Article:

Li, X, Hubacek, K and Siu, YL (2012) Wind power in China - Dream or reality? Energy, 37 (1). pp. 51-60. ISSN 0360-5442

https://doi.org/10.1016/j.energy.2011.09.030

Wind Power in China – Dream or Reality?

*X. Li[a]; K. Hubacek[a,b]; Y.L. Siu[a,c]
[a] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.
[b] Department of Geography, University of Maryland, College Park, MD 20742, USA.
[c] State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, PR China.

*Corresponding author
Telephone number: +44 113-3435572
Fax number: +44 113-3435259
Email: lec3xl@leeds.ac.uk
Postal address: Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.

Abstract

After tremendous growth in recent years, China now has 44.7GW of wind-derived power and has surpassed the US (40.18 GW) to be the largest wind turbine owner since the end of 2010. In 2010, around half of the new wind turbines globally were installed in China. Despite the recent growth rates and promises of a bright future, two important issues - the capability of the grid infrastructure and the availability of backup systems - must be critically discussed and tackled in the medium term.

The study shows that only a relatively small share of investment goes towards improving and extending the electricity infrastructure which is a precondition for transmitting clean wind energy to the end users. In addition, the backup systems are either geographically too remote from the potential wind power sites or currently financially infeasible. Also, the use of coal-fired plants as the backup system is unavoidable because of the coal-dominated electricity mix. 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 is likely to compensate some of the emission savings from wind power.

The current power system is heavily reliant on independently acting but state-owned energy companies optimizing their part of the system, which is partly incompatible with building a robust system supporting renewable energy technologies. Hence, strategic, top-down co-ordination and incentives to improve the overall electricity infrastructure is recommended.

Keywords: wind power, China, power grids, back-up systems

1. Introduction

China's wind energy industry has experienced a rapid growth over the last decade. Since the promulgation of the first Renewable Energy Law in 2006, the cumulative installed capacity of wind energy amounted to 44.7 GW by the end of 2010 [1]. The newly installed capacity in 2010 reached 18.9 GW which accounted for about 49.5% of new windmills globally. The wind energy potential in China is considerable, though with differing estimates from different sources. According to He et al. [2], 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. [3] concluded that wind energy is capable to generate 6.96 million GWh of electricity by 2030, which is sufficient to satisfy China's electricity demand in 2030, if the Chinese government commits to an aggressive low carbon energy future.

Despite the recent growth rates and promises of a bright future, two major issues must critically be discussed and clarified in light of the Chinese wind energy diffusion 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.

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 population and less developed economies. It means that with less wind powered electricity 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 to the national power grid system, including grid investments, grid safety and grid interconnection.

2.1 Power grid investment

Although the two state grid companies - the 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 [4]. This situation is a result of an imbalanced investment between power grid construction and power generation capacity. For example, the Eighth Five-Year Plan, Ninth Five-Year Plan and Tenth Five Year Plan[1], 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 [5]. Figure 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.

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 [6] found that the subsidies were only sufficient to compensate for capital investment and corresponding interests but excluding operational and maintenance costs.

Again, similar to grid connection, the 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 centre where the majority are located in the eastern coastal areas and southern part of China. According to SGCC [7], 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 generation capacity of Three Gorges project is approximately 18.2 GW at this moment and will reach 22.4 GW when fully operating [8], whilst the total generation capacity of the massive wind farms amount to over 100GW. Hence, more transmission capacities are required. 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 wind farm bases are far away from the load centres with the exception of the Eastern Inner Mongolia. For example, Jiuquan located in Gansu has a planned generation capacity of 20 GW. The distances from Jiuquan to the demand centre of Central China grid and Eastern China grid are 1,500 km and 2,500 km, respectively. For Xinjiang, the distances are even longer at 2,500

[1] 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 to2005, and so on and so forth.

km and 4,000 km, respectively. As a result, longer transmission lines are required. Figure 2 depicts the demand centres and wind farms in detail.

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 [9]. 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 [10]. Furthermore, the significant changes in power supply from wind might damage the power quality. Hence, additional regulation capacity would be needed. However, in a power system with majority of its power from baseload provider, the requirements cannot be met easily [11]. In addition, the possible expansion of existing transmission lines would be necessary since integration of large-scale wind would cause congestions in the existing transmission system. Holttinen [12] summarized the major impact 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, adequacy of power on the integration of wind power [12].

