs in Inner Mongolia between 1985 and 2010. Total electricity outputs increased from 80.46 terawatt hours (TWh) in 1985 to 2571.82 TWh in 2010. Shares of exports increased from 13.4% in 1985 to 41.7% in 2000 and remained stable around 40% since 2000.

Figure 6.8 Total electricity outputs and shares of electricity exports in Inner Mongolia of China (in TWh and %)



Source: Various Inner Mongolia Statistical Yearbook (IMARBS, 2006, IMARBS, 2007, IMARBS, 2008, IMARBS, 2009, IMARBS, 2010, IMARBS, 2011)

I assume that domestic outflows would remain at 40% of the total power outputs in Inner Mongolia by 2020. Thus, total power generation capacity would reach 300 GW by 2020. According to Li et al. (2010), 58.1 GW of wind power would be deployed in Inner Mongolia by 2020. Solar power has been at its early stages of development. Total power generation capacity was 0.02 GW by 2010. Inner Mongolia Energy Bureau projected that total power generation capacity of solar PV would reach 0.8 GW by 2015 (IMEB, 2011), with 0.155 GW of solar PV installed annually between 2010 and 2015. I assume that annual installed capacity would be identical between 2016 and 2020. Thus, solar PV would have total installed capacity of approximately 1.6 GW by 2020. Hydropower accounts for a minor proportion of total power generation capacity and remained stable for years in Inner Mongolia. Hence, I neglect the contribution of hydropower to total power generation capacity in 2020. Besides wind power and solar PV, the remainder of the 300 GW power generation capacities would come from coal power. Table 6.2 shows the power generation capacity, total CO_2 emissions and water requirements of each power generation technology by 2020.

Table 6.2 The projected total power generation capacities and annual power generation by source in Inner Mongolia of China in 2020

	Coal power	Wind power	Solar PV
Power generation capacity (GW)	240	58	1.6
Total power generation (GWh)	1070718.4	103660.4	2080.0
Total CO_2 emissions (MT)	1299.3	3.6	0.1
Water consumption (million m^3)	3533.4	72.6	1.9
Dilution water (million m^3)	117.8	9.3	0.4
Total water consumption (million m^3)	3651.1	81.9	2.3

Source: For total power generation, own calculation. Operating hours for coal power, wind power and solar PV are from (CEPY, 2011) and (Li and Wang, 2011).

Jin (2011) estimated that coal power generation would contribute to 680 million tonnes of CO_2 emissions in Inner Mongolia by 2020. However, Jin's study might underestimate the CO_2 emissions from coal power generation since it does not take life-cycle emissions into account. CO_2 emission coefficient was set at 810 g/kWh in her study, which is almost one third lower than the calculated life cycle CO_2 emission coefficient (1213.5 g/kWh) in mystudy. From Table 6.2, total CO_2 emissions from coal power generation would reach 1,299.3 million tonnes by 2020. 40% of the emissions (i.e. 520 million tonnes) would result from power supply to regions outside Inner Mongolia; this would be similar to the total CO_2 emissions in the United Kingdom in 2010 (547.9 million tonnes) (BP, 2011). In addition, coal power generation would consume 3651.2 million m^3 of water by 2020. Figures for wind power and solar PV are 81.9 and 2.3 million m^3, respectively. According to the Inner Mongolia Ministry of Water Resource, total water consumption was 12080 million m^3 in 2010 with an annual growth rate of 2.3% (IMMWR, 2010). If annual growth rate remains constant in the coming decade, coal power generation would represent 24.1% of total water consumption (3651.2 out of 15164.3 million m^3) in Inner Mongolia by 2020. Again, 40% of the water consumption would come from power generation for regions outside Inner Mongolia, which amount to 1460.8 million m^3 of water.

6.6 Discussion and concluding remarks

Renewable energy technologies are regarded as carbon and water saving solutions for the existing coal-dominated power generation system in Inner Mongolia. It shows that wind power and solar PV have considerable environmental advantages to coal power in terms of CO_2 emission and water consumption. Results from myscenario analysis reveal that electricity outflows would represent significant amount of CO_2 emissions and water requirements of power generation in Inner Mongolia.

This chapter also reveals that, other than carbon emissions, different power generation technologies have different impacts on water in terms of both quantity and quality. It is shown that solar PV has higher COD levels than wind power due to mining of metals. Presumably, the environmental repercussions of solar PV can be more considerable if emissions of other pollutants such as cadmium are taken into account.

There are many factors that need to be considered in optimizing the power system from technical point of view such as system operation to environmental issues such as mitigation of CO_2 emissions. A coherent energy policy should consider as many sustainability indicators as possible. For example, besides carbon emissions and water impacts examined in this chapter, coal-fired power plants are the most significant contributors to mercury emissions in China, which amounted to 304 tonnes in 2010 according to Yang et al. (2012b). Whether the switch from coal to renewable energy sources can deal with mercury emissions needs to be examined from a supply chain perspective. Further investigation of other sustainability indicators are required to ensure the current choice of power generation technologies will not compromise sustainability in the future considering the substantial life-span of power generation systems.

The existing LCA database does not have much information about China's power generation system, regardless of the fact that China has the second largest power generation capacities in total, the largest wind power generation capacity and one of the most pioneering countries in solar power in the world. Considering the significant environmental impacts of China's power generation - both domestically and internationally - it is necessary to compile the LCA database for the Chinese power generation system in the near future.

Chapter 7 Conclusion and discussion

In this chapter, I recapitulate the research aim and objectives. Following that, I discuss to what extent the stated research objectives are met. Then, significant research findings are highlighted to provide a basis for the discussion on the contributions and beneficiaries of the current research, limitations and the future research directions.

7.1 A recapitulation of the research aim and objectives

The aim of this study is to examine environmental implications and institutional challenges of wind power development in China. To fulfil the aim, this research needs to

- Objective 1: examine challenges of wind power development in China in terms of grid infrastructure and back-up systems and suggest possible solutions.

Chapter 4 examines the challenges of wind power development in China, including the availability of power grid infrastructure, and feasibility of back-up systems. It shows that only a relatively small share of investment goes towards improving and extending the electricity infrastructure that is a precondition for transmitting clean wind energy to the end users. The considerable distances between areas of high wind potential and electricity demand centres further aggravate the problem. The capital required to improve the transmission lines is greater than the total cost of the Three Gorges Dam - the world's largest hydropower project. In addition, the backup systems such as hydropower and natural gas and energy storage systems such as pumped hydro are either geographically too remote from the potential wind power sites or currently financially infeasible. Finally, the introduction of wind power to the coal-dominated energy production system is not problem-free. Frequent ramp ups and downs of coal-fired plants lead to lower energy efficiency and higher emissions, which are likely to negate some of the emission savings from wind power.

It seems paradoxical for a planning economy such as China but the current system is heavily reliant on independently acting energy companies optimizing their part of the system, which is problematic when building a robust power system. Hence, strategic, national top-down co-ordination and incentives to improve the overall electricity infrastructure must be achieved. Any power system is only as strong as its weakest link. Without careful planning and coordination, the greener electricity system might just move one step forward and two steps back.

- Objective 2: compare the economy-wide emissions and water consumption of wind power with other power generation technologies at national level in order to understand the environmental benefits as well as the repercussions.

Chapter 5 uses input-output based hybrid life cycle analysis to estimate CO_2 emissions and water consumption of wind power in China. A new wind power sector is created by using the following information: CDM feasibility reports from UNFCCC, the 2008 China price yearbook, the 2007 national input-output table, and life cycle data of 800kW wind power generation from Eco-invent database. The results show that China's wind energy consumes 0.64 litre/kWh of water and produces 69.9 grams/kWh of CO_2 emission. Given that the Chinese government aims to increase the wind power generation capacity to 200 GW by 2020, wind power could lead to a 23% reduction in carbon intensity and could save 800 million m^3 of water which could be sufficient to cover water consumption of 11.2 million households.

Presently, China's energy policies address the significant contribution of wind power to China's carbon emission reduction (c.f. Renewable Energy Law; Mid-Long Term Renewable Energy Development Plan, and etc.). Since coal power generation has accounted for a significant proportion in China's water consumption, this research reveals that China would reap double benefits (carbon and water savings) through progressive energy policies when increasing the share of wind power as part of overall efforts to diversify its energy mix.

- Objective 3: estimate the life cycle CO_2 emissions and water quantity-quality of wind power and compare to other power generation technologies such as pulverized coal and solar PV at regional level in China.

Chapter 6 uses integrated hybrid life cycle analysis to evaluate and compare CO_2 emissions and water impacts of coal-fired power, wind power and solar power generation in Inner Mongolia, China. This chapter shows that pulverized coal emits 1,213.5 grams of CO_2 per kilowatt-hour of electricity output, compared with 34.4 g/kWh for wind power and 67.4 g/kWh for solar photovoltaic. Water consumption for pulverized coal, wind power and solar photovoltaic are 3.3, 0.7 and 0.9 litres per kilowatt-hour, respectively. The water requirement to dilute the life-cycle chemical oxygen demand discharge would increase water consumption during production processes of pulverized coal, wind power and solar photovoltaic systems by 0.11, 0.09 and 0.19 litres per kilowatt-hour, respectively.

This chapter confirms and reinforces research findings in Chapter 5 that substantial reductions in CO_2 emissions and water consumption can be attained if the existing coal-dominated power generation was substituted by renewable energy. Results from the scenario analysis reveal that electricity outflows would represent significant amount of CO_2 emissions and water requirements of power generation in Inner Mongolia. Also it reveals that other than carbon emissions, the choices among different power generation technologies need to consider water impacts, especially if the choice has to be made among renewable energy technologies. Further investigation of other sustainability indicators needs to be implemented to ensure the current choice of power generation technologies will not compromise the sustainability in the future, taking into account the substantial life-span of power generation systems.

From the above analysis, I conclude that despite the significant growth in recent years, China's wind power faces considerable challenges due to insufficient grid infrastructure and infeasible back-up systems. Successfully overcoming the barriers would help China to save carbon emissions and water consumption at both national and regional level.

7.2 A brief summary of the thesis

This thesis started with an introduction of the energy consumption and its environmental impacts in China, which lead to a discussion of the significance of China's wind power development. Then, it looked at studies focusing on wind power in China. Given the substantial increase in wind power generation capacity, the majority of these studies centred on factors that promote the growth of wind power, including favourable government policies, wind energy potentials and growths of domestic wind power manufacturing industry. However, the increase in generation capacity is exciting but not convincing because, firstly, a significant proportion of wind turbines were installed but not connected to the power grid due to inadequate power grid infrastructure; and secondly, the variable outputs of wind power has led to instability in power supply which is resulted from infeasible back-up systems in China. Thus, in Chapter 4, I provided an in-depth analysis on these two barriers and highlighted the possible solutions.

