Technology Roadmap

China Wind Energy Development Roadmap 2050

International Energy Agency

能源研究所
Energy Research Institute

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- To operate a permanent information system on international oil markets.
- To provide data on other aspects of international energy markets.
- To improve the world's energy supply and demand structure by developing alternative energy sources and increasing the efficiency of energy use.
- To promote international collaboration on energy technology.
- To assist in the integration of environmental and energy policies, including those relating to climate change.

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This document was originally released in Chinese in October 2011. The IEA and ERI have tried to ensure the consistency of this English translation with the orignial Chinese text, however it is possible that minor differences exist.

Foreword

Energy is vital for economic and social development. It is as necessary as water and air. Over the past century, Western developed countries have used relatively cheap, plentiful fossil fuels to support industrialisation, urbanisation and modernisation. Today, however, population growth and widespread development are increasing the demand for energy, while fossil fuel supplies are decreasing annually by 15 billion tonnes coal equivalent. With this rate of decrease expected to grow, the conflict between limited fossil fuel resources and an infinite demand for energy will only worsen. At the same time, the climate change caused by combustion of fossil fuels is becoming more and more significant.

Since China implemented its opening and reform policy 30 years ago, its energy development model followed the path of industrialisation seen in developed countries. An energy supply dominated by coal has supported rapid economic development, but this has put intense pressure on resources and the environment. Acid rain, which in 1980 affected less than one tenth of China, now concerns most of the country. Energy is the key driver of economic and social development, but fossil fuels can spell an end to clean, blue skies. So simple dependence on fossil fuels cannot be the fundamental solution, not only because it results in serious resource and environmental issues but also because it precludes the development of a global energy solution.

In the next two or three decades, China will need more energy while reducing fossil fuel consumption and ensuring energy security. The only solution is a transition to a clean, reliable, low-carbon energy system, which uses the most cost-effective and environmentally friendly technologies to improve economic development while ensuring competitive energy prices and high living standards. The 21st century is an era for energy reform and innovation. China needs to prepare and plan well to enjoy the bright future and better lives that inexhaustible renewable energy can offer.

Wind power, the most developed and commercialised renewable energy technology, has considerable potential. Since 2006, China has made great advances in wind power. Its proportion of the world's annual newly installed capacity increased from less than 10% in 2006 to 49% in 2010. Its total grid-connected wind power capacity reached 310 GW in 2010. In four short years, driven by the market, China's wind turbine manufacturing industry scaled up production; four Chinese wind turbine manufacturers now rank in the top ten in the world. The industry chain has been established and improved, covering technology research and development (R&D); component manufacturing; turbine assembly, testing and certification; wind farm development and other associated services. As market competitiveness continues to grow, China has solid foundations for large-scale wind power development.

Wind power development is closely linked with the development of the power system, which delivers energy through the grid to end users such as households and enterprises. Power grid infrastructure, operation and dispatch are the core of the power system. Currently, China's power system is not keeping up with the demand for wind power development. The power system needs to evolve to be able to manage greater shares of variable wind power.

Future power systems will need to feature more flexibility on the demand side as well as on the supply side if they are to optimise the full range of non-polluting, low-carbon energy sources, while maintaining security and reliability. This flexibility is essentially the ability to compensate for periods of low wind output, and to manage highs, using a portfolio of flexible generators, trade, storage and demand- side response. Germany's energy strategy and Denmark's 2050 Energy Strategy, which plan for independence from fossil fuels, provide blueprints for accommodating renewable energy within the overall power system.

To meet the demand for large-scale renewable energy development, China will position itself to accelerate power system development for the sake of the state, with a strategic perspective. In support of strategic development of the energy system, this roadmap aims to compile and analyse key factors and issues encountered during wind power development, and propose feasible solutions. Such analysis and solutions will provide a valuable reference to
wind power and power system strategy and policy making.

Innovation is the foundation of survival and development. The example of Apple under the leadership of Steve Jobs shows that only fearless innovation can change the world and improve lives, for enterprises and for countries. I sincerely hope that this roadmap, backed by considerable expertise and effort, will inspire creative approaches to wind power's soaring potential to drive the energy system's transition to a sustainable future. To protect the environment and improve our lives, I believe that, more people must pay attention to wind power and other clean energy technologies. Our collective efforts will make wind power contribute significantly to China's energy security, economic development and climate change mitigation.

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Key Findings

- Energy demand in China will increase rapidly in next 40 years because of China's economic and social development. The Chinese government has proposed a low-carbon development strategy, and wind power has become and will continue to be one of the main energy technologies used to realise low carbon targets.

- This roadmap foresees wind power capacity reaching 200 GW by 2020, 400 GW by 2030 and 1 000 GW by 2050. Wind power will be one of five main power sources, and will meet 17% of electricity demand. As technology improves and wind power is scaled up, there are no insurmountable barriers to realising these ambitious targets, with respect to resources, technology, industry and the power system.

- Depending on the cost of wind energy development and the transmission cost of wind power in different areas, the supply curves in this roadmap will be achieved. If the marginal tariff for wind power is set at CNY 0.55/kWh excluding the transmission cost for long distance, 700 GW could be installed around seven strategic concentrations.

- Before 2020, land-based wind power will dominate, with offshore wind power at the demonstration stage; from 2021 to 2030, both land and offshore wind power will be developed, and far offshore wind power will be in demonstration; after 2030, wind power will be developed further on land and offshore.

- To realise the above targets, the total investment in wind power will be CNY 12 000 billion. Investment costs per unit of wind power will gradually fall; the cost of wind power expected to be the same as or close to the cost of coal power in 2020.

- Environmental and social benefits will be considerable if the above targets are realised. Annual CO_2 emission mitigation will be 1.5 billion tonnes in 2050, and an estimated 720 000 jobs will be created.

- RD&D is crucial for sustainable development of wind power. RD&D will need to be focused on assessing wind resources (including forecasting); advanced wind turbines; wind farm construction and operation, etc.

- Wind power, currently at the stage of scale-up development, should be regarded as an important power source. For wind power to develop rapidly, actions that need to be conducted in the near term include implementing a wind power consumption plan, and co-ordinating the development of wind power, other power sources and the power grid, as well as demonstration of smart grid technologies. In the middle and long term, reform of the electric power sector should be promoted and realised, and the electric power market established. After 2030, advanced technologies will be widely deployed, including advanced and cost-effective storage technologies and smart grids.