One of the grid safety problems caused by wind power is reported by the State Electricity Regulatory Commission [13]. In February and April of 2011, three large-scale wind power drop-off accidents happened in Gansu (twice) and Hebei caused power loss of 840.43MW, 1006.223MW and 854MW, 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 of regional power grid.

The Chinese Renewable Energy Law requires the power grid operators to coordinate the integration of wind mills 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, namely 4 GW, were not connected to the power grid by the end of 2008 [5]. Given that the national grid in China is exclusively controlled by the power companies: state grid corporation of China (SGCC) and China southern grid (CSG), the willingness of these two companies to integrate wind energy into the electricity generation systems is critical.

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[2] 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. It was followed by the interconnection of Central China Power Grid and 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 [14].

It seems that the interconnectivity of regional power grids would help the 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 back-up to the contingencies, which could not support the large-scale long-distance electricity transmission [15]. In addition, the construction of transmission system 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 [15]. 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.

3. Are the backup systems geographically available and technically feasible?

The variability of electricity output from wind power results in difficulties in the integration of wind power into the regional and national power generation systems [16]. Belanger and Gagnon [17] conducted a study on the compensation of wind power fluctuations by using hydropower in Canada. Drake and Hubacek [16], Roques [18] and Kempton et al. [19] examined the deployment of wind turbines at dispersed locations for mutual compensation given diverse wind conditions between wind turbines in the UK, the EU and the US, respectively. A number of attempts have been made to justify the approaches to stabilize the electricity output from wind power plants. For example, Nema et al. [20] discussed the application of wind combined solar PV power generation systems and concluded that the hybrid energy system is a viable alternative to current power supply systems in remote areas. In China, He et al. [2] investigated the choices of combined power generation systems. The combinations

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

of wind-hydro, wind-diesel, wind-solar and wind-gas power were evaluated respectively. They found that, for instance, the wind-diesel hybrid systems have been used at remote areas and isolated islands. It 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 urban areas.

3.1 Wind-hydro combined electricity generation system

There are two types of wind-hydro hybrid systems. The first type of the 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 its quick response to electricity demand. The other type of combined hydro-wind power systems is to use hydro storage systems. The foundation of this combined system, which is discussed in detail in section 3.4, 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 [21]. 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. [2] suggested that wind-hydropower generation system 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 consistent enough (see Figure 3).

Table 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.

3.2 Wind-gas combined electricity generation 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 [2].

The China Academy of Engineering (CAE) has carried out a feasibility study of the combined power generation system in Xinjiang [2]. 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 system 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 power grid is taken into consideration [2].

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 [22], the capital investments of wind mills 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 due to the lengths of transportation from the supply centres to the demand centres. The price for industrial use gas is 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 [23].

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 has 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 [23].

Fourth, the capacity factors of wind farms in China are far below the expected level. The State Electricity Regulatory Commission [5] found that six out of seven wind farms, which were randomly selected in seven provinces, had less operating hours (1,864 hours on average) than the designed operating hours (2,305 hours on average). The capacity factors of these six wind farms are 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 [2]. 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. The wind-natural gas hybrid system remains doubtful in the future.

3.3 The compensation of wind power using other power generation technologies

Besides the wind-hydro and wind-gas hybrid systems, there are several other power generation technologies which would be important in the future Chinese power generation mix and might be useful in the large-scale integration of wind power. Their potentials to compensate the variable wind power outputs are discussed in the following subsections.

3.3.1 Nuclear power

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 7GW in 2005 to 40GW in 2020. Total power output would reach 260 - 280 TWh [24]. 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 [24]. The development of nuclear power has been controversial in China especially since the nuclear crisis after Japan's devastating earthquake in March 2011. Although 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 [25].

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 spatial mismatch. More importantly, as a baseload 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)[3]. The continuous operation mode of nuclear power generation units made them incapable in ramping ups and shutting downs quickly [26]. Consequently, nuclear power is not appropriate to compensate wind powered outputs.