One of the other major themes of this thesis draws on the examination of life-cycle CO_2 emissions, water consumption and water quality impacts of wind power in China. In Chapter 3, I introduced the chosen methodology – input-output analysis with its foundations, applications and limitations. Two hybrid life cycle analysis approaches were introduced specifically, namely input-output based hybrid life cycle analysis and integrated hybrid life cycle analysis. The reason for choosing CO_2 emissions and water quantity-quality impacts drawn from China's two challenges, namely the overdependence on coal for power generation and the water crisis, were also given in Chapter 3. Chapter 5 and Chapter 6 presented the results of life-cycle environmental impacts from wind power at both national and regional level. Comparisons with conventional and other renewable energy technologies had been made to show the benefits of wind power in terms of carbon and water savings.

7.3 Significant contributions

It is shown, in this study, introducing life cycle analysis to the existing input-output analysis can contribute to the intellectual advancement at both theoretical and empirical levels:

On the empirical level, the key contribution is to provide an in-depth analysis for improving the knowledge and understanding of the barriers of wind power development in China. In Chapter 2, it is argued that power grid infrastructure and back-up systems are crucial to China's wind power development, but these factors are often overlooked in most Chinese energy studies. A detailed investigation on these two issues, as shown in Chapter 4, shows that the existing grid infrastructure is not capable of sustaining the growth of wind power in China. Additionally, the back-up systems are either geographically unavailable or financially infeasible. Furthermore, as exemplified in Chapters 5 and 6, wind power could be a carbon saving as well as water saving solution to the existing coal-dominated power generation system in China. At the national level (see Chapter 5), wind power could secure a 23% reduction in carbon emissions and save 800 million m^3 of water which could be enough for use by 11.2 million households since the Chinese government aims to increase the wind power generation capacity to 200 GW by 2020. At the regional level (see Chapter 6), a case study of Inner Mongolia shows that substantial reductions in CO_2 emissions and water consumption can be attained only when the existing coal-dominated power generation was substituted by wind power. Findings from the current research provide supportive evidence for the clarification of whether renewable energy such as wind power can help to alleviate environmental impacts such as CO_2 emissions and water saving. The results of the regional and national study in China can help (the Chinese) policy makers to select appropriate sustainable energy generation technologies to develop and assess future energy strategies. Thus, this research contributes to the (Chinese) government officials, the academic community, the energy and industrial sectors, the local communities and the general public to better understand the potential benefits and barriers of wind power development in China.

Another contribution of this research is to advance the procedures and implementation of integrated hybrid LCA analysis for wind power studies. As demonstrated in Chapter 5, a new wind power sector is developed by disaggregating the electricity sector in China's input-output table and incorporating life cycle dataset. It presents a method to examine the environmental impacts of wind power and compare the results with other power generation technologies.

Furthermore, most existing energy-water nexus studies focus on examining water consumption or withdrawal. A contribution of this thesis is to extend the focus of the energy-water nexus studies from water quantity to water quality (see Chapter 6).

In sum, this research provides an in-depth understanding of the potential benefits and barriers of wind power development in China to a wide range of audience including policy makers, academia as well as the general public. The research findings provide supportive evidence to aid the debate whether wind power is/can be a viable, sustainable electricity generation technology for China's future energy targets on reducing CO_2 emissions and alleviating the water crisis.

7.4 Research limitations

This research study has several limitations with regards to methodology and data availability.

Methodology shortcomings:

1) The choice of representative power generation technologies might lead to uncertainty in the estimation of their environmental impacts. That is due to the following reasons: a) the selected power generation technologies (i.e. 300 MW coal power in Chapter 6, 800 kW wind power in Chapter 5 and Chapter 6 and 3kW solar PV in Chapter 6) may not fully represent the power generation system; b) In general, process-based life cycle emissions of power generation technologies in European countries are lower than those produced in China. Hence, the use of PRO-LCA data based on European countries (800kW wind turbine and 3kW solar PV manufactured in Switzerland chosen for this study) could underestimate the environmental impacts of the power generation technologies in China. As the Chinese data is not currently available, such selection is considered as the most viable means to estimate the life cycle environmental impacts of China's power generation system at present.
2) In Chapter 6, the use of inputs from the process system to the IO system is neglected as the downstream cut-off matrix is set to zero (D = 0). The compilation of the downstream cut-off matrix requires sales information (e.g. the distribution structure) of the product that is not accessible to an LCA practitioner using commercial databases (Suh, 2006). In fact, the contribution of downstream cut-offs on total environmental impacts is minor, especially if a demand on the functional unit is used (Peters and Hertwich, 2006a). Thus, for simplicity, the downstream cut-offs are not taken into consideration in this study although the results can be improved if relevant information for the compilation of downstream cut-offs is available.
3) The requirements of backup systems and grid extensions are not included in this study. It is necessary to point out that the comparison of greenhouse gas (GHG) emissions and water consumption among power generation sources might be inappropriate since the one-to-one replacement of electricity produced with different sources might not be

a valid assumption. A number of studies have expressed concerns on the appropriateness of one-to-one kWh-based replacement. The variable output of wind energy would require either energy storage or additional balancing reserves to deliver consistent outputs. The supplement of such necessary backup is not always considered as part of wind power generation. The incorporation of large-scale wind power would induce partial loading of traditional power plants, which results in lower energy efficiency and higher emissions (Pehnt et al., 2008). Hence, the inclusion of backup systems into the study of renewable energy technologies with variable outputs would be required for a fair comparison of carbon emissions across different energy production technologies. However, the inclusion of backup systems would require data on power system operation. Such data is regarded as being strictly confidential and is not disclosed to any parties (including researchers) by the energy industry and the Chinese government for reasons of national security.

Data availability

1) Since detailed environmental datasets for China are unavailable, in this research, the assumption is made that similar industries have the same CO_2 emission coefficients and water consumption coefficients (Chapters 5 and 6). For example, the 136 IO sectors is aggregated in accordance with the 44 economic sectors classification given in the China Energy Statistical Yearbook in order to generate the CO_2 emission coefficients in both chapters.

7.5 Future research directions

Several research directions can be identified based on the current study. Firstly, the primary focus of the current research is on water consumption and water quality impacts of wind power generation in China. A future research direction can extend the scope of study to include power use in water provision in China The power use in freshwater provision is significant.

For example, in the United States, 3% of the total electricity supply is used for wastewater treatment (McCarty et al., 2011). However, only a few studies have been focused on energy use in water provision in China.

Another future research direction is oriented toward developing scenario projections of CO_2 emissions from power generation in China in the coming decades. This future research can start with an assessment of the water quantity-quality impacts of various power generation technologies in China. The selected power generation technologies could include coal, gas, oil, hydro, nuclear, wind, solar PV and biomass. It could be followed by a scenario analysis to project the water implications of China's power generation in 2020 and 2050, based on the projections of China's power generation mix from Energy Information Administration (EIA, 2011), International Energy Agency (IEA, 2011) and Lawrence Berkeley National Laboratory (Zhou et al., 2011).

Last but not least, the focus of the current research is on a single region (either the entire country or a specific region) and thus only regional IO analysis is used. In other words, interactions between regions (in China) are beyond the scope of the current study. Another future research direction can be developed by applying a multi-regional input-output (MRIO) analysis to examine and compare the water impacts of electricity transmission between and among regions in China.

References

ACQUAYE, A. A., WIEDMANN, T., FENG, K., CRAWFORD, R. H., BARRETT, J., KUYLENSTIERNA, J., DUFFY, A. P., KOH, S. C. L. & MCQUEEN-MASON, S. 2011. Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis. *Environmental Science & Technology,* 45**,** 2471-2478.

ALLAN, G. J., MCGREGOR, P. G., SWALES, J. K. & TURNER, K. 2007. Impact of alternative electricity generation technologies on the Scottish economy: an illustrative input-output analysis. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* 221**,** 243-254.

AQSIP 1996. Integrated Wastewater Discharge Standard. *In:* CHINA, T. G. A. O. Q. S. I. A. Q. O. T. P. S. R. O. (ed.) *GB8978 - 1996.* Beijing.

ARDENTE, F., BECCALI, M., CELLURA, M. & LO BRANO, V. 2008. Energy performances and life cycle assessment of an Italian wind farm. *Renewable and Sustainable Energy Reviews,* 12**,** 200-217.

ASIA_WATER_PROJECT_CHINA. 2011. *Q&A: Energy, Water and China's Economy* [Online]. Asia Water Project. Available: http://www.asiawaterproject.org/more-interviews/5798/ [Accessed 23 July 2011].

AVERYT, K., FISHER, J., HUBER-LEE, A., LEWIS, A., MACKNICK, J., MADDEN, N., ROGERS, J. & TELLINHUISEN, S. 2011. Freshwater use by U.S. power plants: Electricity's thirst for a precious resource. Cambridge: MA: Union of Concerned Scientist.

AWPC. 2011. *Q&A: Energy, Water and China's Economy* [Online]. Asia Water Project China. Available: http://www.asiawaterproject.org/more-interviews/5798/ [Accessed 23 July 2011].

BELANGER, C. & GAGNON, L. 2002. Adding wind energy to hydropower. *Energy Policy,* 30**,** 1279-1284.

BIELLO. 2011. *China forges ahead with nuclear energy* [Online]. Nature. Available: http://www.nature.com/news/2011/110329/full/news.2011.194.html?s=news_rss [Accessed 6 June 2011].

BLAIR, P. 1980. Hierarchies and priorities in regional energy-environmental planning. *Regional Science and Urban Economics,* 10**,** 387-405.

BP 2011. Statistical review of world energy 2011.

BRADSHER, K. 2010. *China Fears Warming Effects of a Rising Consumer Class* [Online]. The New York Times. Available: http://topics.nytimes.com/topics/reference/timestopics/people/b/keith_bradsher/index.html?inline=nyt-per [Accessed July 7 2010].

BRENNAND, T. P. 2001. Wind energy in China: policy options for development. *Energy for Sustainable Development,* 5**,** 84-91.

BUENO, C. & CARTA, J. A. 2006. Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. *Renewable and Sustainable Energy Reviews,* 10**,** 312-340.

BULLARD, C. W. & HERENDEEN, R. A. 1975. The energy cost of goods and services. *Energy Policy,* 3**,** 268-278.

BULLARD, C. W., PENNER, P. S. & PILATI, D. A. 1978. Net energy analysis : Handbook for combining process and input-output analysis. *Resources and Energy,* 1**,** 267-313.

BURKHARDT, J. J., HEATH, G. A. & TURCHI, C. S. 2011. Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives. *Environmental Science & Technology,* 45**,** 2457-2464.

CALDES, N., VARELA, M., SANTAMARIA, M. & SAEZ, R. 2009. Economic impact of solar thermal electricity deployment in Spain. *Energy Policy,* 37**,** 1628-1636.

CALVIN, L. K. 2010. The Inner Mongolia Autonomous Region: A major role in China's renewable energy future. *Utilities Policy,* 18**,** 46-52.

CARTER, A. P. 1974. Applications of Input-Output Analysis to Energy Problems. *Science,* 184**,** 325 - 329.