Key actions to 2020

- Reform the power market to achieve market-based power pricing, reflecting environmental externalities, the value of flexibility, and integration costs.

- Strengthen priority grid access and dispatch of wind power; maximise the ability of northern provinces to accommodate locally produced wind power; facilitate inter-provincial transmission using the smartest available technology.

- Accelerate deployment of flexible resources; deploy the best available output forecasting techniques.

- Establish public R&D platforms. Develop and deploy cost-competitive 5 MW technology by 2015, and near offshore technology by 2020. Strengthen supply chains, especially offshore transport and installation infrastructure.

- Develop specialist wind power training courses and university curricula by 2015.

Introduction

China's economic development will still be an important strategic task over the next 20 or 30 years. Wind energy is one of the renewable energy sources most likely to be developed commercially on a large scale – and hence support China's economic development – because of its cost effectiveness and low environmental impact. Between 2006 and 2009, China's wind power growth rates were more than 100% on average. At the end of 2010, installed wind power capacity in China was more than 40 GW and the grid connected operation capacity was more than 30 GW. Compared with conventional power generation technologies, however, China's wind power contributes only a very small share. Wind power can and should play a much greater part in China's sustainable energy and electricity supply in the future.

In 2007, the Chinese government announced its medium- and long-term plan for renewable energy development, proposing that installed wind power capacity rise to 30 GW by 2020. That target was achieved by 2010, ten years ahead of schedule. Development and utilisation of renewable energy sources (including wind power) is not limited by resources and environmental constraints. Wind can be sustainably developed on a large scale, however technical improvements are needed. Wind power development targets and strategies should be established on a long-term basis, taking into account technology development trends and the future energy structure. By 2030, wind power needs to be a flexible, grid-friendly technology that can be one of the dominant power generation sources. This roadmap outlines a goal-oriented way of achieving this aim.

Outlook for energy demand in China

As economic development needs the support of energy, China's energy consumption will continue to grow steadily for a long time. Analysis of China's economic development trends indicates that the process of industrialisation and urbanisation will continue over the next two decades. China's economy will grow more modestly from 2030 to 2050 than it did in the past decade. Adequate energy supplies will be required to support such economic growth, but resource and environmental constraints mean that China must maintain a lower growth rate in its use of fossil fuels and develop clean energy on a large scale.

Many domestic and international research institutions have estimated China's future energy demand (Table 1). Compared with the past three years' energy consumption growth data, however, these study results, obtained from past three to five years, seem optimistic. Many domestic and foreign institutions have also analysed China's future demand for electricity and obtained similar growth trends, concluding that electricity demand will grow rapidly in the coming decades (Table 2).

These estimations by domestic and foreign organisations are based on different scenarios, however, so their forecasts vary significantly. For example, forecasts of energy demand in China in 2020 range from 2.34 billion of coal equivalent (btce) to 4.9 btce (1.64 billion tonnes of oil equivalent [btoe] to 3.43 btoe). By comparison, real energy consumption in 2010 was 3.25 btce (2.28 btoe).

Given the industrial structure and energy demand during the equivalent development phase in developed countries; current and future energy needs; and international pressure on climate change, social sustainable development and energy conservation, China's final energy consumption is more likely to reach 4.5 to 5.0 btce (3.15 to 3.50 btoe) by 2020, 5.5 to 6.0 btce (3.85 to 4.20 btoe) by 2030, and about 6.5 btce (4.55 btoe) by 2050. With significant energy conservation efforts, energy demand could be further reduced.

With respect to electricity demand, economic and social development will continue to increase electrification of communities. The electric power demand growth rate will be higher than the growth rate of overall energy demand. China's final power consumption is likely to reach 8 000 TWh by 2020, 10 000 TWh by 2030 and 13 000 TWh by 2050. While electric power demand is increasing in middle and western areas, demand in eastern areas is increasing even more rapidly, so electricity transmission from north to south and from west to east will remain significant in the coming 40 years.

Table 1. Estimations by domestic and international organisations of China’s long-term energy demand in billion tce

Organisations		Scenario	2015	2020	2025	2030	2040	2050
International	IEA, 2011	New Policy Scenario	3.00	3.35		3.69		
		Current Policy Scenario		3.47		4.07		
		450 Scenario		3.19		3.15		
	IEEJ, 2007	BAU*	/	3.60	/	4.47		
		Advanced technology	/	3.07	/	3.55		
	Green peace and EU RE directive, 2007	Energy Revolution	2.13	2.34	2.52	2.60		
Chinese	State Information Center DRC, 2007	BAU		4.32		5.23	5.92	6.30
		Low rate growth		3.80		4.39	4.90	5.15
		High rate growth		4.90		6.27	7.29	7.91
	NDRC ERI, Priority of Energy Conservation Group, 2007			3.68		4.14		
	NDRC ERI Low carbon development group, 2008	EE		4.77		5.85 (2035)		6.69
		Low carbon		3.96		4.84 (2035)		5.56
		Very low carbon		3.85		4.60 (2035)		5.02

* Business-as-usual

Table 2. China energy and power demand forecast for 2030

Organisation/Baseline year	Scenario	Primary energy demand (billion tce)	Total power demand (PWh)
IEA, 2007 BY: 2005	BAU	5.46	8.5
	Policy options	4.65	7.4
	High economic growth	6.70	N/A
IEA, 2008 BY: 2006	BAU	5.55	8.2
IEEJ BY: 2005	BAU	4.47	6.4
	Technology progress	3.55	5.3
ERI, 2050 Scenario analysis; BY:2005	BAU	5.78	8.2
	Low carbon	4.34	6.7
China long-term energy strategy study (2030, 2050) BY: 2007	As planned	N/A	9.0
	High rate growth	N/A	10.4
	Low rate growth	N/A	8.1

China's low-carbon energy strategy

China's energy resources are abundant, but less so on a per-capita basis; high-quality resources are limited, unevenly distributed and difficult to develop. China has abundant coal, but oil, natural gas and other fossil energy resources are limited. Oil shale, coalbed methane and other unconventional fossil energy reserves may have great potential. China's coal, hydro and wind energy resources are mainly located in the west, while the principal load centres are in the east. Therefore, large-scale and long-distance transmission of coal and electricity form the basis of China's energy development and utilisation.