3.3.2 Carbon capture and storage systems

By capturing and storing the emissions, carbon capture and storage (CCS) technologies are considered as a promising option to the mitigation of CO_2 emissions caused by coal combustion. One of the advantages of CCS power plant is its capability of flexible operation [27]. The capture facilities could help to adjust the power outputs by starting and stopping the carbon capture and compression process during the peak and light load periods [26]. Hence, CCS power plant provides a similar operation mode to the pumped storage systems, which could be used as a compensation to the variable wind power outputs [28]. To investigate the technical and financial feasibilities of CCS in the integration of large-scale wind power in China, Chen et al. [29] compared the costs and capability of coal-fired power plants, natural gas power plants, pumped hydro and CCS in dealing with the wind power integration. The authors concluded that CCS power plant could accommodate up to 20% more wind capacity than the traditional coal-fired power plants due to its flexible operation mode. In addition, the cost of using CCS power plant in peak-load would be lower than the application of natural gas power plants which has been widely used in peak-load shaving. However, there are significant barriers in the deployment of CCS technologies such as immature CCS technologies, extensive capital investments, energy penalties and insufficient experiences in dealing with the risk of CO_2 storage [26] [30].

Although CCS technologies are competitive in coping with the large-scale integration of wind power in terms of costs, the deployment of CCS technologies would require a long-term strategic planning in terms of supportive policies, financial incentives and technology advancements. Consequently, the application of CCS technologies in large-scale wind integration is not seen as being able to play a significant role in the near future.

3.4 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.

[3] own calculation, figures from [27]

There are two types of energy storage systems available at present. First, physical energy storage systems such as wind powered pumped hydro storage system [31] and compressed-air system [32] 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) [33]. 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 [2]. Since the majority of the wind farms have a generation capacity of 50 MW, the 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.

3.5 The available choices for backup systems under current conditions

In China, coal is dominating the energy system. More than 70% of primary energy consumption was provided by coal in 2007 [34]. In addition, coal-fired power plants accounted for approximately 76% of electricity generation and over 97% of thermal power plants [35]. 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 [36-37]. Table 2 gives the composition of the electricity mix for 6 selected wind farms.

With thermal power serving more than 90% of the electricity demand, the choices of using coal-fired plants as backup system in provinces such as Inner Mongolia, Hebei and Jiangsu are inevitable. Besides that, other non wind-farm based provinces are also looking for backup capacities from coal-fired plants. For instance, the local authority of Gansu is trying to look for investment in other 20 GW coal-fired plants in order to smoothen out the intermittent electricity supply from wind farms. The choice of using coal-fired power plants as backup system raises a number of questions; namely, what is the efficiency loss of using coal-fired plants to backup wind power; to what extent do coal-fired backup systems cancel out the ‘emission savings’ from wind energy; is it economically viable to construct coal-fired plants in remote areas and transmit the electricity to the demand centres?

To answer these questions, a brief introduction of the electricity systems' operation is needed. In electric power systems, the system operator usually schedules the hourly electricity supply the day before dispatch. However, the forecasting inaccuracies are to some extent inevitable because of the contingencies such as the time-varying (intra-hour) demand and unscheduled blackouts of power plants. The scheduled supply, also known as base load, is provided with lowest marginal costs units such as coal-fired plants and nuclear power plants. The discrepancies between the scheduled supply and the actual demand are met with balancing reserve units, such as natural gas-fired plants and hydropower plants, which could balance the supply and demand with quick responses to the electricity output. Compared with other energy sources, coal power plants provide the cheapest electricity as the externalities of burning coal are not taken into account. However, the coal-fired plants are difficult to operate when a quick response to changing electricity demand is needed as it results in lower energy efficiency [38].

As stated by Goggin [39], the integration of wind power to the power grid 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. However, the frequent adjustment of power output of coal-fired plants results in much higher CO_2 emissions per kWh power output than in normal operation mode. For example, White [38] concluded 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. The figure for a greener power generation system – the combined cycle gas turbine plant – is still 30-50 grams per kWh power output. Consequently, the loss of energy efficiency might have significant impacts on the overall CO_2 emission from conventional power plants. In addition, the design and operation of these base load providers fit a stable and continuous power output mode. The ramping ups and downs might cause more frequent and higher costs of maintenance [38]. Another issue of using coal as a backup is the same as previously mentioned challenges in section 3.2 – 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.

3.6 The asymmetrical relations 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 would need to be prioritised from the beginning of the construction of conventional power plants construction rather than the hybridizing with wind power. For example, thermal plants in the northern part of China are important since they provide simultaneously electricity and heat to the end-users in winter. The proportion of these combined heat and power generation plants to the total thermal power plants are significant in the northern China (72% in Jilin, for instance). It is not possible to adjust the peak and light load by using these combined heat and power 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 [40]. Thus it is naturally hard to make the combination of wind power with those possible options well match each other in reality.