CCCHINA. 2011a. *China Acadamy of Science Estimates CO2 Emissions by Sector in 2011 (中科院估算 2011 年我国分行业二氧化碳排放量）* [Online]. Beijing: China Climate Change Infor-Net. Available: http://www.ccchina.gov.cn/cn/NewsInfo.asp?NewsId=27086 [in Chinese] [Accessed September 30 2011].

CCCHINA. 2011b. *China Acadamy of Science Estimates Sectoral CO_2 Emissions in 2011* [Online]. Beijing: China Climate Change Infor-Net. Available: http://www.ccchina.gov.cn/cn/NewsInfo.asp?NewsId=27086 [in Chinese] [Accessed September 30 2011].

CEC 2009. Bulletin of China's Electric Power Industry Statistics in 2008. Beijing: China Electricity Council.

CEC. 2012a. *Energy planning from the perspective of power supply [in Chinese]* [Online]. Beijing: China Electricity Council. Available: http://www.cec.org.cn/zhuanti/zhongguodianliyunengyuan/benshuguandian/2012-05-07/84129.html [Accessed July 22 2012].

CEC. 2012b. *Raw coal production amounted to 3520 million tonnes in 2011* [Online]. China Electricity Council. Available: http://www.cec.org.cn/nengyuanyudianlitongji/xiangguanshuju/meitan/2012-02-27/80742.html [Accessed 5 May 2012].

CEG 2007. China Energy Databook Version 7.0. China Energy Group and Lawrence Berkley National Laboratory.

CEPY 1996. *China Electric Power Yearbook 1996,* Beijing, China Electric Power Press.

CEPY 2001. *China Electric Power Yearbook 2001,* Beijing, China Electric Power Press.

CEPY 2006. *China Electric Power Yearbook 2006,* Beijing, China Electric Power Press.

CEPY 2008. *China Electric Power Yearbook 2008,* Beijing, China Electric Power Press.

CEPY 2009. *China Electric Power Yearbook 2009* Beijing, China Electric Power Press.

CEPY 2010. *China Electric Power Yearbook 2010,* Beijing, China Electric Power Press.

CEPY 2011. *China Electric Power Yearbook 2011* Beijing, China Electric Power Press.

CHALMERS, H. & GIBBINS, J. 2006. Potential for synergy between renewables and carbon capture and storage. *29th IAEE International Conference.* Berlin, Germany.

CHANDEL, M. K., PRATSON, L. F. & JACKSON, R. B. 2011. The potential impacts of climate-change policy on freshwater use in thermoelectric power generation. *Energy Policy,* 39**,** 6234-6242.

CHANG, X., LIU, X. & ZHOU, W. 2010a. Hydropower in China at present and its further development. *Energy,* 35**,** 4400-4406.

CHANG, Y., RIES, R. J. & WANG, Y. 2010b. The embodied energy and environmental emissions of construction projects in China: An economic input-output LCA model. *Energy Policy,* 38**,** 6597-6603.

CHEN, Q., KANG, C., XIA, Q. & GUAN, D. 2011. Preliminary exploration on low-carbon technology roadmap of China's power sector. *Energy,* 36**,** 1500-1512.

CHEN, W. & XU, R. 2010. Clean coal technology development in China. *Energy Policy,* 38**,** 2123-2130.

CHEN, Z. & BLAABJERG, F. 2009. Wind farm--A power source in future power systems. *Renewable and Sustainable Energy Reviews,* 13**,** 1288-1300.

CHI, Y., LIU, Y., WANG, W. & DAI, H. Voltage Stability Analysis of Wind Farm Integration into Transmission Network. Power System Technology, 2006. PowerCon 2006. International Conference on, 22-26 Oct. 2006 2006. 1-7.

COOLEY, H., FULTON, J. & GLEICK, P. H. 2011. Water for Energy: Future Water Needs for Electricity in Intermountain West. Oakland, California: Pacific Institute.

COOPER, D. C. & SEHLKE, G. 2012. Sustainability and Energy Development: Influences of Greenhouse Gas Emission Reduction Options on Water Use in Energy Production. *Environmental Science & Technology,* 46**,** 3509-3518.

CRAWFORD, R. H. 2008. Validation of a hybrid life-cycle inventory analysis method. *Journal of Environmental Management,* 88**,** 496-506.

CRAWFORD, R. H. 2009. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews,* 13**,** 2653-2660.
CWEA 2012a. Report on the wind power curtailment in 2011. Beijing: China Wind Energy Association.
CWEA 2012b. Statistics on China's wind power generation capacity, 2011. Beijing: China Wind Energy Association.
DAI, Y., HU, X., JIANG, K., XU, H., ZHU, Y., BAI, Q. & YU, S. 2009. *Low Carbon Develpment Pathway for China towards 2050 - Scenario Analysis on Energy Demands and Carbon Emissions* Beijing, Science and Technology Press [in Chinese].
DALLA MARTA, A., NATALI, F., MANCINI, M., FERRISE, R., BINDI, M. & ORLANDINI, S. 2011. Energy and Water Use Related to the Cultivation of Energy Crops: a Case Study in the Tuscany Region. *Ecology and Society,* 16.
DANY, G. Power reserve in interconnected systems with high wind power production. Power Tech Proceedings, 2001 IEEE Porto, 2001 2001. 6 pp. vol.4.
DENHOLM, P., KULCINSKI, G. L. & HOLLOWAY, T. 2005. Emissions and Energy Efficiency Assessment of Baseload Wind Energy Systems. *Environmental Science & Technology,* 39**,** 1903-1911.
DI, X., NIE, Z., YUAN, B. & ZUO, T. 2007. Life cycle inventory for electricity generation in China. *The International Journal of Life Cycle Assessment,* 12**,** 217-224.
DIETZENBACHER, E. & STAGE, J. 2006. Mixing oil and water? Using hybrid input-output tables in a Structural decomposition analysis. *Economic Systems Research,* 18**,** 85-95.
DOBOS, I. & TALLOS, P. 2011. A dynamic input-output model with renewable resources. *Central European Journal of Operations Research***,** 1-11.
DORE, D., GUO, P., NETTE, A.-S. & AN, J. 2010. Water in China. Singapore: The Aisa Water Project China.

DRAKE, B. & HUBACEK, K. 2007. What to expect from a greater geographic dispersion of wind farms?--A risk portfolio approach. *Energy Policy,* 35**,** 3999-4008.

DU, L., YANAN, H. & WEI, C. 2010. The relationship between oil price shocks and China's macro-economy: An empirical analysis. *Energy Policy,* 38**,** 4142-4151.

DUCHIN, F. & LANGE, G. 1995. The Choice of Technology and Associated Changes in Prices in the U.S. Economy. *Structural Change and Economic Dynamics,* 6**,** 335-357.

DUCHIN, F. & LEVINE, S. H. 2011. SECTORS MAY USE MULTIPLE TECHNOLOGIES SIMULTANEOUSLY: THE RECTANGULAR CHOICE-OF-TECHNOLOGY MODEL WITH BINDING FACTOR CONSTRAINTS. *Economic Systems Research,* 23**,** 281-302.

DUCHIN, F. & STEENGE, A. 2007. Mathematical Models in Input-Output Economics. Rensselaer Polytechnic Institute.

DUCHIN, F. & SZYLD, D. B. 1985. A dynamic input-output model with assured positive output. *Metroeconomica,* 37**,** 269-282.

EIA. 2010. *Country Analysis Briefs - China* [Online]. Energy Information Administration. Available: http://www.eia.gov/EMEU/cabs/China/pdf.pdf [Accessed May 15 2011].

EIA 2011. International Energy Outlook 2011. Washington, D.C.: U.S. Energy Information Administration.

ENIS, B., LIEBERMAN, P. & RUBIN, I. 2003. Operation of hybrid wind-turbine compressed-air system for connection to electric grid networks and cogeneration. *Wind Engineering,* 27**,** 449-459.

EVANS, A., STREZOV, V. & EVANS, T. J. 2009. Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews,* 13**,** 1082-1088.

FANG, C. L. 2007. A prospect of wind energy industry development in China. *China Energy,* 29**,** 30-43.

FENBY, J. & QU, D. 2008. China's Grids Power Up. London: Trusted Sources UK Ltd.

FENG, K., MINX, J., BARRETT, J., SCOTT, K., HUBACEK, K. & WIEDMANN, T. 2010. The role of infrastructure in meeting UK climate change targets: a case study of wind energies. *18th International Input-Output Conference.* Sydney, Austrilia.

FENG, K., SIU, Y. L., GUAN, D. & HUBACEK, K. 2012. Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: A consumption based approach. *Applied Geography,* 32**,** 691-701.

FERRAO, P. & NHAMBIU, J. 2009. A Comparison Between Conventional LCA and Hybrid EIO-LCA: Analyzing Crystal Giftware Contribution to Global Warming Potentia. *In:* SUH, S. (ed.) *Handbook of Input-Output Economics in Industrial Ecology.* Springer Netherlands.

FTHENAKIS, V. & KIM, H. C. 2009. Land use and electricity generation: A life-cycle analysis. *Renewable and Sustainable Energy Reviews,* 13**,** 1465-1474.

FTHENAKIS, V. & KIM, H. C. 2010. Life-cycle uses of water in U.S. electricity generation. *Renewable and Sustainable Energy Reviews,* 14**,** 2039-2048.

FU, B.-J., WU, B.-F., LÜ, Y.-H., XU, Z.-H., CAO, J.-H., DONG NIU, YANG, G.-S. & ZHOU, Y.-M. 2010. Three Gorges Project: Efforts and challenges for the environment. *Progress in Physical Geography,* 34**,** 741-754.

GERDES, K. & NICHOLS, C. 2009. Water Requirements for Existing and Emerging Thermoelectric Plant Technologies. National Energy Technology Laboratory, Department of Energy.

GLASSMAN, D., WUCHER, M., ISAACMAN, T. & CHAMPILOU, C. 2011. The Water-Energy Nexus - Adding Water to the Energy Agenda. World Policy Institute.

GLEICK, P. 2009. *The World's Water 2008 - 2009,* Washington, D.C., Island Press.

GOGGIN, M. 2008. 20% Wind Energy by 2030: Wind, Backup Power, and Emissions. *AWEA's Wind Energy Fact Sheets.* Washington, DC: American Wind Energy Association.

GUAN, D. & HUBACEK, K. 2008. A new and integrated hydro-economic accounting and analytical framework for water resources: A case study for North China. *Journal of Environmental Management,* 88**,** 1300-1313.

GUAN, D., HUBACEK, K., WEBER, C. L., PETERS, G. P. & REINER, D. M. 2008. The drivers of Chinese CO2 emissions from 1980 to 2030. *Global Environmental Change,* 18**,** 626-634.