To this end, the government has stated out that China's future energy strategy will no longer be based on coal but on "domestic sources, with diversified development and with a focus on environmental protection" – a more sustainable energy supply strategy. The 12th Five-Year Plan for Economic and Social Development (2011-15), published in March 2011, proposed that "a modern energy industry in China will be based on energy conservation, domestic development, diversity and environment protection, to strengthen international co-operation and mutual benefit, adjust and optimise the energy structure, and build a safe, stable, economical and clean modern energy industry system." China "will promote diversified clean energy diversity and other measures to encourage changes in energy production and use."

To promote these changes, the Chinese government is vigorously encouraging wind power, hydropower, nuclear power and other non-fossil energy development, and has recently introduced official mid-term development goals. In September 2009, the Chinese government proposed that by 2020 non-fossil energy sources contribute 15% in total primary energy consumption. The 12th Five-Year Plan proposed three binding targets for 2015: that non-fossil fuels in primary energy consumption increase to 11.4% in 2015 (from 8.3% in 2010); and that energy consumption and CO_2 emissions per unit of GDP be reduced by 16% and 17% respectively. Although a longer-term target has not been announced, China is vigorously promoting its low-carbon energy strategy, and wind power will continue to be one of the main technologies to achieve the low-carbon strategy.

Purpose of this roadmap

Wind power is a "sunrise industry" – fast-growing, with great potential – but there are many development obstacles to overcome. It generally takes a new energy industry 20 or 30 years to progress from technology development to commercialisation. While the future of wind power in China is assured, clear guidelines are needed for its development over the next two or three decades. The purpose of this roadmap is to provide scientific guidelines for policymaking by analysing resource potential, RD&D, grid integration and policy support, and by identifying gaps and milestones to government, enterprises, research institutes and the public.

Methodology and content

This study combines quantitative and qualitative approaches to analyse China's wind resource potential and distribution, and power generation and distribution costs and benefits, in order to identify wind power development targets and possible technology development routes. Specifically, wind resource numerical simulation and wind power supply curves are used to identify the impact of wind power development on electricity costs and benefits, on the environment and on social development, and to estimate the scale of investment needed in wind power by 2050. To explain the feasibility of its wind power development targets for 2050, this study analyses resource development, technology and industry development, the future power system structure and policy support. It provides a pathway to achieve the targets, clarifying the duties and functions of government, enterprises and public at different stages of wind power development. This study incorporates all the available research experience from international and domestic experts, to formulate a roadmap that is both scientific and practical.

This introduction is followed by a section that reviews the history of wind power development in China, examines its current status and immediate prospects, analyses resource potentials and makes a quantitative assessment of resource against costs.

Section 3 proposes wind power targets for 2020, 2030 and 2050, and presents accompanying scenarios. Costs and benefits of achieving these objectives are analysed. Costs includes investment cost, operational cost and required government subsidies, while benefits include increased energy supply and job opportunities, and reduced greenhouse-gas emissions.

With regard to the overall development objectives and technology development routes identified in the previous sections, the next section discusses specific technology R&D strategies, tasks and approaches, covering critical areas including wind resource assessment, the wind manufacturing supply chain, wind farm development, grid integration and wind power consumption.

In Section 5, power grid connection and wind power consumption challenges in the near future are analysed with regard to wind power system development trends. An overall strategy is proposed for wind power grid integration, transmission and consumption in the near and medium term (before 2020) and in long term (2030, 2050).

The next section analyses aspects of the policy framework in terms of the wind power market, grid consumption, technology progress, financial incentives, human resource development and other factors.

The last section provides a detailed action plan, focusing on activities to be led by government, the wind power industry and the power system actors.

Status Quo and Prospects

Wind power is becoming a vital part of low-carbon energy strategies aimed at dealing with energy supply and environmental challenges. According to an assessment of wind resource potential and an analysis of development costs, China has economically exploitable wind power potential of at least 1 TW in the long term, so ambitious long-term wind power development objectives are warranted.

History and status quo of wind power

Improvement in policy support

Wind power development in China can be divided into four phases.

(1) Initial demonstration (1986-1993): several small demonstration wind farms were developed.

(2) Early industrialisation (1994-2003): trial implementation of incentive policies of mandatory purchase, payback tariffs and cost-sharing systems.

(3) Scale development and localisation (2003-07): stabilised cost-sharing mechanisms were established through a series of regulations, including concession bidding programs for wind farm investors, developer-specific prices and feed-in tariffs, and binding management regulations under the Renewable Energy Law. Wind power development project size and local manufacturing capacity were quickly improved.

(4) Large-scale development (2008-present): Development concessions were awarded on the basis of tenders, establishing benchmark prices for wind power from land-based plants – referred to as feed-in tariffs.[1] Detailed investigation was conducted on wind energy resources on the basis of the preliminary proposed construction of seven wind power bases in 2009 (Shandong base was added later), each of at least 10 GW. Construction began on an offshore wind power demonstration project. The Renewable Energy Law was revised, and planning began on the large-scale integration of wind energy in the power system.

Fast expanding wind power uses

Wind power in China has entered the large-scale development phase. From 2006 to 2009, China's total wind power installed capacity doubled each year. By the end of 2010, total installed capacity was 41 GW, operational wind power capacity was 31 GW and 50 TWh of electricity was generated from wind power (Figure 1). More than 10 TWh were generated from wind power in the Mengxi grid (western Inner Mongolia), contributing 9% of regional power demand in 2010.

Because of wind resource distribution, wind power in China will be characterised by large-scale, centralised development and long-distance transmission. In the future, China will continue large-scale development of wind farms in

1. According to local wind resources and construction conditions, wind power benchmark prices are determined for four wind resource zones at CNY 0.51/kWh, CNY 0.54/kWh, CNY 0.58/kWh, and CNY 0.61/kWh.