4. Future prospects of wind energy development in China

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 [41]. However, even when operated with the modern and efficient power grids, transmission losses are still significant which amounting to more than 6% of the electricity produced [40]. In addition, due to the uneven distribution of energy sources and the huge territory, the excessive amount 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[4]. Ultra-high voltage (UHV) transmission system has been planned by the State Grid Corporation of China as the primary electricity carrier in China's future transmission system [42]. 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, [40] pointed out that the use of UHV transmission system would save up to 100TWh electricity per year, which equals the annual power generation from 20GW-equivalent coal-fired plants. Furthermore, the costs and land use of UHV transmission lines are lower than the other high voltage transmission systems for long-distance power transmission [13] [43]. Although the feasibility of UHV transmission lines and related grid safety issues have been very controversial, over 600 billion Yuan (88 billion US dollar) investment have been initiated by SGCC for the next decade to extend and enhance grid infrastructure with a special focus on UHV transmission system [40]. Of which, 42.8 billion Yuan (6.3 billion US dollar) would be directly invested in wind integration related grid construction [44]. 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[5]. With

[4] High voltage levels: 100(110)kV, 138 kV, 161 kV, 230 (220)kV; Extra high voltage: 345(330)kV, 400 kV, 500 kV, 765(750)kV; Ultra high voltage: alternating current larger than 765kV and direct current larger than 600kV [43]

[5] For the choice of transmission system (different voltage levels, and AC or DC), see Zhang et al. [43].

the completion of the UHV transmission system, the capability of power grids in wind power integration would be doubled which could accommodate up to 90 and 150 GW of wind power by 2015 and 2020, respectively [44].

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 [45]. Non-grid wind power has attracted a lot of attentions in the international power system research [46] [47]. The direct application of wind energy in these end-use devices is because of the following two 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 consistent power supply. Second, load period is matched to wind power supply period. For example, wind power outputs reached its highest level when space heating is needed [48]. Zhou and Min [49] 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 fully usage of wind power and ensures the power quality to the consumers through the complementary supply from power grid. Taking into account the power supply requirements of cement industry and the characteristics of wind power, Miller et al. [50] proposed a hybrid wind-gas power system to provide reliable and cleaner electric power to the energy intensive industry. Other off-grid applications, such as small-scale wind power (less than 100kW) in the remote areas [51], and the applications in desalination and aluminium smelting are also discussed in the literature [46].

During the past 15 years, energy-intensive industries such as chemical, mineral and cement industry 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 [40]. There are several advantages of non-grid-connecting wind power, including avoidance of grid safety issues induced by wind power integration; effective harness of wind source; reduction in equipment required in grid-connection; cutting cost for intensive-energy consumers by using low-cost wind source [49]. The development of clean energy direct application would be addressed in the national grid connection standard, which has been proposed by the Chinese government [42].

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 the east and southeast China are also significant. For example, Jiangsu province is one of the seven large-scale wind farms, which has total wind generation capacity of 10GW to be installed by the end of 2020. Shandong, Shanghai and

Guangdong also have significant offshore wind power potentials [45]. 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, a lot of 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 3.7GW for Zhejiang and 7GW for Shandong at the end of 2020. Total offshore wind capacity would reach 15.1GW and 32.8GW by the end of 2015 and 2020, respectively [15]. Hence, development of offshore wind power would be significant in China in the next decades.

5. Policy implications

5.1 A policy switch from capacity growth to performance improvement

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 contributing to the actual operating hours of wind turbines being much lower than the expected operating hours. According to Liu and Yang [22], 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 when 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.

5.2 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 dispatch in the power grid operation at present according to the Renewable Energy Law. Hence, during the full-load operation of wind power, it is inevitable to restrict the operation of conventional power plants. Especially coal-fired power plants have already been operating under significant profit losses due to the central planned electricity prices[6]. The restrictions on conventional power plants operations would induce further profit losses and further damage their willingness to provide power generation.