GUINÉE, J. B., HEIJUNGS, R., HUPPES, G., ZAMAGNI, A., MASONI, P., BUONAMICI, R., EKVALL, T. & RYDBERG, T. 2010. Life Cycle Assessment: Past, Present, and Future†. *Environmental Science & Technology,* 45**,** 90-96.

GWEC. 2011. *China adds 18.9GW of new wind power capacity in 2010* [Online]. Global Wind Energy Council. Available: http://www.gwec.net/index.php?id=30&no_cache=1&tx_ttnews%5Btt_news%5D=287&tx_ttnews%5BbackPid%5D=4&cHash=c5a5b5659f [Accessed 15 May 2011].

HAN, J., MOL, A. P. J., LU, Y. & ZHANG, L. 2009. Onshore wind power development in China: Challenges behind a successful story. *Energy Policy,* 37**,** 2941-2951.

HAN, X. & LAKSHMANAN, T. 1994. Structural Changes and Energy Consumption in the Japanese Economy 1975-95: An Input-Output Analysis. *The Energy Journal,* 15**,** 165 - 188.

HE, D., LI, Z., NI, W., YANG, Y., WANG, Z. & DAI, H. 2008. *The Strategic Development of Renewable Energy in China - A Special Issue on Wind Energy,* Beijing, China Electric Power Press.

HE, Y. & CHEN, X. 2009. Wind turbine generator systems. The supply chain in China: Status and problems. *Renewable Energy,* 34**,** 2892-2897.

HEIJUNGS, R. 1994. A generic method for the identification of options for cleaner products. *Ecological Economics,* 10**,** 69-81.

HEINLOTH, K. 1983. Energie B G Teubner. Stuttgart, Germany.

HENDRICKSON, C. T., LAVE, L. B. & SCOTT, M. H. 2006. *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach,* Baltimore, MD: Johns Hopkins University Press.

HENSEL, F. & UHL, K. 2004. Low energy desalination and wind energy -- sustainable solutions for drinking water production. *Desalination,* 168**,** 125-126.

HERTWICH, E. G. 2005. Life cycle approaches to sustainable consumption: a critical review. *Environmental Science & Technology,* 39**,** 4673-4684.

HIGASHI, N. 2009. Natural Gas in China - Market Evolution and Strategy. *Working Paper Series: Energy Market and Security 2009.* Paris: International Energy Agency.

HOEKSTRA, R. & JANSSEN, M. A. 2006. Environmental responsibility and policy in a two-country dynamic input–output model. *Economic Systems Research,* 18**,** 61-84.

HOLTTINEN, H. 2005. Impact of hourly wind power variations on the system operation in the Nordic countries. *Wind Energy,* 8**,** 197-218.

HOLTTINEN, H. 2009. Design and Operation of Power Systems with Large Amounts of Wind Power. Paris: International Energy Agency.

HOLTTINEN, H. & TUHKANEN, S. 2004. The effect of wind power on CO2 abatement in the Nordic Countries. *Energy Policy,* 32**,** 1639-1652.

HONDO, H. 2005. Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy,* 30**,** 2042-2056.

HUBACEK, K., GUAN, D. & BARUA, A. 2007. Changing lifestyles and consumption patterns in developing countries: A scenario analysis for China and India. *Futures,* 39**,** 1084-1096.

HUBACEK, K. & SUN, L. 2001. A scenario analysis of China's land use and land cover change: incorporating biophysical information into input-output modeling. *Structural Change and Economic Dynamics,* 12**,** 367-397.

HUBACEK, K. & SUN, L. 2007. Economic and Societal Changes in China and their Effects on Water Use. International Institute for Applied Systems Analysis.

HUSTON, S., BARBER, N., KENNY, J., LINSEY, K., LUMIA, D. & MAUPIN, M. 2005. Estimated Use of Water in the United States in 2000. Reston, Virginia: U.S. Geological Survey.

HUTSON, S. S., BARBER, N. L., KENNY, J. F., LINSEY, K. S., LUMIA, D. S. & MAUPIN, M. A. 2004. Estimated Use of Water in the United States in 2000. *U.S. Geological Survey Circular 1268.* Reston, Va.: U.S. Department of the Interior.

IEA 2010a. CO_2 Emissions from Fuel Combustion. Paris, France: International Energy Agency.

IEA 2010b. World Energy Outlook 2010. Paris: OECD publishing.

IEA 2011. *World Energy Outlook 2011,* Paris, OECD Publishing.

IEA/NDRC 2011. Technology Roadmap: China Wind Energy Development Roadmap 2050. Paris/Beijing.

IMARBS 2006. Inner Mongolia Statistical Yearbook 2005. Hohhot: Inner Mongolia Autonomous Region Bureau of Statistics.

IMARBS 2007. Inner Mongolia Statistical Yearbook 2006. hohhot: Inner Mongolia Autonomous Region Bureau of Statistics.

IMARBS 2008. Inner Mongolia Statistical Yearbook 2007. hohhot: Inner Mongolia Autonomous Region Bureau of Statistics.

IMARBS 2009. Inner Mongolia Statistical Yearbook 2008. Hohhot: Inner Mongolia Autonomous Region Bureau of Statistics.

IMARBS. 2010. *Energy demand in Inner Mongolia energy intensive industries* [Online]. hohhot: Inner Mongolia Autonomous Region Bureau of Statistics. Available: http://www.nmgtj.gov.cn/Html/tjxx/2010-5/14/1051411440332486.shtml [Accessed 22 July 2012].

IMARBS 2011. Inner Mongolia Statistical Yearbook 2010. Hohhot: Inner Mongolia Autonomous Region Bureau of Statistics.

IMEB. 2011. *The construction of solar power industry in Inner Mongolia* [Online]. Beijing: National Government. Available: http://www.gov.cn/jrzg/2011-07/06/content_1900846.htm [Accessed July 5 2012].

IMG. 2012. *An introduction of Inner Mongolia* [Online]. Available: http://intonmg.nmg.gov.cn/ [Accessed 4 April 2012].

IMMWR 2008. Inner Mongolia Water Resource Bulletin 2008. Inner Mongolia: Ministry of Water Resources, Inner Mongolia.

IMMWR 2010. Inner Mongolia Water Resource Bulletin 2010. Inner Mongolia: Ministry of Water Resource, Inner Mongolia.

IMQSIP 2003. Industries Water Requirement Quota and Standards of Inner Mongolia *In:* MONGOLIA, A. O. Q. S. I. A. Q. O. I. (ed.) *DB15/T385.* Inner Mongolia.

IPAKCHI, A. & ALBUYEH, F. 2009. Grid of the future. *Power and Energy Magazine, IEEE,* 7**,** 52-62.

IPCC 2008a. Climate Change and Water. Intergovernmental Panel on Climate Change.

IPCC 2008b. Climate Change and Water. IPCC Technical Paper VI.

IPCC 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation.

JIN, Y. 2011. Status Quo and Trends of Carbon Emissions of China's Provincial Power Industries. *Energy Technology and Economics,* 23**,** 56 - 60.

JOSHI, S. 1999. Product Environmental Life-Cycle Assessment Using Input-Output Techniques. *Journal of Industrial Ecology,* 3**,** 95-120.

JSDRC 2008. Development Plan for Wind Power Equipment. Jiangsu: Jiangsu Development Reform Commission.

JUNGBLUTH, N., BAUER, C., DONES, R. & FRISCHKNECHT, R. 2005. Life Cycle Assessment for Emerging Technologies: Case Studies for Photovoltaic and Wind Power (11 pp). *The International Journal of Life Cycle Assessment,* 10**,** 24-34.

JUNNILA, S. I. 2006. Empirical Comparison of Process and Economic Input-Output Life Cycle Assessment in Service Industries. *Environmental Science & Technology,* 40**,** 7070-7076.

KAHRL, F. & ROLAND-HOLST 2008. China's water-energy nexus. *Water Policy,* 10**,** 51-65.

KAHRL, F., WILLIAMS, J., JIANHUA, D. & JUNFENG, H. 2011. Challenges to China's transition to a low carbon electricity system. *Energy Policy,* 39**,** 4032-4041.

KEMPTON, W., ARCHER, C. L., DHANJU, A., GARVINE, R. W. & JACOBSON, M. Z. 2007. Large CO2 reductions via offshore wind power matched to inherent storage in energy end-uses. *Geophys. Res. Lett.,* 34**,** L02817.

KEMPTON, W., PIMENTA, F. M., VERON, D. E. & COLLE, B. A. 2010. Electric Power from Offshore Wind via Synoptic-Scale Interconnection. *Proceedings of the National Academy of Sciences of the United States of America,* 107**,** 7240 - 7245.

KIANG, C. S., YANG, X. & FENG, C. 2009. The Interface of Energy and Water - A View from China. World Energy Forum.

KING, C. W. & WEBBER, M. E. 2008. Water Intensity of Transportation. *Environmental Science & Technology,* 42**,** 7866-7872.

KPMG 2010. China's grid: keeping pace with a transformig economy. KPMG.

LAVE, L. B., COBAS-FLORES, E., HENDRICKSON, C. T. & MCMICHAEL, F. C. 1995. Using input-output analysis to estimate economy-wide discharges. *Environmental Science & Technology,* 29**,** 420A-426A.

LEHR, U., NITSCH, J., KRATZAT, M., LUTZ, C. & EDLER, D. 2008. Renewable energy and employment in Germany. *Energy Policy,* 36**,** 108-117.

LEMA, A. & RUBY, K. 2006. Towards a policy model for climate change mitigation: China's experience with wind power development and lessons for developing countries. *Energy for Sustainable Development,* 10**,** 5-13.

LEMA, A. & RUBY, K. 2007. Between fragmented authoritarianism and policy coordination: Creating a Chinese market for wind energy. *Energy Policy,* 35**,** 3879-3890.

LENZEN, M. 2000. Errors in Conventional and Input-Output—based Life—Cycle Inventories. *Journal of Industrial Ecology,* 4**,** 127-148.

LENZEN, M. 2009. Current state of development of electricity-generating technologies - a literature review. University of Sydney.

LENZEN, M. 2011. AGGREGATION VERSUS DISAGGREGATION IN INPUT–OUTPUT ANALYSIS OF THE ENVIRONMENT. *Economic Systems Research,* 23**,** 73 - 89.

LENZEN, M. & CRAWFORD, R. 2009. The Path Exchange Method for Hybrid LCA. *Environmental Science & Technology,* 43**,** 8251-8256.

LENZEN, M. & MUNKSGAARD, J. 2002. Energy and CO2 life-cycle analyses of wind turbines--review and applications. *Renewable Energy,* 26**,** 339-362.

LENZEN, M. & WACHSMANN, U. 2004. Wind turbines in Brazil and Germany: an example of geographical variability in life-cycle assessment. *Applied Energy,* 77**,** 119-130.

LEONTIEF, W. 1986. Technological Change, Prices, Wages and Rats of Return on Capital in the U.S. Economy. *Input-Output Economics.* New York: Oxford University Press.

