

Wind power in China – Dream or reality?

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ABSTRACT

After tremendous growth of wind power generation capacity in recent years, China now has 44.7 GW of wind-derived power. 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. 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.

The current power system is heavily reliant on independently acting but state-owned energy companies optimizing their part of the system, and this 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.

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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 600–1000 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 if the Chinese government commits to an aggressive low carbon energy future, wind energy is capable of generating 6.96 million GWh of electricity by 2030, which is sufficient to satisfy China's electricity demand in 2030.

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 [4–7]. For instance, Lema and Ruby [8] 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 [9]; the potential of wind power [10]; the significance of wind turbine manufacturing [11]; wind resource assessment [5]; the application of small-scale wind power in rural areas [12]; clean development mechanism in the promotion of wind energy in China [4], social, economic and technical performance of wind turbines [13] etc.

There are few studies which assess the challenge of grid infrastructure in the integration of wind power. For instance, Wang [14] studied grid investment, grid security, long-distance transmission and the difficulties of wind power integration at present. Liao et al. [15] criticised the inadequacy of transmission lines in the wind energy development. However, we 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

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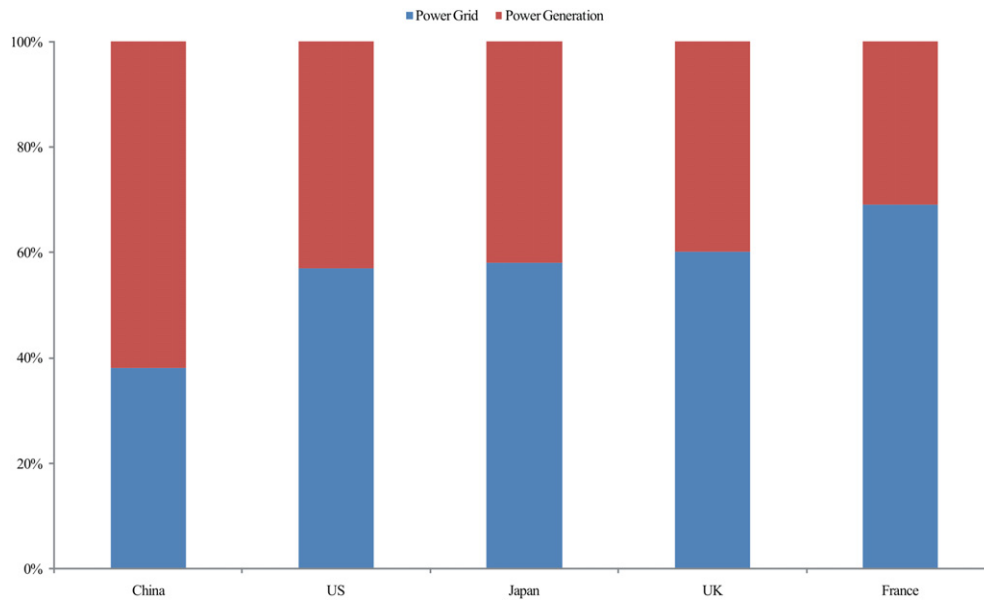


Fig. 1. Ratio of accumulated investment in power grid and power generation since 1978, Source: [16].

context. In this paper, we 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.

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.

2.1. Power grid investment

Although the two state grid companies-(SGCC) State Grid Corporation of China and (CSG) China Southern Grid - 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 [16]. 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,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 [17]. Fig. 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 [18] 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 the southern part of China. According to SGCC [19], 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 [20], 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 hydropower 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 1100 km), Guangzhou (located in Guangdong province, with a length of 1000 km) and Changzhou (located in Jiangsu province, with a length of 1000 km) with a transmission capacity of 3 GW each and the 500 kV AC transmission lines to central China with

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 to 2005, and so on and so forth.