5.3 Demand side management

Previous regulations regarding power planning in China often emphasize the supply side. As an alternative to alter 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 companies are regulated to reduce 0.3% power sales and 0.3% of maximum power load by implementing demand side management. The regulation highlight the improvement of energy efficiency, but it does not address the planning and management from end-user perspective. Currently, the application of wind power at some specific industry, 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 [42]. Hence, it is necessary to legitimate the demand-side activities such as the deployment of distributed wind power by introducing a comprehensive government policy.

5.4 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 US [12]. It is noticeable that these countries have either significant proportions of flexible power generation units or 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 a 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 CO2 emissions [52], which might cancel out the part of the emission savings of wind energy. For example, Lenzen [8] concluded that between 35 and 75g of CO_2

[6] 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 cause of such large-scale power plants maintenance is because the central planned electricity price could not cover the generation cost. Consequently, thermal power plants are reluctant to operate as usual.

emissions would be emitted from the altered operation in conventional power plants due to the integration of wind, which outweighed the emissions from the wind turbine lifecycle. The authors 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.

5.5 Strategic planning of the power grid at regional and local levels

Grid connection and grid reinforcement are critical to the development of wind energy in China. New transmission lines are required as the installation of new wind turbines are increasing. The planning of new transmission capacity is a long-term and strategic task. First, the deployment of windmills takes years to complete. Second, wind electricity costs at source are already higher than conventional power sources; higher added cost could damage the willingness to accept wind electricity. Another issue worth mentioning is that the SGCC, which owns the majority of the electricity transmission and distribution assets, has invested in wind farms. Because of the monopoly in the power grid operation by SGCC and CSG, the participation of power grid owners in wind energy development might induce an unfair competition, such as giving priorities to their own wind farms during integration and electricity purchase. Consequently, a policy focusing on the responsibility of the grid company, such as whether the power distribution and transmission companies should invest in power generation assets, is critical and necessary. 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.

6. Conclusion

The study 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 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.

7. References

1. GWEC, Global Wind Energy Council, *China adds 18.9GW of new wind power capacity in 2010*. 2011 [cited 2011 15 May];. Available from: http://www.gwec.net/index.php?id=30&no_cache=1&tx_ttnews[tt_news]=287&tx_ttnews[backPid]=4&cHash=c5a5b5659f.
2. He D, Li ZC, Ni WD, Yang YS, Wang ZY, Dai HZ. *The Strategic Development of Renewable Energy in China - A Special Issue on Wind Energy*. 2008, Beijing: China Electric Power Press.
3. McElroy MB, Lu X, Nielsen CP, Wang YX. *Potential for Wind-Generated Electricity in China*. Science, 2009. **325**(5946): p. 1378-1380.
4. Fenby J, Qu D. *China's Grids Power Up*. 2008, Trusted Sources UK Ltd: London.
5. SERC, State Electricity Regulatory Commission, *China's Wind Power Development Report [In Chinese]*, 2009: Beijing.
6. Mo X. *An Analysis of the Barriers in Wind Energy Development in the Northwest China*. 2009, The Northwest Electricity Regulatory Commission: Xi'an. [In Chinese]
7. SGCC.State Grid Corporation of China. *Why different voltages are needed in high voltage electricity transmission system?* 2007 [cited 2010 3rd July]; Available from: http://www.sgcc.com.cn/dlkp/dlhb/kpzs/sbdssjbzs/61089.shtml.[In Chinese]
8. Lenzen M. *Current state of development of electricity-generating technologies - a literature review*. 2009, University of Sydney.
9. Chen Z, Blaabjerg F. *Wind farm--A power source in future power systems*. Renewable and Sustainable Energy Reviews, 2009. **13**(6-7): p. 1288-1300.
10. Chi Y, Liu YH, Wang WS, Dai HZ. *Voltage Stability Analysis of Wind Farm Integration into Transmission Network*. in *Power System Technology, 2006. PowerCon 2006. International Conference on*. 2006.
11. Ipakchi A, Albuyeh A. *Grid of the future*. Power and Energy Magazine, IEEE, 2009. **7**(2): p. 52-62.
12. Holttinen H. *Design and Operation of Power Systems with Large Amounts of Wind Power*. 2009, International Energy Agency: Paris.
13. SERC. State Electricity Regulatory Commission. *Notice of the Three Recent Large-Scale Wind Power Drop-Off Accident*. 2011 [cited 2011 11 May]; Available from: http://www.serc.gov.cn/ywdd/201105/t20110506_14631.htm.[In Chinese]
14. Zhou X, Yi J, Song RH, Yang XY, Li Y, Tang HY. *An overview of power transmission systems in China*. Energy, 2010. **35**(11): p. 4302-4312.
15. Li J, Shi P, Gao H. *China Wind Power Outlook 2010*. 2010, Haikou: Hainan Press [In Chinese].
16. Drake B, Hubacek K. *What to expect from a greater geographic dispersion of wind farms?--A risk portfolio approach*. Energy Policy, 2007. **35**(8): p. 3999-4008.