LEONTIEF, W. & DUCHIN, F. 1986. *The Future Impact of Automation on Workers,* New York, Oxford University Press.

LEONTIEF, W. W. 1936. Quantitative Input and Output Relations in the Economic Systems of the United States. *The Review of Economics and Statistics,* 18**,** 105-125.

LEONTIEF, W. W. 1951. *The Structure of American Economy, 1919 - 1939: an empirical application of equilibrium analysis,* New York, Oxford University Press.

LEW, D. J. 2000. Alternatives to coal and candles: wind power in China. *Energy Policy,* 28**,** 271-286.

LI, H., CHIEN, S.-H., HSIEH, M.-K., DZOMBAK, D. A. & VIDIC, R. D. 2011. Escalating Water Demand for Energy Production and the Potential for Use of Treated Municipal Wastewater. *Environmental Science & Technology,* 45**,** 4195-4200.

LI, J. & RICHARD, S. 2011. China Looks to Balance Its Carbon Books. *Science,* 334**,** 886-887.

LI, J., SHI, J., XIE, H., SONG, Y. & SHI, P. 2006. A Study on the Pricing Policy of Wind Power in China. China Renewable Energy Industries Association, Green Peace and Global Wind Energy Council.

LI, J. & SHI, L. 2006. Brief description of hydropower resources in China. *Water Power,* 32**,** 3 - 7.

LI, J., SHI, P. & GAO, H. 2010. *China Wind Power Outlook 2010,* Haikou, Hainan Press.

LI, J. & WANG, S. 2011. *China Solar PV Outlook 2011,* Beijing, China Environmental Science Publishing House.

LI, J. F. & GAO, H. 2007. *China Wind Power Report 2007,* Beijing, China Environment Science Press.

LI, J. F., GAO, H., WANG, Z. Y., MA, L. J. & DONG, L. Y. 2008. *China Wind Power Report 2008,* Beijing, China Environment Science Press.

LI, X., FENG, K., SIU, Y. L. & HUBACEK, K. 2012a. Energy-water nexus of wind power in China: The balancing act between CO2 emissions and water consumption. *Energy Policy,* 45**,** 440-448.

LI, X., HUBACEK, K. & SIU, Y. L. 2012b. Wind power in China – Dream or reality? *Energy,* 37**,** 51-60.

LI, Z. 2009. From Strong to Smart: the Chinese Smart Grid and its relation with the Globe. Asia Energy Planform.

LIANG, Q.-M., FAN, Y. & WEI, Y.-M. 2007. Multi-regional input-output model for regional energy requirements and CO2 emissions in China. *Energy Policy,* 35**,** 1685-1700.

LIAO, C., JOCHEM, E., ZHANG, Y. & FARID, N. R. 2010. Wind power development and policies in China. *Renewable Energy,* 35**,** 1879-1886.

LIN, X. & POLENSKE, K. R. 1995. Input–Output Anatomy of China's Energy Use Changes in the 1980s. *Economic Systems Research,* 7**,** 67 - 84.

LINDNER, S., LEGAULT, J. & GUAN, D. 2012. DISAGGREGATING INPUT–OUTPUT MODELS WITH INCOMPLETE INFORMATION. *Economic Systems Research,* 24**,** 329-347.

LING, Y. & CAI, X. 2012. Exploitation and utilization of the wind power and its perspective in China. *Renewable and Sustainable Energy Reviews,* 16**,** 2111-2117.

LIU, H.-T., GUO, J.-E., QIAN, D. & XI, Y.-M. 2009. Comprehensive evaluation of household indirect energy consumption and impacts of alternative energy policies in China by input-output analysis. *Energy Policy,* 37**,** 3194-3204.

LIU, J. & DIAMOND, J. 2005. China's environment in a globalizing world. *Nature,* 435**,** 1179-1186.

LIU, L. & YANG, F. 2008. Which wind turbine manufacturer is going to lead the market (feng dian zhi zao qi ye shui jiang xiao ao qun xiong). *Wind energy development report.* Beijing: CITIC Securities Company Limited.

LIU, W., LUND, H. & MATHIESEN, B. V. 2011a. Large-scale integration of wind power into the existing Chinese energy system. *Energy,* 36**,** 4753-4760.

LIU, W., LUND, H., MATHIESEN, B. V. & ZHANG, X. 2011b. Potential of renewable energy systems in China. *Applied Energy,* 88**,** 518-525.

LIU, W.-Q., GAN, L. & ZHANG, X.-L. 2002. Cost-competitive incentives for wind energy development in China: institutional dynamics and policy changes. *Energy Policy,* 30**,** 753-765.

LIU, Y. & KOKKO, A. 2010. Wind power in China: Policy and development challenges. *Energy Policy,* 38**,** 5520-5529.

MACKNICK, J., NEWMARK, R., HEATH, G. & HALLETT, K. 2011. A Review of Operational Water Consumption and Withdrawal factors for Electricity

Generating Technologies. Golden, Colorado: National Renewable Energy Laboratory.

MADLENER, R. & KOLLER, M. 2007. Economic and CO2 mitigation impacts of promoting biomass heating systems: An input-output study for Vorarlberg, Austria. *Energy Policy,* 35**,** 6021-6035.

MARRIOTT, J. 2007. *An Electricity-focused Economic Input-output Model: Life-cycle Assessment and Policy Implications of Future Electricity Generation Scenarios.* Doctor of Phylosophy, Carnegie Mellon University.

MARTÍNEZ, E., SANZ, F., PELLEGRINI, S., JIMÉNEZ, E. & BLANCO, J. 2009. Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy,* 34**,** 667-673.

MATTILA, T. J., PAKARINEN, S. & SOKKA, L. 2010. Quantifying the Total Environmental Impacts of an Industrial Symbiosis - a Comparison of Process-, Hybrid and Input−Output Life Cycle Assessment. *Environmental Science & Technology,* 44**,** 4309-4314.

MCCARTY, P. L., BAE, J. & KIM, J. 2011. Domestic Wastewater Treatment as a Net Energy Producer–Can This be Achieved? *Environmental Science & Technology,* 45**,** 7100-7106.

MCELROY, M. B., LU, X., NIELSEN, C. P. & WANG, Y. 2009. Potential for Wind-Generated Electricity in China. *Science,* 325**,** 1378-1380.

MIELKE, E., DIAZ ANADON, L. & NARYANAMURTI, V. 2010. Water Consumption of Energy Resource Extraction, Processing and Conversion. Energy Technology Innovation Policy Research Group, Belfer Centre for Science and International Affairs, Harvard Kennedy School.

MILLER, N. W., DILLIP, G. & CLARK, K. 2008. Wind Generation Applications for the Cement Industry. *Cement Industry Technical Conference Record, 2008 IEEE.*

MILLER, R. E. & BLAIR, P. D. 2009. *Input-Output Analysis: Foundations and Extensions,* New York, Cambridge University Press.

MO, W., NASIRI, F., ECKELMAN, M. J., ZHANG, Q. & ZIMMERMAN, J. B. 2010. Measuring the Embodied Energy in Drinking Water Supply Systems: A Case Study in The Great Lakes Region. *Environmental Science & Technology,* 44**,** 9516-9521.

MO, X. 2009. An Analysis of the Barriers in Wind Energy Development in the Northwest China (Qian xi xi bei feng dian fa zhan ji ge wen ti). Xi'an: The Northwest Electricity Regulatory Commission.

MORIGUCHI, Y., KONDO, Y. & SHIMIZU, H. 1993. Analyzing the life cycle impact of cars: the case of CO2. *Industry and Environment,* 16**,** 42-45.

MOST/SDPC/SETC 2002. Evaluation of Policies Designed to Promote the Commercialization of Wind Power Technology in China. P.R.China: The MInistry of Science and Technology, The State Development Planning Commission, the State Economic and Trade Commission.

MUNKSGAARD, J. & PEDERSEN, K. A. 2001. CO2 accounts for open economies: producer or consumer responsibility? *Energy Policy,* 29**,** 327-334.

MWR 2006. China Water Bulletin 2005. Beijing: Ministry of Water Resources.

MWR 2011. Gazette of the Ministry of Water Resources of the People's Republic of China. Beijing: Ministry of Water Resources.

NAKAMURA, S. & KONDO, Y. 2002. Input-Output Analysis of Waste Management. *Journal of Industrial Ecology,* 6**,** 39-63.

NBS 2008a. *China Energy Statistical Yearbook 2007,* Beijing, China Statistics Press.

NBS 2008b. China Statistical Yearbook 2007. Beijing: National Bureau of Statistical.

NBS 2010. *China Energy Statistical Yearbook,* National Bureau of Statistics, Beijing, China Statistics Press.

NBS 2011. *China Statistical Yearbook,* Beijing, National Bureau of Statistics.

NDRC 2007a. Mid-Long Term Development Plan for Nuclear Power (2005 - 2010). Beijing [In Chinese]: National Development Reform Commission.

NDRC 2007b. Mid-Long Term Development Plan for Renewable Energy in China. Beijing: National Development and Reform Commission.

NDRC 2008. *Price Yearbook of China,* Beijing, Langfang Lanxinyacai.

NDRC 2009. Policies and strategies to combet the climate change in China. *In:* COMMISSION, N. D. A. R. (ed.). Beijing: National Development and Reform Commission.

NDRC. 2012. *NDRC: China coal market analysis 2011 (发改委：2011 年全国煤炭市场的供需分析）* [Online]. China Electricity Council. Available: http://www.cec.org.cn/nengyuanyudianlitongji/xiangguanshuju/meitan/2012-02-01/79393.html [Accessed 4 May 2012].

NEMA, P., NEMA, R. K. & RANGNEKAR, S. 2009. A current and future state of art development of hybrid energy system using wind and PV-solar: A review. *Renewable and Sustainable Energy Reviews,* 13**,** 2096-2103.

NETWORK, C. P. S. P. 2010. *China Pumped Storage Plants (exisiting, under construction and proposed projects)* [Online]. Beijing. Available: http://www.psp.org.cn:8080/news_list.asp?c_id=178&s_id=311 [Accessed 02/07/2010.

NICOT, J.-P. & SCANLON, B. R. 2012. Water Use for Shale-Gas Production in Texas, U.S. *Environmental Science & Technology*.

OECD 2007. Infrastructure to 2030 - Mapping Policy for Electricity, Water and Transport. Paris: Organisation for Economic Co-operation and Development.

ORSZAG, P. 2011. *Why We Care About the Price of Water in China: Peter Orszag* [Online]. Bloomberg. Available: http://www.bloomberg.com/news/2011-07-06/why-we-care-about-the-price-of-water-in-china-peter-orszag.html [Accessed 1 July 2012].

OU, X., XIAOYU, Y. & ZHANG, X. 2011. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. *Applied Energy,* 88**,** 289-297.

PAN, X. 2010. China: A Responsible Country in Mitigating Climate Change. *Environmental Science & Technology,* 44**,** 7981-7981.