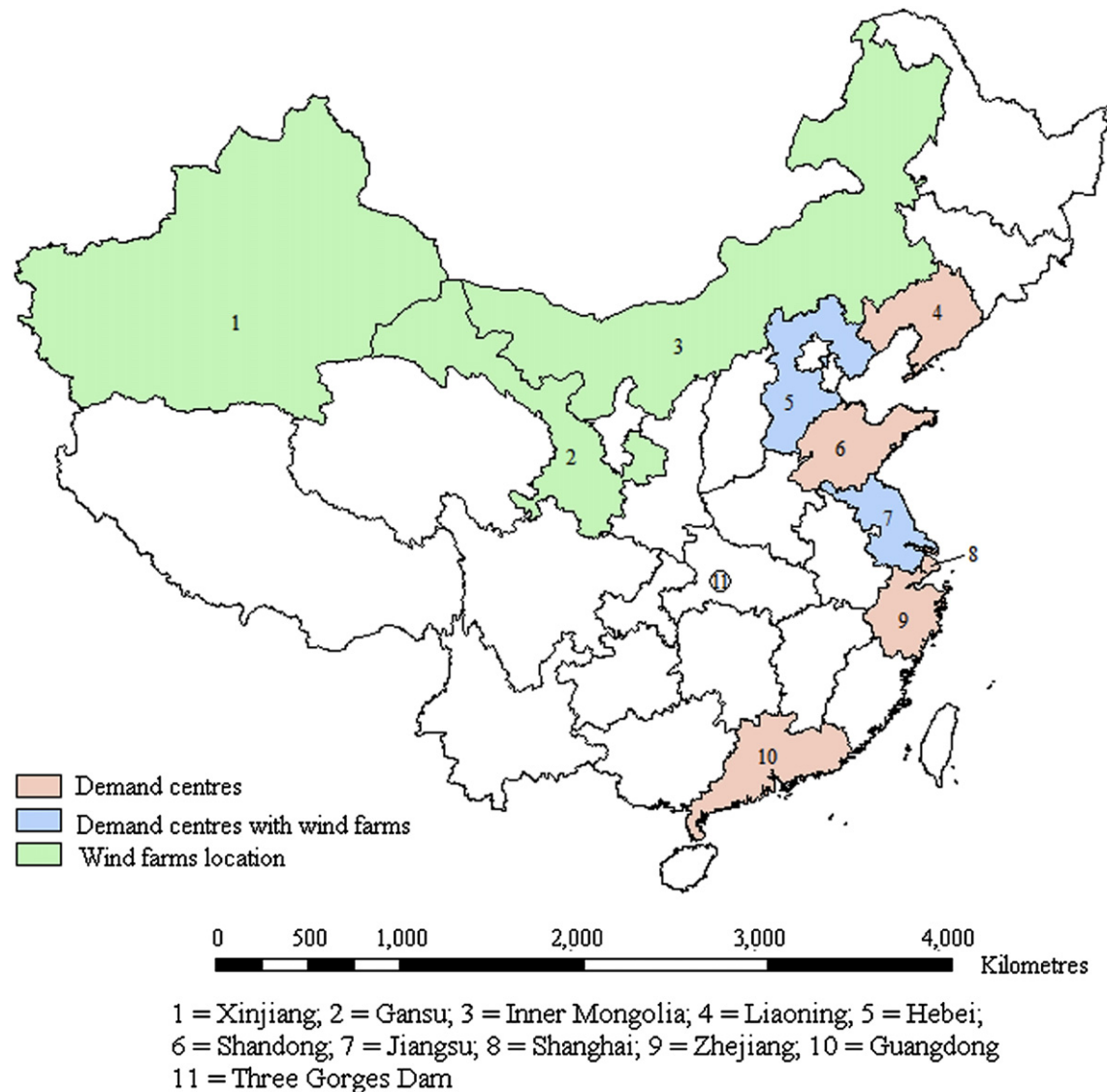


Fig. 2. Locations of wind farms and electricity demand centres, Source: Figures for wind farms from [68]; Figures for demand centres from [69].

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 1500 km and 2500 km, respectively. For Xinjiang, the distances are even longer at 2500 km and 4000 km, respectively. As a result, longer transmission lines are required. Fig. 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 [21]. 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 [22]. Furthermore, the significant changes in power supply from wind might damage the power quality [23]. Hence,

additional regulation capacity would be needed. However, in a power system with the majority of its power from base load provider, the requirements cannot be met easily [24]. 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 [23] 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 [23].

One of the grid safety problems caused by wind power is reported by the (SERC) State Electricity Regulatory Commission [25]. 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 49.854 Hz, 49.815 Hz and 49.95 Hz 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 [17]. 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.

2.3. The interconnection of provincial and regional power grids

The interconnection of trans-regional power grids started at the end of 1980s. A (HVDC) high voltage direct current transmission line was established to link the Gezhouba² 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 330 kV and 500 kV transmission lines as the backbone and six interconnected regional power grids and one Tibet power grid [26].

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 a backup to contingencies, and could not support the large-scale, long-distance electricity transmission [27]. 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 inter-regional electricity transmission is fixed [27]. Additional wind power in the inter-regional 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?

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 [28], power reserves are always used to keep the production and generation in balance under a range of circumstances, including power plant outages, uncertain variations in load and fluctuations in power generations (such as wind) [29]. As wind speed varies on all time scales (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 [29].