Figure 1. Wind power capacity in China (GW), 2003-10

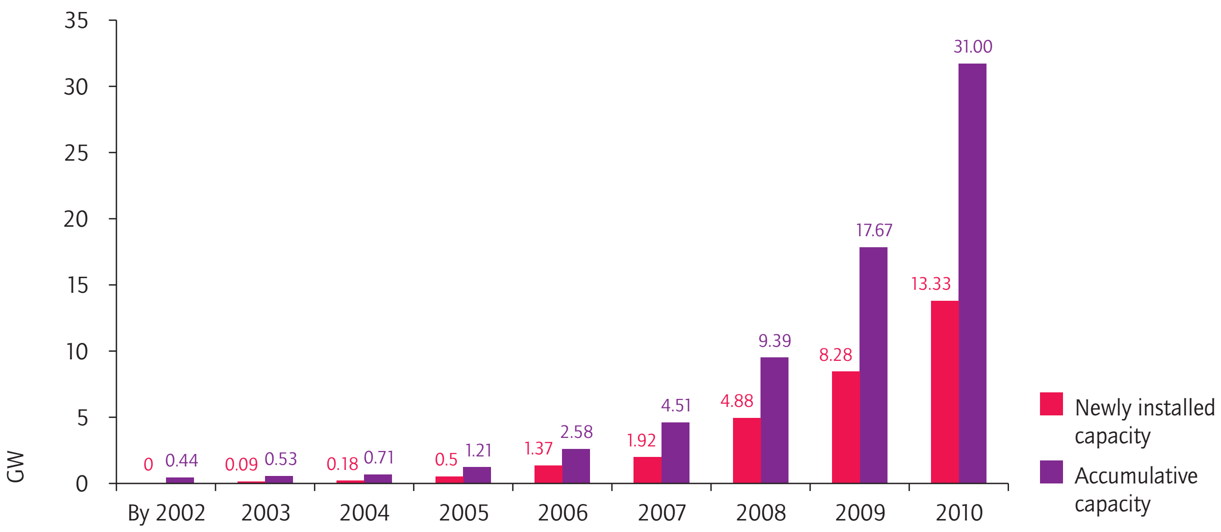
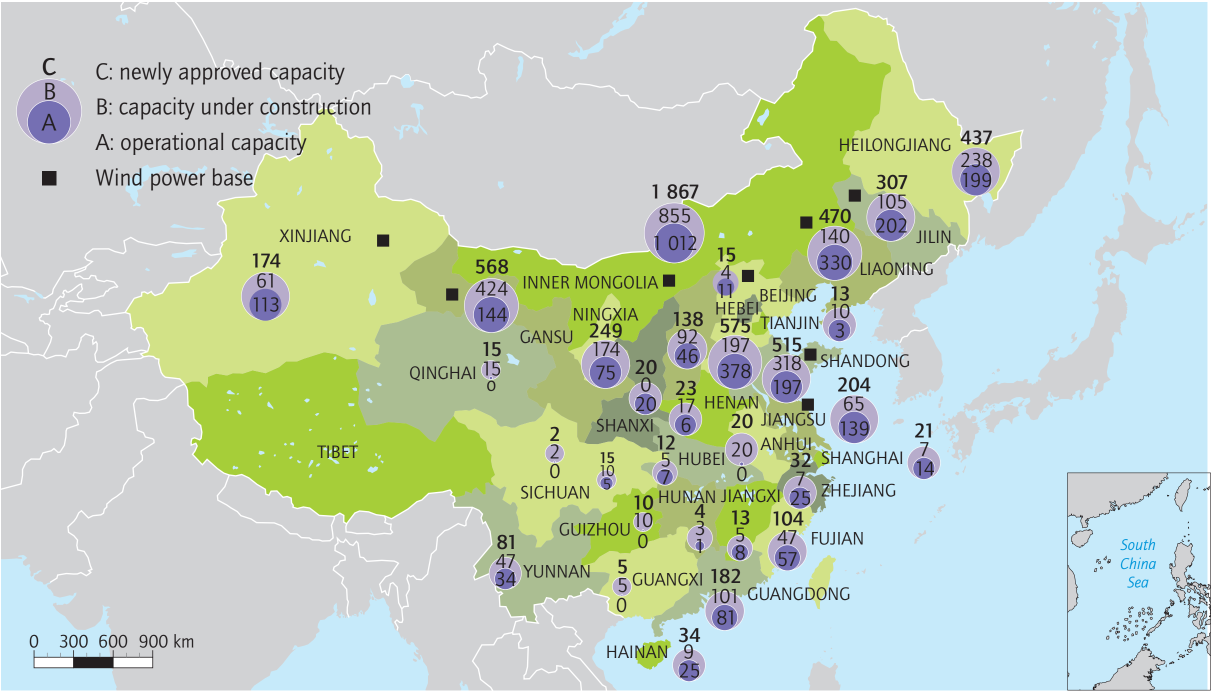


Figure 2. Wind power distribution in China



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Source: HydroChina.

northern China. At the same time, wind resource development in the east will take advantage of a good power grid infrastructure and a high potential wind power consumption capacity. Offshore wind power in China is in the early demonstration phase. In the near term, a gigawatt-scale offshore project will be started in order to gain experience in offshore technologies (Figure 2).

Increasing grid integration and wind energy consumption

Wind power grid integration and consumption is becoming a critical factor for future wind power deployment. China's existing large wind farms are concentrated in the north, where power grid infrastructure is insufficient to match large-scale wind power production, and where local load is low, with fewer balancing resources, and an immature inter-regional power market. Grid connection bottlenecks and excess local power supply have become major problems for wind power programmes in northern China, leading to large-scale wind power curtailment.

From January to June 2010, 2.76 TWh of wind electricity were curtailed, of which 1.58 TWh were from north China (north China grid plus western Inner Mongolia grid) and 1.06 TWh from northeastern China. This represents a disproportionately high level of curtailment: the northern region accounts for 42% of Chinese wind electricity production but 57.2% of curtailment, while the northeast produces 31% of national production and sees 38% of curtailment. At the province level, Inner Mongolia curtailed the most wind electricity, 2.1 TWh, accounting for 75.7% of total curtailment, while it represents only 32.3 % of national wind electricity production.

Wind energy development prospects

Resource potentials and development conditions

Land-based wind resources

China enjoys abundant wind resources with substantial development potential. Since the 1970s, China has conducted four nationwide wind resource surveys. The first three were mainly resource investigations, while the fourth, undertaken since 2007, is a detailed investigation and assessment of national wind resources.

According to this detailed survey, the China Meteorological Administration (CMA) erected 400 wind towers with heights of 70 m, 100 m and 120 m, and established a national wind measurement network. CMA also developed a wind energy numerical simulation and evaluation system (WERAS/CWERA) to carry out historical data filtering, numerical simulation and geographical information system (GIS) analysis.

Based on the horizontal resolution of 5 km × 5 km numerical simulation results for nationwide wind resources, GIS analysis is used to eliminate unsuitable wind energy areas, such as those with a slope greater than 4%; water bodies; wetlands; marshes; nature reserves; historical sites; national parks; 3km buffer zones around cities; farmland; and desert areas.