PAVLAK, A. 2008. The Economic Value of Wind Energy. *The Electricity Journal,* 21**,** 46-50.

PEHNT, M., OESER, M. & SWIDER, D. J. 2008. Consequential environmental system analysis of expected offshore wind electricity production in Germany. *Energy,* 33**,** 747-759.

PETERS, G. & HERTWICH, E. 2004. A comment on "Fuctions, commodities and environmental impacts in an eclogical-economic model". *Program for inudstriell okologi.*

PETERS, G. P. & HERTWICH, E. G. 2006a. A comment on “Functions, commodities and environmental impacts in an ecological–economic model”. *Ecological Economics,* 59**,** 1-6.
PETERS, G. P. & HERTWICH, E. G. 2006b. Pollution embodied in trade: The Norwegian case. *Global Environmental Change,* 16**,** 379-387.
PETERS, G. P., WEBER, C. & LIU, J. 2006. Construction of Chinese Energy and Emissions Inventory. Industrial Ecology Programme, Norwegian University of Science and Technology.
PETERS, G. P., WEBER, C. L., GUAN, D. & HUBACEK, K. 2007. China's Growing CO2 EmissionsA Race between Increasing Consumption and Efficiency Gains. *Environmental Science & Technology,* 41**,** 5939-5944.
PROOPS, J. L. R., GAY, P. W., SPECK, S. & SCHRER, T. 1996. The lifetime pollution implications of various types of electricity generation. An input-output analysis. *Energy Policy,* 24**,** 229-237.
QIU, J. 2009. China's climate target: is it achievable? *Nature,* 462**,** 550-551.
RAADAL, H. L., GAGNON, L., MODAHL, I. S. & HANSSEN, O. J. 2011. Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power. *Renewable and Sustainable Energy Reviews,* 15**,** 3417-3422.
REBITZER, G., EKVALL, T., FRISCHKNECHT, R., HUNKELER, D., NORRIS, G., RYDBERG, T., SCHMIDT, W. P., SUH, S., WEIDEMA, B. P. & PENNINGTON, D. W. 2004. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International,* 30**,** 701-720.
REBOURS, Y. G., KIRSCHEN, D. S., TROTIGNON, M. & ROSSIGNOL, S. 2007. A Survey of Frequency and Voltage Control Ancillary Services—Part I: Technical Features. *Power Systems, IEEE Transactions on,* 22**,** 350-357.
ROQUES, F., HIROUX, C. & SAGUAN, M. 2010. Optimal wind power deployment in Europe--A portfolio approach. *Energy Policy,* 38**,** 3245-3256.
SAIDUR, R., RAHIM, N. A., ISLAM, M. R. & SOLANGI, K. H. 2011. Environmental impact of wind energy. *Renewable and Sustainable Energy Reviews,* 15**,** 2423-2430.

SCHAEFFER, R. & DE SÁ, A. 1996. The embodiment of carbon associated with Brazilian imports and exports. *Energy Conversion and Management,* 37**,** 955-960.

SCHLEISNER, L. 2000. Life cycle assessment of a wind farm and related externalities. *Renewable Energy,* 20**,** 279-288.

SCHNEIDER. 2011a. *Coal is China's largest industrial water consumer* [Online]. Available: http://grist.org/article/2011-02-23-coal-is-chinas-largest-industrial-water-consumer/ [Accessed 22 July 2012].

SCHNEIDER, K. 2011b. *New Wind and Solar Sectors Won't Solve China's Water Scarcity* [Online]. Circle of blue. Available: http://www.circleofblue.org/waternews/2011/world/new-wind-and-solar-sectors-wont-solve-chinas-water-scarcity/ [Accessed 06 July 2011].

SERC 2009. China's Wind Power Development Report [In Chinese]. *In:* COMMISSION, S. E. R. (ed.). Beijing.

SERC 2011a. Circular of Electricity Generation in 2010 (2010 年度发电业务情况通报). Beijing [In Chinese]: State Electricity Regulatory Commission.

SERC. 2011b. *Notice of the Three Recent Large-Scale Wind Power Drop-Off Accident [in Chinese]* [Online]. Beijing: State Electricity Regulatory Commission Available: http://www.serc.gov.cn/ywdd/201105/t20110506_14631.htm [Accessed 11 May 2011].

SGCC. 2007. *Why different voltages are needed in high voltage electricity transmission system?* [Online]. Beijing. Available: http://www.sgcc.com.cn/dlkp/dlhb/kpzs/sbdssjbzs/61089.shtml [Accessed 3rd July 2010].

SGCC. 2010. *Electricity transmision as the sixth form of energy transportation* [Online]. Beijing. Available: http://www.sgcc.com.cn/bps/news/04/221525.shtml [In Chinese] [Accessed 24 July 2011].

SGCC. 2011. *State Grid Releases White Paper on Wind Power Development* [Online]. Beijing: State Grid Corporation of China. Available: http://www.sgcc.com.cn/ywlm/mediacenter/corporatenews/04/245999.shtml [Accessed 11 May 2011].

SHI, P. 2007. China wind power generation capacity in 2006. Beijing: China Wind Energy Association.

SHI, P. 2008. China wind power generation capacity in 2007 Beijing: China Wind Energy Association.

SHUI, B. & HARRISS, R. C. 2006. The role of CO2 embodiment in US-China trade. *Energy Policy,* 34**,** 4063-4068.

SIDDIQI, A. & ANADON, L. D. 2011. The water-energy nexus in Middle East and North Africa. *Energy Policy,* 39**,** 4529-4540.

SIOSHANSI, R. 2011. Emissions Impacts of Wind and Energy Storage in a Market Environment. *Environmental Science & Technology,* 45**,** 10728-10735.

SKEER, J. & WANG, Y. 2007. China on the move: Oil price explosion? *Energy Policy,* 35**,** 678-691.

SOVACOOL, B. K. & SOVACOOL, K. E. 2009. Identifying future electricity-water tradeoffs in the United States. *Energy Policy,* 37**,** 2763-2773.

STONE, R. 1961. *Input-Output and National Accounts,* Paris, Office of European Economic Cooperation.

SUH, S. 2004a. Functions, commodities and environmental impacts in an ecological-economic model. *Ecological Economics,* 48**,** 451-467.

SUH, S. 2004b. Functions, commodities and environmental impacts in an ecological–economic model. *Ecological Economics,* 48**,** 451-467.

SUH, S. 2006. Reply: Downstream cut-offs in integrated hybrid life-cycle assessment. *Ecological Economics,* 59**,** 7-12.

SUH, S. & HUPPES, G. 2005. Methods for Life Cycle Inventory of a product. *Journal of Cleaner Production,* 13**,** 687-697.

SUH, S., LENZEN, M., TRELOAR, G. J., HONDO, H., HORVATH, A., HUPPES, G., JOLLIET, O., KLANN, U., KREWITT, W., MORIGUCHI, Y., MUNKSGAARD, J. & NORRIS, G. 2003. System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environmental Science & Technology,* 38**,** 657-664.

SUH, S., LENZEN, M., TRELOAR, G. J., HONDO, H., HORVATH, A., HUPPES, G., JOLLIET, O., KLANN, U., KREWITT, W., MORIGUCHI, Y., MUNKSGAARD, J. & NORRIS, G. 2004. System Boundary Selection in Life-

Cycle Inventories Using Hybrid Approaches. *Environmental Science & Technology,* 38**,** 657-664.
SUH, S. & NAKAMURA, S. 2007. Five years in the area of input-output and hybrid LCA. *The International Journal of Life Cycle Assessment,* 12**,** 351-352.
TEN RAA, T. 1986. Dynamic Input-Output Analysis with Distributed Activities. *The Review of Economics and Statistics,* 68**,** 300-310.
TIWARI, P. 2000. An analysis of sectoral energy intensity in India. *Energy Policy,* 28**,** 771-778.
TRELOAR, G. J., LOVE, P. E. D., FANIRAN, O. O. & IYER-RANIGA, U. 2000. A Hybrid Life Cycle Assessment Method for Construction. *Construction Management and Economics,* 18**,** 5-9.
TREMEAC, B. & MEUNIER, F. 2009. Life cycle analysis of 4.5 MW and 250 W wind turbines. *Renewable and Sustainable Energy Reviews,* 13**,** 2104-2110.
UDO DE HAES, H., HEIJUNGS, R., SUH, S. & HUPPES, G. 2004. Three Strategies to Overcome the Limitations of Life Cycle Assessment. *Journal of Industrial Ecology,* 8**,** 19-32.
UN 1992. United Nations Framework Convention on Climate Change.
USDOE 2006. Energy Demands on Water Resources. U.S. Department of Energy.
VALENTINO, L., VALENZUELA, V., BOTTERUD, A., ZHOU, Z. & CONZELMANN, G. 2012. System-Wide Emissions Implications of Increased Wind Power Penetration. *Environmental Science & Technology,* 46**,** 4200-4206.
VARUN, BHAT, I. K. & PRAKASH, R. 2009. LCA of renewable energy for electricity generation systems--A review. *Renewable and Sustainable Energy Reviews,* 13**,** 1067-1073.
VARUN, PRAKASH, R. & BHAT, I. K. 2010. Life Cycle Energy and GHG Analysis of Hydroelectric Power Development in India. *International Journal of Green Energy,* 7**,** 361-375.
VESTAS 2011. Water, Energy, Climate Nexus. Vestas.
WANG, F., YIN, H. & LI, S. 2010. China's renewable energy policy: Commitments and challenges. *Energy Policy,* 38**,** 1872-1878.

WANG, Q. 2010. Effective policies for renewable energy--the example of China's wind power--lessons for China's photovoltaic power. *Renewable and Sustainable Energy Reviews,* 14**,** 702-712.
WANG, Q. & CHEN, Y. 2010. Barriers and opportunities of using the clean development mechanism to advance renewable energy development in China. *Renewable and Sustainable Energy Reviews,* 14**,** 1989-1998.
WANG, T. & WATSON, J. 2010. Scenario analysis of China's emissions pathways in the 21st century for low carbon transition. *Energy Policy,* 38**,** 3537-3546.
WANG, Y., GOSENS, J., WANG, H. & HAO, Z. 2011. China's increasingly positive and active stance on climate change. *Environmental Science & Technology,* 45**,** 2525-2526.
WANG, Y. & SUN, T. 2012. Life cycle assessment of CO2 emissions from wind power plants: Methodology and case studies. *Renewable Energy,* 43**,** 30-36.
WEBER, C. L., JARAMILLO, P., MARRIOTT, J. & SAMARAS, C. 2010. Life Cycle Assessment and Grid Electricity: What Do We Know and What Can We Know? *Environmental Science & Technology,* 44**,** 1895-1901.
WEBER, C. L. & MATTHEWS, H. S. 2007. Embodied Environmental Emissions in U.S. International Trade, 1997-2004. *Environmental Science & Technology,* 41**,** 4875-4881.
WEINZETTEL, J., REENAAS, M., SOLLI, C. & HERTWICH, E. G. 2009. Life cycle assessment of a floating offshore wind turbine. *Renewable Energy,* 34**,** 742-747.
WEISSER, D. 2007. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy,* 32**,** 1543-1559.
WFN 2011. Glossary. Water Footprint Network.
WHITE, D. 2004. Reduction in Carbon Dioxide Emissions: Estimating the Potential Contribution from Wind-Power. London: Renewable Energy Foundation.
WIEDMANN, T. O., SUH, S., FENG, K., LENZEN, M., ACQUAYE, A., SCOTT, K. & BARRETT, J. R. 2011. Application of Hybrid Life Cycle Approaches to Emerging Energy Technologies – The Case of Wind Power in the UK. *Environmental Science & Technology,* 45**,** 5900-5907.