17. Belanger C, Gagnon L. *Adding wind energy to hydropower.* Energy Policy, 2002. **30**(14): p. 1279-1284.
18. Roques F, Hiroux C, Saguan M. *Optimal wind power deployment in Europe--A portfolio approach.* Energy Policy, 2010. **38**(7): p. 3245-3256.
19. Kempton W, Pimenta F, Veron D, Colle A. *Electric Power from Offshore Wind via Synoptic-Scale Interconnection.* Proceedings of the National Academy of Sciences of the United States of America, 2010. **107**(16): p. 7240 - 7245.
20. Nema P, Nema RK, Rangnekar S. *A current and future state of art development of hybrid energy system using wind and PV-solar: A review.* Renewable and Sustainable Energy Reviews, 2009. **13**(8): p. 2096-2103.
21. Li J, Shi L. *Brief description of hydropower resources in China.* Water Power, 2006. **32**(1): p. 3 - 7.
22. Liu L, Yang F. *Which wind turbine manufacturer is going to lead the market*, in *Wind energy development report*. 2008, CITIC Securities Company Limited: Beijing.[In Chinese]
23. Higashi N. *Natural Gas in China - Market Evolution and Strategy*, in *Working Paper Series: Energy Market and Security 2009*. 2009, International Energy Agency: Paris.
24. NDRC. National Development and Reform Commission. *Mid-Long Term Development Plan for Nuclear Power (2005 - 2010)*. 2007: Beijing. [in Chinese]
25. Biello. *China forges ahead with nuclear energy*. Nature, 2011 [cited 2011 6 June]; Available from: http://www.nature.com/news/2011/110329/full/news.2011.194.html?s=news_rss.
26. Chalmers H, Gibbins J. *Potential for synergy between renewables and carbon capture and storage*, in *29th IAEE International Conference*. 2006: Berlin, Germany.
27. Lucquiaud M, Chalmers H, Gibbins J. *Capture-ready supercritical coal-fired power plants and flexible post-combustion CO2 capture.* Energy Procedia, 2009. **1**(1): p. 1411-1418.
28. Chen Q, Kang C, Xia Q. *Modeling Flexible Operation Mechanism of* CO_2 *Capture Power Plant and Its Effects on Power-System Operation.* Energy Conversion, IEEE Transactions on, 2010. **25**(3): p. 853-861.
29. Chen Q, Kang C, Xia Q. *Operation Mechanism and Peak-load Shaving Effects of Carbon-capture Power Plant.* Proceedings of the Chin. Soc. for Elec. Eng., 2010. **30**(7): p. 22 - 28.
30. Liang D, Wu W. *Barriers and incentives of CCS deployment in China: Results from semi-structured interviews.* Energy Policy, 2009. **37**(6): p. 2421-2432.
31. Bueno C, Carta JA. *Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands.* Renewable and Sustainable Energy Reviews, 2006. **10**(4): p. 312-340.
32. Enis B, Lieberman P, and Rubin I. *Operation of hybrid wind-turbine compressed-air system for connection to electric grid networks and*