For limited wind energy resource development areas, low land-use efficiency is assumed, such as: grassland 80%; forest 20%; and bush 65%.

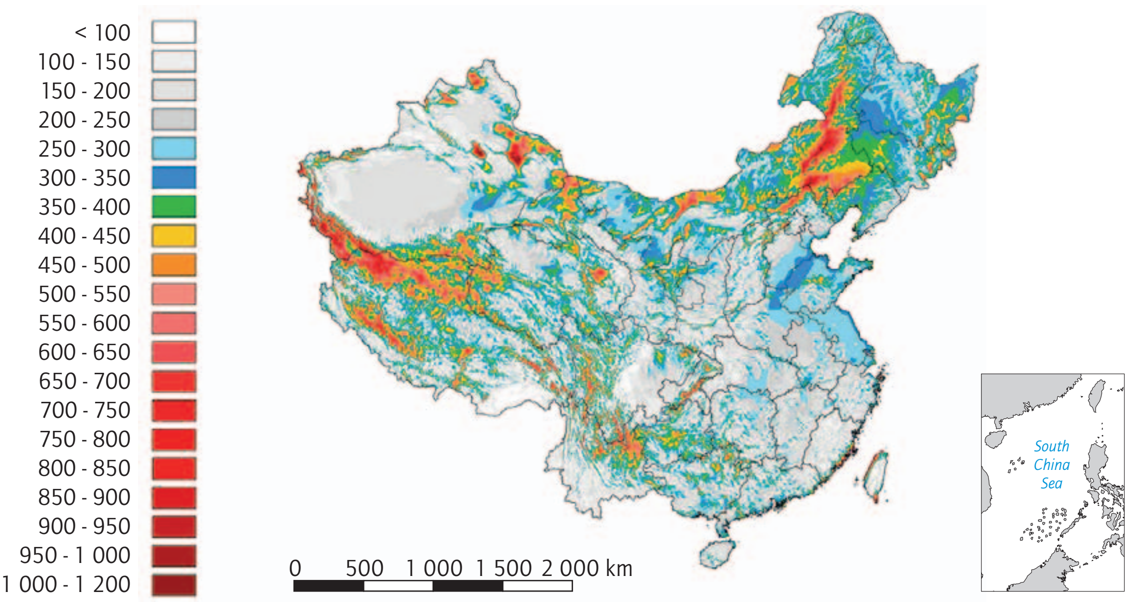
For areas with a slope less than 2%, the average wind energy capture rate can be 5 MW/km^2. In areas with a slope of 2% to 4%, lower average wind catches are estimated.

GIS analysis was used to process data from exploitable areas and obtain development potentials of wind power density grades 2, 3, 4 at heights of 50 m, 70 m, and 100 m (Table 3 and Figure 3). If wind resource regions with wind power density of grade 3 and above are considered exploitable, wind resource development potentials will be between 2 TW and 3.4 TW (excluding the areas with altitudes over 3500m in the Qinghai-Tibet Altiplano).

Table 3. Technically exploitable potential of land-based wind resources (GW)

Height above ground	*Grade 4 or higher (wind power density ≥400w/m²)*	*Grade 3 or higher (wind power density ≥300w/m²)*	*Grade 2 or higher (wind power density ≥200w/m²)*
50 m	800	2 000	2 900
70 m	1 000	2 600	3 600
100 m	1 500	3 400	4 000

Figure 3. Distribution of land-based wind resource potential (WPD≥300 W/m^2, 70 m height)



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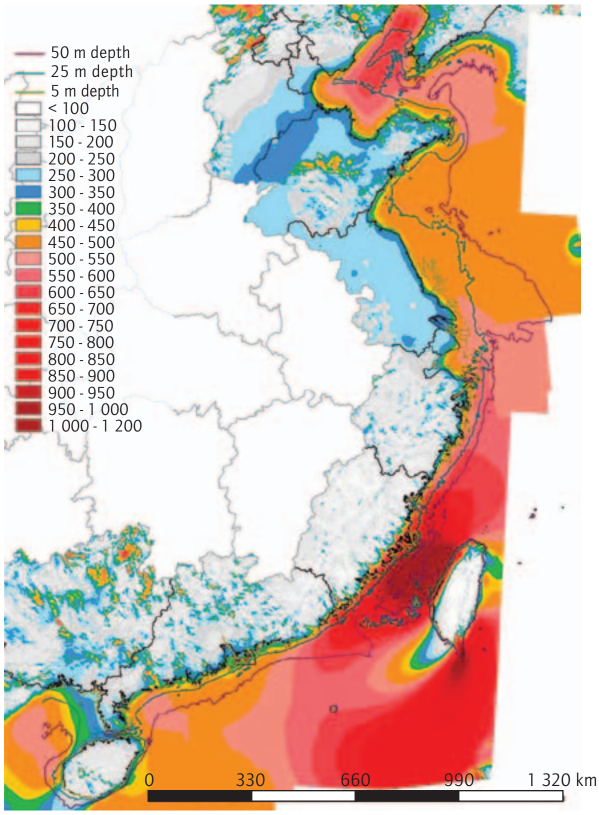
Source: ERI.

Near offshore wind resources

Numerical simulation shows that the Taiwan Strait is the area with the most abundant offshore wind of grade 6 and above (Figure 4). Offshore areas near Fujian, southern Zhejiang, Guangdong and Guangxi are also rich in wind resources, mainly because of frequent summer typhoons and the tropical summer monsoon.

Development of offshore wind energy is greatly influenced by water depth. Offshore wind technology is relatively mature for depths of 5 m to 25 m and is being developed for depths of 25 m to 50 m. For depths over 50 m, wind turbines will need floating foundations. Such technology is still at the R&D stage, so this roadmap assesses and analyses offshore wind energy development potential for depths of 5 m to 50 m. China's total land-based and near offshore wind resource potential to a height of 100 m has been assessed, eliminating shipping routes, fishing use and areas where typhoon of Force 3 or stronger occur (Table 4). In offshore areas with water depths of 5 m to 50 m, total wind energy potential is 500 GW. Wind resources in near offshore areas with grade 3 or above are much lower than on land.

Figure 4. Distribution of annual average wind power densities in 5 - 50 m depth sea areas



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Source: ERI.