A number of studies have examined the approaches to stabilize the electricity output from wind power plants. For example, Belanger and Gagnon [30] conducted a study on the compensation of wind power fluctuations by using hydropower in Canada. Nema et al. [31] 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. [2] 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 [2]. Liu et al. [32] 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 time scales due to wind power integration.

Because of the smoothing effects of dispersing wind turbines at different locations (as exemplified by Drake and Hubacek [33] for the U.K., Roques [34] for the E.U. and Kempton et al. [35] 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 [36]. However, the increased reserve requirements are considerable on secondary reserves (available within 10–15 min) which mainly consist of hydropower plants and gas turbine power plants [29]. 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, we examine the availability of power plants providing secondary and long-term reserves and investigate the viability of energy storage system in China.

3.1. The availability of secondary reserve capacity

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 section 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 [37]. 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

² Gezhouba – the first dam on the Yangtze River – is located in northwest of Yichang City with a total length of 2561 m. It is 38 km away from the Three Gorges Dam and 1000 km away from Shanghai.

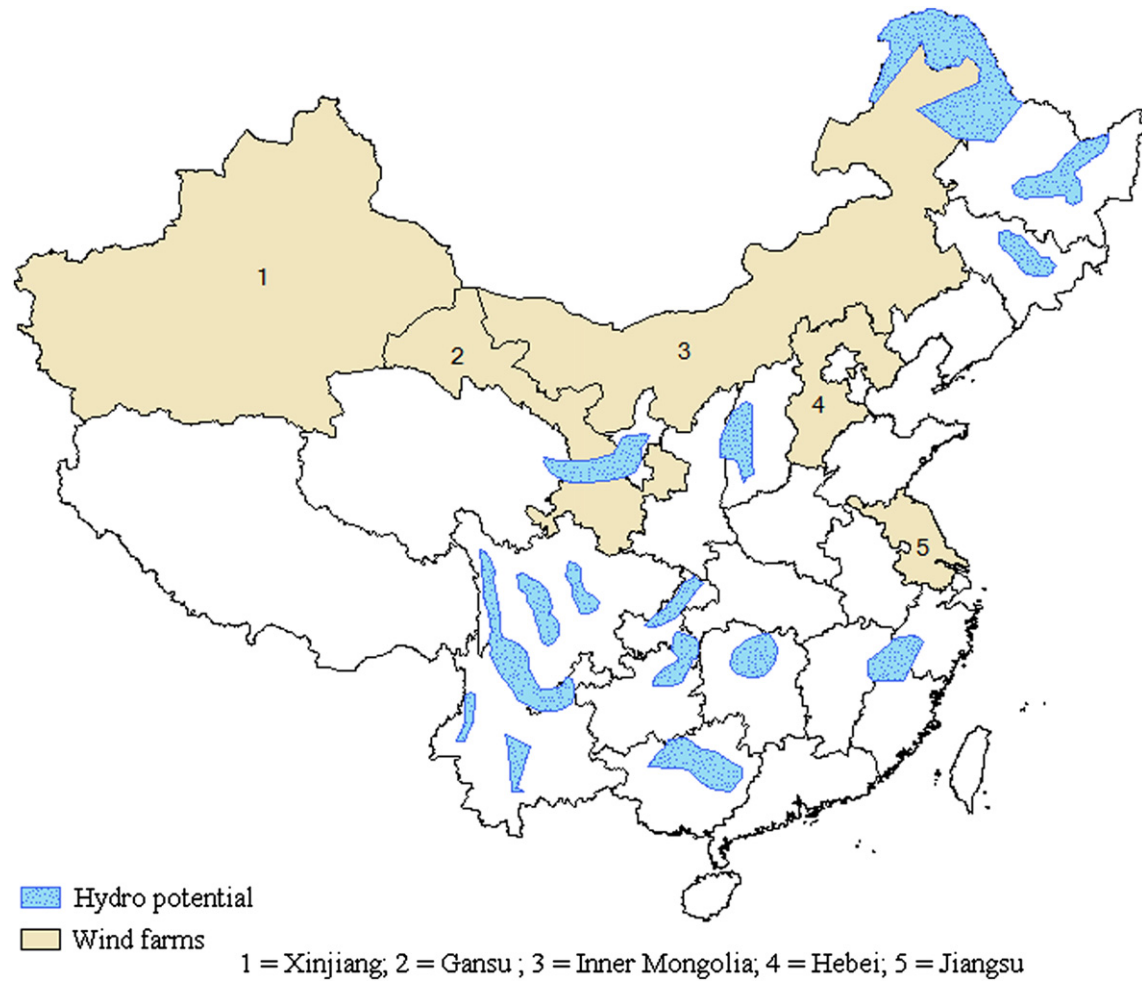


Fig. 3. The distribution of hydropower potential and the locations of wind farms in China, Source: Figures for hydropower potential from Wang and Chen [4]; Figures for wind farm locations from Xinhua [68].

resources are located in south-west China, He et al. [2] suggested that wind-hydro power 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 Fig. 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.