cogeneration. Wind Engineering, 2003. **27**(6): p. 449-459.
33. China Pumped Storage Network, *China Pumped Storage Plants (exisiting, under construction and proposed projects).* [accesseed 3rd July 2010]; Available from: http://www.psp.org.cn:8080/news_list.asp?c_id=178&s_id=311.[In Chinese]
34. Shealy M, Dorian JP. *Growing Chinese coal use: Dramatic resource and environmental implications*. Energy Policy, 2010. **38**(5): p. 2116-2122.
35. Chen W, Xu R. *Clean coal technology development in China*. Energy Policy, 2010. **38**(5): p. 2123-2130.
36. Guan DB, Hubacek K, Weber CL, Peters GP, Reiner DM. *The drivers of Chinese CO2 emissions from 1980 to 2030*. Global Environmental Change, 2008. **18**(4): p. 626-634.
37. Hubacek K, Guan DB, Barua A. *Changing lifestyles and consumption patterns in developing countries: A scenario analysis for China and India*. Futures, 2007. **39**(9): p. 1084-1096.
38. White D *Reduction in Carbon Dioxide Emissions: Estimating the Potential Contribution from Wind-Power*. 2004, Renewable Energy Foundation: London.
39. Goggin M. *20% Wind Energy by 2030: Wind, Backup Power, and Emissions*, in *AWEA's Wind Energy Fact Sheets*. 2008, American Wind Energy Association: Washington, DC.
40. Li Z. *From Strong to Smart: the Chinese Smart Grid and its relation with the Globe*. 2009, Asia Energy Planform.
41. KPMG, *China's grid: keeping pace with a transformig economy*. 2010, KPMG.
42. Liu W, Lund H, Mathiesen B, Zhang XL. *Potential of renewable energy systems in China*. Applied Energy, 2011. **88**(2): p. 518-525.
43. Zhang XP, Rehtanz C, Song Y. *A grid for tomorrow*. Power Engineer, 2006. **20**(5): p. 22-27.
44. SGCC. State Grid Corporation of China. *State Grid Releases White Paper on Wind Power Development*. 2011 [cited 2011 11 May]; Available from: http://www.sgcc.com.cn/ywlm/mediacenter/corporatenews/04/245999.shtml. [In Chinese]
45. Xu J, He D, Zhao X. *Status and prospects of Chinese wind energy*. Energy, 2010. **35**(11): p. 4439-4444.
46. Hensel F, Uhl K. *Low energy desalination and wind energy -- sustainable solutions for drinking water production*. Desalination, 2004. **168**: p. 125-126.
47. Pavlak A. *The Economic Value of Wind Energy*. The Electricity Journal, 2008. **21**(8): p. 46-50.
48. Kempton W, Archer C, Dhanju A, Garvine R, Jacobson M. *Large CO2 reductions via offshore wind power matched to inherent storage in energy end-uses*. Geophys. Res. Lett., 2007. **34**(2): p. L02817.
49. Zhou L, Min F. *Research on application of non-grid-connected wind power in less developed areas*, in *World Non-Grid-Connected Wind Power and Energy*

Conference, 2009. WNWEC 2009. 2009. p. 1-3.

50. Miller NW, Dillip G, Clark K. *Wind Generation Applications for the Cement Industry*, in *Cement Industry Technical Conference Record, 2008 IEEE*. 2008. p. 103-112.
51. Zhang S, Qi J. *Small wind power in China: Current status and future potentials.* Renewable and Sustainable Energy Reviews, 2011. **15**(5): p. 2457-2460.
52. Pehnt M, Oeser M, Swider DJ. *Consequential environmental system analysis of expected offshore wind electricity production in Germany.* Energy, 2008. **33**(5): p. 747-759.
53. Xinhua. *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).* 2009 [cited 2010 3rd July]; Available from: http://news.xinhuanet.com/newscenter/2009-02/16/content_10828897.htm.[in Chinese]
54. China Electric Power Yearbook. *China Electric Power Yearbook 2009*. 2009, Beijing: China Electric Power Press.
55. Wang Q, Chen Y. *Barriers and opportunities of using the clean development mechanism to advance renewable energy development in China.* Renewable and Sustainable Energy Reviews, 2010. **14**(7): p. 1989-1998.

Figures

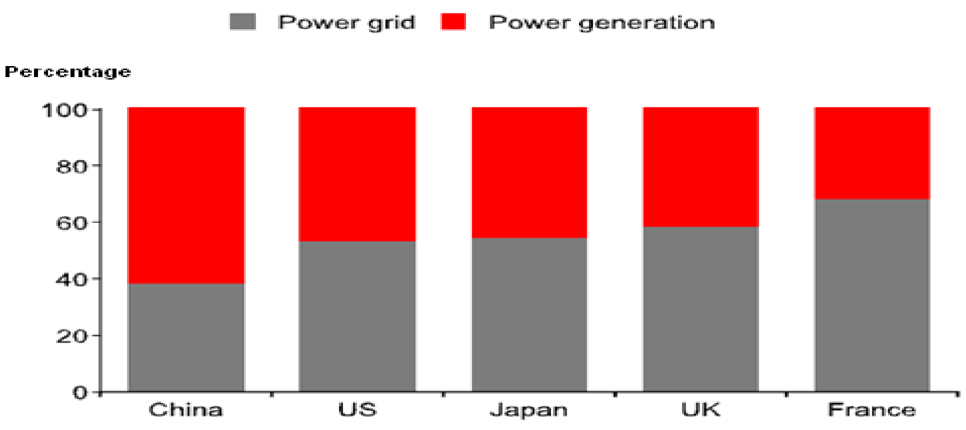

Figure 1: Ratio of accumulated investment in power grid and power generation since 1978