Table 4. Land-based and offshore wind energy potential

Region	Total area ($10^4 km^2$)	Exploitable potentials (GW)
Onshore (70 m height)	≈960	2 600
Offshore (Water depth 5-25 m, 100 m height)	39.4	500

Wind resources at gigawatt-scale wind power bases

At the end of 2008, China launched six land-based gigawatt scale wind power bases in northern China and an offshore wind base in coastal Jiangsu province. Because of the availability of land, northern China will become a key wind power area.

CMA conducted a wind resource assessment for the seven bases using the computerised wind resource numerical simulation assessment system (WERAS/CMA). Using a horizontal resolution of 1 km × 1 km at a height of 50 m, the assessment resulted in a long-range average distribution of wind resources and projected installation capacity. Projected installation capacity refers to the total estimated capacity based on local construction requirements for mega wind farms and wind turbine density based on geographical conditions (Table 5).

In conclusion, China has very rich wind resources with grade 3 or above wind energy potential more than 2.6 TW (70 m height). Under current technologies, the resource can accommodate more than 1 TW wind power capacity. In addition, in the near offshore with water depth within 50 m, the practical offshore wind capacity potential can be as much as 500 GW. Combined with wind resource potentials, land resources, offshore areas, and available wind power technologies, China's wind resources can be sufficient to support wind power capacity of 1 TW. Wind power can be an important contributor of China's future energy supply and in the power structure.

Table 5. Wind resources at China's seven gigawatt-scale wind bases

Wind bases	*Resource potentials (GW)*	*Possible installed capacity (GW)*
Inner Mongolia (east and west)	1 305	382
Xinjiang Hami	249	65
Gansu Jiuquan	205	82
Hebei (Bashang area)	79	24
Jilin (west)	15	5
Jiangsu near offshore 5-25 m depth or less	–	14
Total	**1 854**	**557**

Note: Potential of grade 3 or higher grade at 50 m height.

In conclusion, China is rich in wind resources, with a potential of more than 2.6 TW (grade 3 or above at 70 m hub height). With technology currently available, capacity could reach more than 1 TW. In addition, practical near offshore wind capacity at water depth of less than 50 m could amount to 500 GW.

Expected cost and economic competitiveness

Current wind power costs

Many factors affect wind power cost, including wind resources, construction conditions of wind farms, wind turbine manufacturing technologies and cost, and the cost of managing and maintaining wind farm operations. Taking these factors into account, the current onshore wind power cost lies between CNY[2] 0.35/kWh and CNY 0.50/kWh, with the corresponding feed-in tariff level set at CNY 0.51/kWh to CNY 0.61/kWh. Under the current pricing mechanism – that is, without considering the environmental benefits of wind power – costs and tariffs are higher for wind power than for coal-generated thermal power.

The price gap between wind and coal tariffs differs from region to region because of differences in wind resources and thermal power prices. Because of advantageous wind resources development conditions, the wind power feed-in tariff in northern China is generally CNY 0.51/kWh to CNY 0.54/kWh – about CNY 0.25/kWh higher than the coal power tariff – while the wind feed-in tariff in eastern China is CNY 0.61/kWh. Though this is higher than for northern China, it is only CNY 0.20 higher than the local coal power tariff. A reasonable tariff for offshore wind power should be at least CNY 0.30/kWh higher than for coal power, because offshore wind turbines and construction can be much more expensive than for land-based projects.

On average, using current technology and without accounting for long-distance power transmission costs, wind power tariffs should be CNY 0.20/kWh to CNY 0.25/kWh higher than coal power tariffs. If wind power's benefits in terms of providing an alternative resource and protecting the environment are taken into account, however, wind power costs should be similar to coal power costs. This analysis does not consider the incremental costs of wind power in grid connection, integration and long-distance transmission, which can be about CNY 0.05/kWh to CNY 0.30/kWh.

Possible wind power cost reduction

Within the next 10 years or so, wind power is expected to be able to compete with conventional energy technologies. According to the *Technology Roadmap: Wind Energy* (IEA, 2009), the lifecycle

2. At 20 October 1 USD = 6.38 CNY.

cost of energy will range from USD 0.07/kWh to USD 0.13/kWh for onshore wind power and from USD 0.11/kWh to USD 0.13/kWh for offshore wind power.

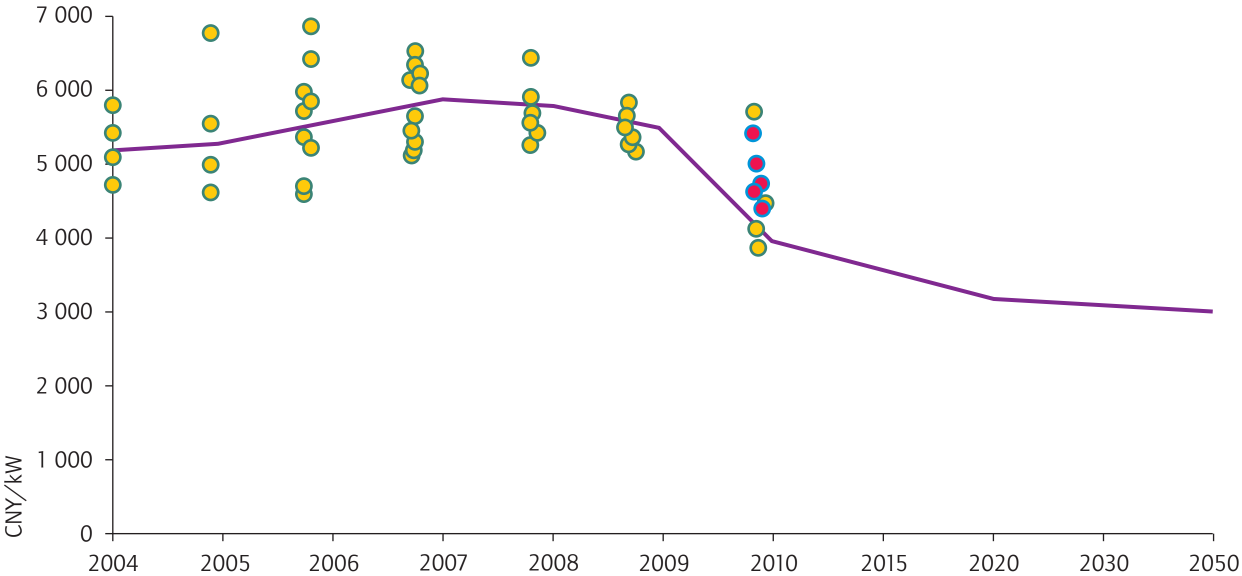
Since 2005, the Chinese wind power market has expanded rapidly. From 2005 to 2008, because of market supply and demand imbalances and other reasons, increased investment in wind power resulted in volatile investment costs. In general, however, wind power investment costs fell after 2005. In 2010-11, the investment cost of wind power development ranged from CNY 8 000/kW to CNY 9 000/kW (USD 1 250 to USD 1 400/kW), of which the wind turbine itself generally accounted for nearly half.