3.1.2. 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 [2].

The (CAE) China Academy of Engineering 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 7500 yuan/kW for wind farms, natural gas price at 1.2 yuan/m³ 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 [2].

However, these findings might be misleading due to a number of reasons. First, the capital costs of wind farms are higher than 7500 yuan/kW. According to Liu and Yang [38], the capital investments of

Table 1

A comparison of the 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 [37]; Figures for proposed wind generation capacity from [68].

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/m³, 1.25 yuan/m³, 1.25 yuan/m³, 2.00 yuan/m³ and 2.75 yuan/m³, respectively [39].

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 [39].

Fourth, the capacity factors of wind farms in China are far below the expected level. The State Electricity Regulatory Commission [17] found that six out of seven wind farms, which were randomly selected in seven provinces, had fewer operating hours (1864 h on average) than the designed operating hours (2305 h 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 [2]. Considering most of the electricity needs to be transmitted to the demand centres, which are around 3000 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.

3.2. The availability of long-term reserve capacity

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 [40]. 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 [40]. 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 [41].

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 baseload

Table 2

The share of power generation capacity in 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 [69].

provider, nuclear power plants always deliver stable and continuous power outputs. For example, in 2007, existing nuclear power plants in China operates 7793 on average, which is significantly higher than coal-fired power plants (5466 h).³ The continuous operation mode of nuclear power generation units made them incapable in ramping ups and downs quickly [42]. Consequently, nuclear power is not appropriate to compensate for the variation of wind powered outputs.

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 [43]. In addition, coal-fired power plants accounted for approximately 76% of electricity generation and over 97% of thermal power plants [44]. 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 [45,46]. Table 2 gives the composition of the electricity mix for six planned wind farms.

As stated by Goggin [47], 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 shutdown of these plants in order to balance the fluctuating electricity output of windmills. For example, White [48] found that a 2% energy efficiency loss would result in a 150 g CO₂ emission growth per kWh electricity output for a coal-fired boiler. Consequently, the loss of energy efficiency might have significant impacts on the overall CO₂ 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 [48]. Another issue of using coal as a backup is that, as mentioned in Section 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.

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 [49] and compressed-air

³ own calculation, figures from [69].

systems [50] 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) [51]. 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, 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.

3.4. 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, (CHP) combined heat and power 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 [52]. Thus, it is naturally hard to make the combination of wind power with those possible options match each other well 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 [53]. 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 [52]. 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.⁴ An (UHV) ultra-high voltage transmission system has been planned by SGCC as the primary electricity carrier in China's future transmission system [54]. 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 [52] 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 [55]. 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 [52]. Of this, 42.8 billion yuan (6.3 billion US dollar) would be directly invested in wind integration related grid construction [56]. The future UHV transmission system would consist of ± 800 kV DC lines for large-capacity electricity transmission from the west and north to the east and south and 800–1000 kV AC lines for building an interconnected regional network in China.⁵ With the completion of the UHV transmission system, the capability of power grids in wind power integration would be doubled and could accommodate up to 90 and 150 GW of wind power by 2015 and 2020, respectively [56].

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 [9]. Non-grid wind power has attracted a lot of attention in the international power system research [57,58]. 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 [59]. Zhou and Min [60] 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. [61] 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 100 kW) in the remote areas [62], and the applications in desalination and aluminium smelting are also discussed in the literature [57].

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 [52]. 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 [60]. The development of clean energy direct

⁴ 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 765 kV and direct current larger than 600 kV [55].

⁵ For the choice of transmission system (different voltage levels, and AC or DC), see Zhang et al. [55].

application would be addressed in the national grid connection standard, which has been proposed by the Chinese government [54].

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 [9]. 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 [27]. Hence, development of offshore wind power would be significant in China in the next decades.

5. Policy implications

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 [63]. 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 [64]. 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 [65] 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 [65]. 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 [66]. 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.

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 5000 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 [38], 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.

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.⁶ The restrictions on conventional power plants operations would induce further profit losses and further damage their willingness to provide power generation.

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 shutdown 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.

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 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 [54]. Hence, it is necessary to legislate the demand-side activities such as the deployment of distributed wind power by introducing a comprehensive government policy.

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. [23]. 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 CO₂ 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 CO₂ 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 [67], which might cancel out part of the emission savings of wind energy. For example, Lenzen [20] concluded that between 35 g and 75 g of CO₂ 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.

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 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.

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