Source: [4]

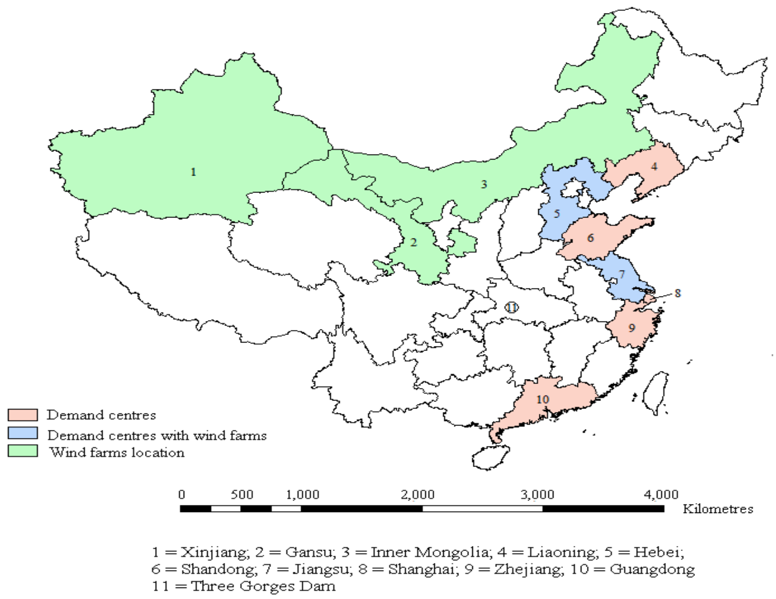

Figure 2: Locations of wind farms and electricity demand centres

Source: Figures for wind farms from [53]; Figures for demand centres from [54]

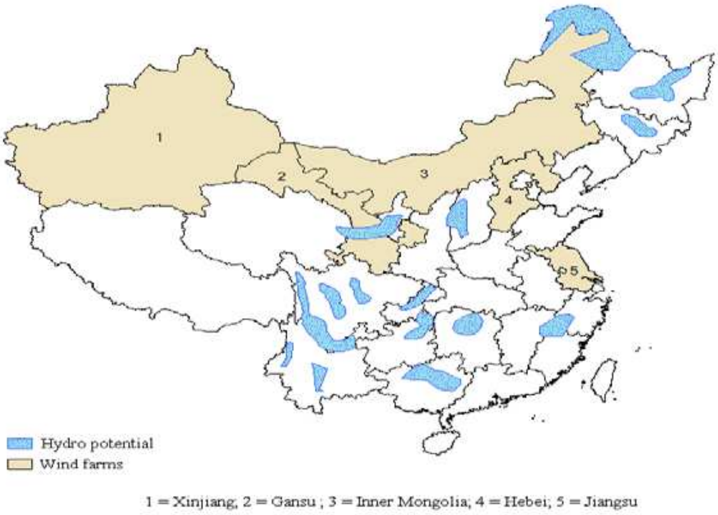

Figure 3: The distribution of hydropower potential and the locations of wind farms in China

Source: Figures for hydropower potential from Wang and Chen [55]; Figures for wind farm locations from Xinhua [53]

Tables

Table 1: A comparison of the proposed wind turbine installed capacity and hydropower potentials in five wind farm provinces by 2020

Source: Figures for hydropower potential from [21]; Figures for proposed wind generation capacity from [53]

Provinces	Proposed wind turbine installed capacity	Hydropower potential
Inner Mongolia	50GW	2.6GW
Gansu	20GW	9GW
Xinjiang	20GW	15.6GW
Jiangsu	10GW	0.02GW
Hebei	10GW	1.3GW

Table 2: The share of power generation capacity in case study provinces in 2008
Source: own calculation, figures from [54]

	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%