WILLIAMS, J. H. & KAHRL, F. 2008. Electricity reform and sustainable development in China. *Environmental Research Letters,* 3**,** 044009.
WNA. 2011. *Plans for New Reactors Worldwide* [Online]. World Nuclear Association. Available: http://www.world-nuclear.org/info/default.aspx?id=416&terms=china nuclear [Accessed September 30 2011].
WOLSKY, A. 1984. Disaggregating Input-Output Models. *The Review of Economics and Statistics,* 66**,** 283-291.
WORLDBANK 2007. Cost of pollution in China: Economic estimates of physical damages. Washington DC: The World Bank.
WORLDBANK 2012. World Bank Databank. Washington DC.
WYCKOFF, A. W. & ROOP, J. M. 1994. The embodiment of carbon in imports of manufactured products : Implications for international agreements on greenhouse gas emissions. *Energy Policy,* 22**,** 187-194.
XIE, J., LIEBENTHAL, A., WARFORD, J. J., DIXON, J. A., WANG, M., GAO, S., WANG, S., JIANG, Y. & MA, Z. 2009. Addressing China's Water Scarcity. Washington D.C.: The World Bank.
XINHUA. 2005. *The Eleventh Five Year Plan* [Online]. Beijing: Xinhua News Agency. Available: http://news.xinhuanet.com/politics/2005-10/18/content_3640318.htm [Accessed August 28 2010].
XINHUA. 2009. *China to build six 10-GW-Level wind farm bases (zhong guo qi dong 6 ge qian wan qian wa ji feng dian ji di gui hua he jian she)* [Online]. Beijing: Xinhua News Agency. Available: http://news.xinhuanet.com/newscenter/2009-02/16/content_10828897.htm [Accessed 3rd July 2010].
XINHUA. 2011. *Inner Mongolia is short of water supply* [Online]. Available: http://www.nmg.xinhuanet.com/xwzx/2011-09/10/content_23667872.htm [Accessed 24 April 2012].
XINHUA. 2012. *Top five power groups invest in renewable energy* [Online]. Available: http://news.xinhuanet.com/energy/2012-03/12/c_122820870.htm [Accessed 10 August 2012].
XU, J., HE, D. & ZHAO, X. 2010. Status and prospects of Chinese wind energy. *Energy,* 35**,** 4439-4444.

XU, S. & CHEN, W. 2006. The reform of electricity power sector in the PR of China. *Energy Policy,* 34**,** 2455-2465.

YANG, M., PATIÑO-ECHEVERRI, D. & YANG, F. 2012a. Wind power generation in China: Understanding the mismatch between capacity and generation. *Renewable Energy,* 41**,** 145-151.

YANG, Y. 2010. *SGCC invests wind farms is considered as an aggrandizement of monopoly (国家电网投资风电被指借道新能源强化垄断)* [Online]. Beijing. Available: http://finance.sina.com.cn/chanjing/cyxw/20100524/00127987790.shtml [in Chinese] [Accessed 23 August 2011].

YANG, Y., HUANG, Q. & WANG, Q. 2012b. Ignoring Emissions of Hg from Coal Ash and Desulfurized Gypsum Will Lead to Ineffective Mercury Control in Coal-Fired Power Plants in China. *Environmental Science & Technology*.

YANG, Y. & SUH, S. 2011. Environmental Impacts of Products in China. *Environmental Science & Technology,* 45**,** 4102-4109.

YU, X. & QU, H. 2010. Wind power in China--Opportunity goes with challenge. *Renewable and Sustainable Energy Reviews,* 14**,** 2232-2237.

ZENG, N., DING, Y., PAN, J., WANG, H. & GREGG, J. 2008. Climate Change--the Chinese Challenge. *Science,* 319**,** 730-731.

ZHANG, D., AUNAN, K., MARTIN SEIP, H., LARSSEN, S., LIU, J. & ZHANG, D. 2010. The assessment of health damage caused by air pollution and its implication for policy making in Taiyuan, Shanxi, China. *Energy Policy,* 38**,** 491-502.

ZHANG, D., MA, L., LIU, P., ZHANG, L. & LI, Z. 2012. A multi-period superstructure optimisation model for the optimal planning of China's power sector considering carbon dioxide mitigation: Discussion on China's carbon mitigation policy based on the model. *Energy Policy,* 41**,** 173-183.

ZHANG, P., YANG, Y., SHI, J., ZHENG, Y., WANG, L. & LI, X. 2009. Opportunities and challenges for renewable energy policy in China. *Renewable and Sustainable Energy Reviews,* 13**,** 439-449.

ZHANG, Q., KARNEY, B., MACLEAN, H. L. & FENG, J. 2007. Life-Cycle Inventory of Energy Use and Greenhouse Gas Emissions for Two

Hydropower Projects in China. *Journal of Infrastructure Systems,* 13**,** 271-279.

ZHANG, Q.-Y., WEI, Y.-M., CHEN, Y.-X. & GUO, H. 2008. Environmental damage costs from fossil electricity generation in China, 2000~2003. *Journal of Zhejiang University - Science A,* 8**,** 1816-1825.

ZHANG, S. & QI, J. 2011. Small wind power in China: Current status and future potentials. *Renewable and Sustainable Energy Reviews,* 15**,** 2457-2460.

ZHANG, X. 2011. Assessing China's Carbon Intensity Pledge for 2020: Stringency and Credibility Issues and their Implications. *Fondazione Eni Enrico Mattei Working Papers.*

ZHANG, X. P., REHTANZ, C. & SONG, Y. 2006. A grid for tomorrow. *Power Engineer,* 20**,** 22-27.

ZHANG, Z. 2010. China in the transition to a low-carbon economy. *Energy Policy,* 38**,** 6638-6653.

ZHANG, Z., YANG, H. & SHI, M. 2011. Analyses of water footprint of Beijing in an interregional input–output framework. *Ecological Economics,* 70**,** 2494-2502.

ZHAO, Z. Y., HU, J. & ZUO, J. 2009. Performance of wind power industry development in China: A DiamondModel study. *Renewable Energy,* 34**,** 2883-2891.

ZHOU, L. & MIN, F. 2009. Research on application of non-grid-connected wind power in less developed areas. *World Non-Grid-Connected Wind Power and Energy Conference, 2009. WNWEC 2009.*

ZHOU, N., FRIDLEY, D., MCNEIL, M., ZHENG, N., KE, J. & LEVINE, M. 2011. China's Energy and Carbon Emissions Outlook to 2050. Lawrence Berkeley National Laboratory.

ZHOU, S. & ZHANG, X. 2010. Nuclear energy development in China: A study of opportunities and challenges. *Energy,* 35**,** 4282-4288.

Appendices

Appendix One: Data source and data compilation

The total turnover of the 50 wind farms is 24.1 billion yuan. Hence, the average turnover of each wind farm is 0.482 billion yuan. Owing to insufficient data on all the wind farms in China, it is assumed that the turnover of the other wind farms is identical to those 50 CDM wind farms. This assumption is a reasonable one based on that this research aims to evaluate the economy-wide emissions and water consumption of wind power in general. Besides, the turnover per MW of wind turbine installed is 9.25 million yuan (24.1 billion yuan divided by 2,603.55 MW). It is consistent with the value presented by Liu and Yang (2008), which the turnover per MW of the installed wind turbine is about 9.227 million yuan in China (9,227 yuan per kW according to Liu and Yang's report). Based on the above, the computed turnover of wind energy sector is 54.5 billion yuan.

Appendix Two: List of figures on water consumption

Economic sector	Water consumption (litre/kWh)
Total	0.63962
Crop cultivation	0.15894
Electricity and steam production and supply	0.08277
Livestock and livestock products	0.06861
Forestry	0.05425
Fishery	0.03263
Steel-smelting	0.01939
Nonferrous metal smelting	0.01471
Technical services for agriculture, forestry, livestock and fishing	0.01141
Switchboards and related equipment	0.01027
Raw chemical materials	0.00999
Scrap and waste	0.00923
Steel-processing	0.00796
Paper and products	0.00787
Instruments, meters and other measuring equipment	0.00758
Synthetic chemicals	0.00688
Plastic products	0.00641
Finance	0.00614
Other general industrial machinery	0.00609
Other computer devices	0.00559
Nonferrous metal processing	0.00557
Chemicals for special usages	0.00524
Wholesale and retail trade	0.00472
Coal mining and processing	0.00469
Iron-smelting	0.00468
Wires, cables and related electrics	0.00354
Highway freight and passengers transport	0.00354
Crude petroleum products and natural gas products	0.00328
Ferrous ore mining	0.00297
Printing and record medium reproduction	0.00290

Telecommunication	0.00274
Motor vehicles	0.00266
Water freight and passengers transport	0.00263
Non-ferrous ore mining	0.00251
General technical services	0.00242
Chemicals for painting, dying and others	0.00224
Other services	0.00208
Metal products	0.00199
Rubber products	0.00189
Business services	0.00187
Railway passenger and freight transport	0.00183
Bricks and other construction materials	0.00181
Cement and cement asbestos production	0.00175
Gas production and supply	0.00165
Glass and glass products	0.00154
Special equipment for mines, metallurgy and construction	0.00149
Boiler, engines and turbine	0.00143
Cotton textiles	0.00138
Pump, valve, compressor and related equipment	0.00129
Water production and supply	0.00128
Eating and drinking places	0.00121
Non-metal minerals and other mining	0.00108
Chemical fibres	0.00104
Petroleum and nuclear fuel refining	0.00102
Alloy iron smelting	0.00100
Insurance	0.00098
Tobacco products	0.00092
Medical and pharmaceutical products	0.00092
Other electric machinery and equipment	0.00088
Metalworking machinery	0.00085
Arts and crafts, and other manufacturing products	0.00082
Non-alcoholic beverage	0.00082
Removing and other transport services	0.00081
Health services	0.00080
Electronic computer	0.00079