Land-based wind turbines should have some room for cost reduction. With continuous improvements in wind power scale and technology, the wind turbine unit cost may fall to match the unit cost of coal-fired thermal power. Even considering the possibility of price rises for steel, copper and other raw materials and because of improved technical standards, wind turbine prices still have room for cost reductions of 10% to 20% in constant prices (Figure 5). Although labour and construction prices are likely to rise, land-based wind power development investment costs will fall to CNY 7 500/kW by 2020, CNY 7 200/kW by 2030, and CNY 7 000/kW by 2050 (at current exchange rates). Current investment costs for offshore wind power are 1.5 to 2 times greater, at about CNY 14 000/kW to CNY 19 000/kW. It is expected that they will drop to CNY 14 000/kW by 2020, CNY 12 000/kW by 2030 and CNY 10 000/kW by 2050 (Table 6).

Wind farm operation and maintenance (O&M) costs are an important part of cost calculation, including service, spare parts, insurance, management and other expenses. China's large-scale wind power development programme has just started, so limited data available on O&M costs and may not be representative or reliable. In addition, wind power development companies' experiences, management philosophies and methods differ. Given these caveats, the current average onshore wind farm operational cost is 25% of total wind power cost, at about CNY 0.10/kWh. Because of technological advances and changes in labour and other costs, it is difficult to forecast O&M costs for the next 10 to 40 years, but this roadmap assumes that wind power O&M costs on land will remain at CNY 0.10/kWh.

Offshore wind power O&M costs depend on factors such as the accessibility of offshore wind farms, the reliability of turbine systems and the parts supply chain. Currently, they are about 1.5 times those for land-based wind power, mainly because of lack of experience from demonstration projects. In the future, however, offshore wind power O&M costs will fall to the level of onshore costs,

Figure 5. Wind turbine price variation and expectation



Note: Yellow circle represents mainstream turbine prices, red circle is the prices of turbines 2.5 MW or larger.

or even slightly lower; they are expected to be at CNY 0.15/kWh by 2020, and CNY 0.10/kWh in 2030 and 2050. Widespread use of floating foundations, however, would result in higher investment and O&M costs for far offshore wind projects (Table 6).

At the same time as decreasing wind turbine prices, wind farm investment costs and O&M costs are lowering the cost of wind power generation in China, higher thermal power prices will be difficult to avoid, because of higher coal mining costs and prices. It is expected that after 2020, even without fossil energy resource taxes (or environmental taxes, carbon taxes, etc.) wind power costs and prices will tend to match those of thermal power, while after 2020, wind power tariffs will be lower than coal power tariffs (without considering wind power consumption and long-distance transmission factors).

Table 6. Expected investment cost and feed-in tariffs of typical wind farms (in 2010 prices)

		2010	2020	2030	2050
Unit investment (CNY/kW)	Land-based	8 000-9 000	7 500	7 200	7 000
	Near offshore	14 000-19 000	14 000	12 000	10 000
	Far offshore	-	50 000	40 000	20 000
O&M cost (CNY/kWh)	Land-based	0.10	0.10	0.10	0.10
	Near offshore	0.15	0.15	0.10	0.10
	Far offshore	-	0.30	0.20	0.10
Projected average tariff (CNY/kWh)	Land-based	0.57	0.51	0.48	0.45
	Near offshore	0.77-0.98	0.77	0.60	0.54
	Far offshore	-	>2	2	1

Development prospects

Methodology

As the analysis above shows, China's wind power capacity could reach more than 1 TW. But the cost, scale and time schedules of wind power development can differ markedly from region to region. Many factors must be taken into account in determining economically exploitable wind power potential.

In this roadmap, economically exploitable wind power potential is calculated using GIS analysis, based on land characteristics, ground observation and remote sensing data (1 km^2 units). This is combined with economic analysis to generate projections of installed capacity in the seven concentration areas and calculations of the price of electricity from each additional unit of capacity, taking into account a reasonable margin of profit. This results in a gross supply curve (GSC) for each of the seven large-scale wind power bases (Figures 6 through 9).

Grid access and long-distance transmission could be very expensive for some regions, because wind resources and load are unevenly distributed, so two price metrics are used in estimating wind power potential:

Feed-in tariff (this is the amount paid to owner to stimulate development) and is based on the economic evaluation of wind projects, including annual electricity production of a unit area, assumed internal rate of return (IRR) and installation cost. This tariff does not take into account costs of grid connection and transmission.

Full cost: The feed-in tariff plus local grid access cost and inter-provincial transmission costs. Taking into account the insufficient wind power consumption in northeast, north and northwest China, this roadmap assumes that wind power from northern China will be transmitted to eastern and central China load regions, and that the cost per kWh will be calculated according to conceptual transmission routes. Transmission costs will depend

Table 7. Assessment parameters and development potential for China's seven large-scale wind power bases

Bases	Covering areas	Unit capacity cost (CNY/kW)			Average operational hours (or capacity factor)
		2020	2030	2050	
East Inner Mongolia	Chifeng, Keshiketengqi, Wengniute, Alukerqinqi, Tongliao, Kailu, Kezuozhongqi	7 500	7 200	7 000	3 116
West Inner Mongolia	Wu Lancha City Shangdu county, Chayouhouqi, Chayouzhongqi, Siziwangqi, Xilinhot, Baotou DAMAOQI, Guyang, Hohhot Wuchuan, Wulatezhongqi / after flag, Dengkou, Linhe, Hangjin Houqi	7 500	7200	7 000	3 192
Xinjiang	Hami City, Santanghu, nom, Barkol County, Yiwu	7 500	7 200	7 000	2 682
Gansu	Jiuquan, Yumen, Dunhuang City, Jinta County, Guazhou, Subei Mongolian Autonomous County, Anxi county area	7 200	7 100	7 000	2 831
Hebei	Zhangbei, Shangyi, Guyuan county, Chongli, Donpao County, Fengning, Weichang	7 500	7 200	7 000	2 833
Jilin	Baicheng, Songyuan and Siping	7 500	7 200	7 000	2 629
Jiangsu	Xiangshui, Binhai County, Sheyang, Dafeng, Rudong, Nantong county and coastal waters within 20 km	14 000	12 000	10 000	2 620

Note: Density of wind turbine deployment is 3 MW/km^2.

on the location of the sending end and receiving end, and transmission routes, as well substation costs along the way and current taxation rules.