Real estate	0.00072
Air passenger and freight transport	0.00069
Cultural goods, toys, sporting and athletic and recreation products	0.00068
Chemical products for daily use	0.00068
Other special industrial equipment	0.00067
Computing services	0.00066
Household electric appliances	0.00065
Scientific research	0.00063
Wines, spirits and liquors	0.00063
Sawmills and fibreboard	0.00057
Vegetable oil and forage	0.00057
Generators	0.00055
Pipeline transport	0.00054
Hotels	0.00054
Wearing apparel	0.00049
Chemical fertilizers	0.00046
Other textiles not elsewhere classified	0.00046
Fireproof products	0.00046
Cultural and office equipment	0.00045
Hemp textiles	0.00038
Educational services	0.00036
Slaughtering, meat processing	0.00034
Coking	0.00034
Other non-metallic mineral products	0.00033
Prepared fish and seafood processing	0.00032
Domestic public transport	0.00032
Special equipment for chemical production, non-metallic production	0.00031
Chemical pesticides	0.00030
Crane transportation equipment	0.00029
Recreational services	0.00028
Other food processing	0.00028
Grain mill products	0.00027
Feeding stuff production and processing	0.00026

Construction	0.00025
Communication equipment	0.00023
Other transport machinery	0.00022
Woollen textiles	0.00021
Water conservancy	0.00020
Post	0.00019
Scientific communication services	0.00019
Leather, furs, down and related products	0.00018
Radio, film and television	0.00018
Furniture and products of wood, bamboo, cane, palm, straw, etc.	0.00016
Audio, video products	0.00014
Other electronic equipment	0.00014
Other food products	0.00014
Warehousing	0.00013
Resident services	0.00013
Environmental resources and public infrastructure	0.00011
Knitted mills	0.00010
Railroad transport equipment	0.00010
Pottery, china and earthenware	0.00009
Sugar refining	0.00008
Tourism	0.00008
Flavouring and fermentable products	0.00007
Ship building	0.00007
Cement and cement asbestos related products	0.00007
Dairy products	0.00007
Leasehold	0.00007
Media publishing	0.00005
Fast food production	0.00004
Public administration	0.00004
Geological prospecting	0.00004
Culture and arts	0.00003
Agriculture, forestry, animal husbandry and fishing machinery	0.00002
Social security	0.00002

Radar and broadcasting equipment	0.00002
Software	0.00001
Public infrastructure management	0.00000
Social welfare	0.00000
Wind power	0.00000
Sports	0.00000

Appendix Three: Industrial water recycle rate

Economic sector	Recycle rate	
	Lower	Upper
Coal mining & processing	90%	90%
Petroleum & Natural Gas Pumped	90%	90%
Mining & Dressing of Ferrous Metals	50%	85%
Mining & Dressing of Nonferrous Metals	35%	90%
Mining & Dressing of Non-metal Minerals	95%	95%
Processing of Agricultural Side-Line Food	75%	85%
Manufacturing of Food	35%	95%
Manufacturing of Beverage	70%	80%
Tobacco Products	85%	85%
Textile Industry	50%	65%
Textile, Clothes, Shoes & Hats	50%	65%
Leather, Furs, Down & Related Products	50%	65%
Timber Processing, Bamboo, Cane,	90%	95%
Palm Fibre & Straw Products	90%	90%
Paper-making & Paper Products	60%	85%
Printing & Record Pressing	90%	90%
Petroleum Processing, Coke Products & Processing of Nuclear Fuel	50%	95%
Chemical Materials & Products	60%	95%
Manufacturing of Medicine	80%	90%
Plastic Products	70%	85%

Non-metal Mineral Products	60%	70%
Smelting & Pressing of Ferrous Metals	95%	95%
Smelting & Pressing of Nonferrous Metals	90%	95%
Metal Products	80%	90%
General-Purpose Equipment	70%	80%
Special Equipment	35%	80%
Transported Equipment	60%	60%
Electric Equipment & Machinery	60%	80%
Manufacturing of Telecoms, Computer & Other Electronic Equipment	30%	90%
Instruments, Meters, Cultural & Office Machinery	30%	90%
Production & Supply of Electric Power	92%	95%
Production & Supply of Gas	92%	95%
Production & Supply of Water	92%	95%

Source: (IMQSIP, 2003)

Appendix Four: Sectoral water consumption and water coefficients

Economic sectors	**Water consumption (10,000 m^3)**	**Economic output (10,000 yuan)**	**Water consumption coefficient (m^3/10,000 yuan)**
Agriculture	779200.0	6421574.0	1213.4
Forest, finishing, livestock	127500.0	6342863.0	201.0
Coal mining & processing	20558.3	7629806.4	26.9
Petroleum & Natural Gas Pumped	12.4	630965.8	0.2
Mining & Dressing of Ferrous Metals	349.4	2341200.7	1.5
Mining & Dressing of Nonferrous Metals	2338.7	2021735.9	11.6
Mining & Dressing of Non-metal Minerals	212.5	1628769.9	1.3
Processing of Agricultural Side-Line Food	4666.1	912753.5	51.1
Manufacturing of Food	2161.3	8914647.1	2.4
Manufacturing of Beverage	3006.5	1254994.5	24.0
Tobacco Products	28.5	386674.8	0.7
Textile Industry	440.9	1425883.0	3.1
Textile, Clothes, Shoes & Hats	49.7	1639205.6	0.3
Leather, Furs, Down & Related Products	34.6	108823.2	3.2
Timber Processing,	2398.7	859677.6	27.9

Bamboo, Cane			
Palm Fibre & Straw Products	548.5	196560.3	27.9
Paper-making & Paper Products	5469.6	374270.4	146.1
Printing & Record Pressing	93.7	390490.8	2.4
Petroleum Processing, Coke Products & Processing of Nuclear Fuel	206.0	1587319.4	1.3
Chemical Materials & Products	2660.0	3867593.5	6.9
Manufacturing of Medicine	1817.0	575195.6	31.6
Plastic Products	45.2	453652.5	1.0
Non-metal Mineral Products	376.1	3773112.8	1.0
Smelting & Pressing of Ferrous Metals	41496.8	7032359.4	59.0
Smelting & Pressing of Nonferrous Metals	2202.8	10513854.2	2.1
Metal Products	2.2	38571.3	0.6
General-Purpose Equipment	19.8	760220.0	0.3
Special Equipment	174.3	840643.9	2.1
Transported Equipment	25.2	2065849.2	0.1
Electric Equipment & Machinery	15.4	421611.8	0.4
Manufacturing of Telecoms, Computer &	8.2	845809.3	0.1

Other Electronic Equipment			
Instruments, Meters, Cultural & Office Machinery	5.9	162573.1	0.4
Production & Supply of Electric Power	31938.7	7780758.0	41.0
Production & Supply of Gas	26.5	751728.3	0.4
Production & Supply of Water	2131.8	146129.5	145.9
Construction	5852.9	11705703.3	5.0
Transport and warehousing	3123.5	10075826.0	3.1
Post and telecommunication	309.7	1290483.6	2.4
Wholesale and retail trade	1538.4	6992825.7	2.2
Eating and drinking places	566.2	2573768.2	2.2
Passenger transport	136.8	427536.0	3.2
Finance and insurance	709.7	3226008.0	2.2
Real estate	321.6	1461761.7	2.2
Social services	263.2	1461970.6	1.8
Health Services, social welfare	1186.7	3596116.6	3.3
Education and culture	617.5	1992087.5	3.1
Scientific research	45.8	190703.1	2.4
General technical services	100.9	252170.8	4.0

Public and other services	3141.9	6283872.6	5.0
Total	**1050136.1**	**136628711.7**	**76.9**

Appendix Five: COD discharge and COD discharge standard by sectors

Economic Sectors	Wastewater discharge	COD discharge	Average COD level	COD discharge standard (Grade I)
Unit	**10,000 m^3**	**tonne**	**g/m^3**	**g/m^3**
Agriculture	8807.46	25541.64	290.000	100
Coal Mining & Processing	2829.56	4038.91	142.740	100
Petroleum & Natural Gas Pumped	1.70	0.09	5.318	60
Mining & Dressing of Ferrous Metals	240.42	107.04	44.520	100
Mining & Dressing of Nonferrous Metals	2092.28	18988.36	907.545	100
Mining & Dressing of Non-metal Minerals	14.62	65.49	447.910	100
Mining of Other Mineral	0.00	0.00	0.000	100
Processing of Agricultural Side-Line Food	1605.55	12635.80	787.006	100
Manufacturing of Food	1933.61	10653.12	550.946	100
Manufacturing of Beverage	1241.40	13488.52	1086.561	100
Tobacco Products	5.88	18.04	306.718	100
Textile Industry	303.44	2254.47	742.962	100

Textile, Clothes, Shoes & Hats	34.20	84.67	247.533	100
Leather, Furs, Down & Related Products	23.82	82.68	347.143	100
Timber Processing, Bamboo, Cane,	330.15	428.49	129.789	100
Palm Fibre & Straw Products	0.00	0.00	0.000	100
Paper-making & Paper Products	3011.23	49981.95	1659.851	100
Printing & Record Pressing	0.00	0.00	0.000	100
Petroleum Processing, Coke Products & Processing of Nuclear Fuel	141.77	98.12	69.211	100
Chemical Materials & Products	1464.47	2903.29	198.249	100
Manufacturing of Medicine	500.17	1766.53	353.188	100
Plastic Products	0.00	0.00	0.000	100
Non-metal Mineral Products	207.08	120.07	57.982	100
Smelting & Pressing of Ferrous Metals	2855.72	1777.99	62.261	100
Smelting & Pressing of Nonferrous Metals	303.18	213.38	70.382	100
Metal Products	0.60	1.12	186.291	100

General-Purpose Equipment	8.19	23.35	285.076	100
Special Equipment	155.96	116.87	74.938	100
Transported Equipment	13.88	10.81	77.871	100
Electric Equipment & Machinery	8.48	5.24	61.765	100
Manufacturing of Telecoms, Computer	7.86	10.11	128.633	100
Instruments, Meters, Cultural	0.00	0.00	0.000	100
Production & Supply of Electric Power	3516.72	2029.68	57.715	100
Production & Supply of Gas	2.92	43.42	1486.986	100
Production & Supply of Water	234.73	280.88	119.659	100
Housing & Civil Construction	0.00	0.00	0.000	100
Railway Transport	0.00	0.00	0.000	100
Other Sectors	120.03	515.52	429.503	100
Total	**32017.07**	**148285.66**	**463.15**	

Source: Wastewater discharge data and COD discharge data are from (IMARBS, 2008); COD discharge standard are from (AQSIP, 1996).

Appendix Six: Industrial wastewater discharge standard for COD content (grams per cubic meter)

Industry	Grade I	Grade II	Grade III
Beet sugar manufacturing, fatty acid synthesis, wet fibreboard processing, dye manufacturing, organophosphorus pesticides industry	100	200	1000
Monosodium glutamate, ethanol, medicines, medicines, biochemistry, fur industry, pulp purification industry	100	300	1000
Petroleum refinery	60	120	150
Secondary wastewater treatment plant	60	120	-
Other wastewater discharge	100	150	500

Source: (AQSIP, 1996)