Supply curve

This roadmap analyses economic development potential for the seven planned 10 GW wind power bases, including the base in the Jiangsu coastal area (Table 7).

The supply curves of the seven wind bases have been calculated, without including costs of grid access and transmission for 2020 (Figure 6) and 2030 (Figure 7).

Wind power supply curves have also been calculated taking into account grid access and transmission costs, for 2020 (Figure 8) and 2030 (Figure 9).

Figure 6. Supply curves of China's seven large-scale wind bases in 2020, not including grid connection and transmission costs

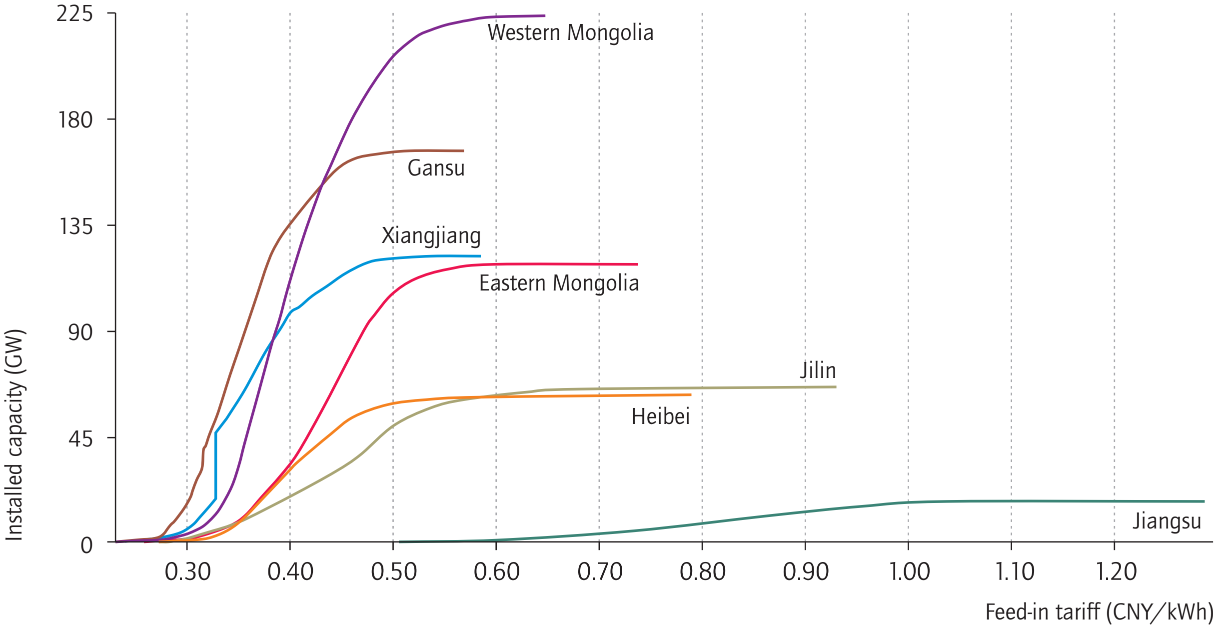


Figure 7. Supply curves of China's seven large-scale wind power bases in 2030, not including grid connection and transmission costs

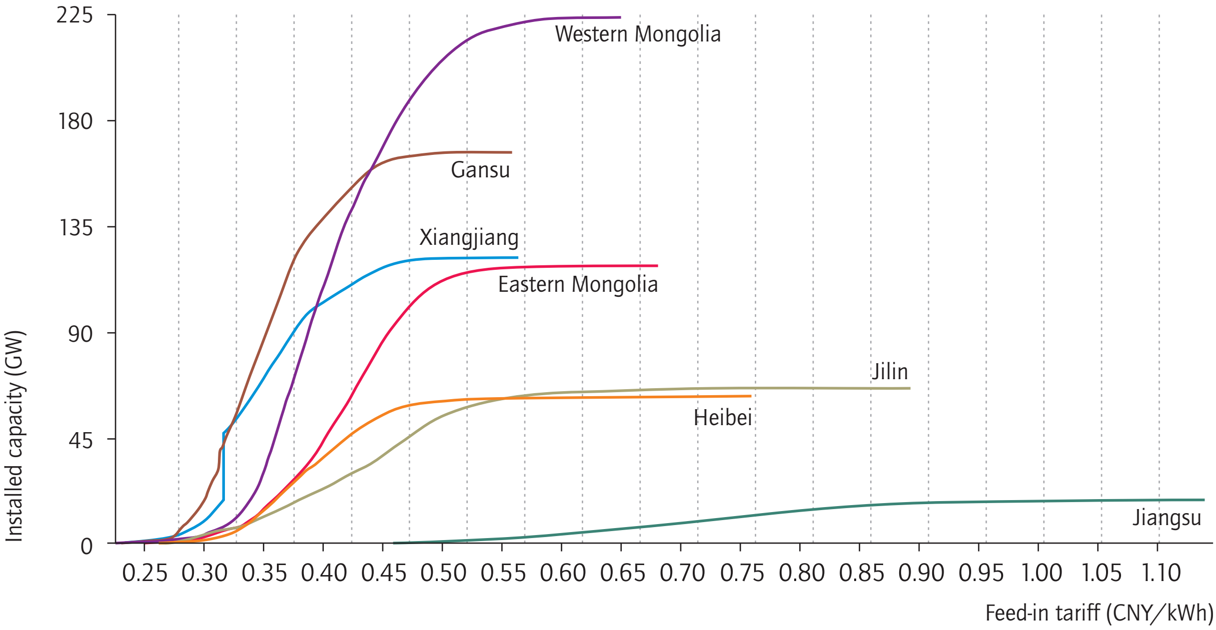


Figure 8. Supply curves of the seven large-scale wind power bases in 2020, including grid connection and transmission costs

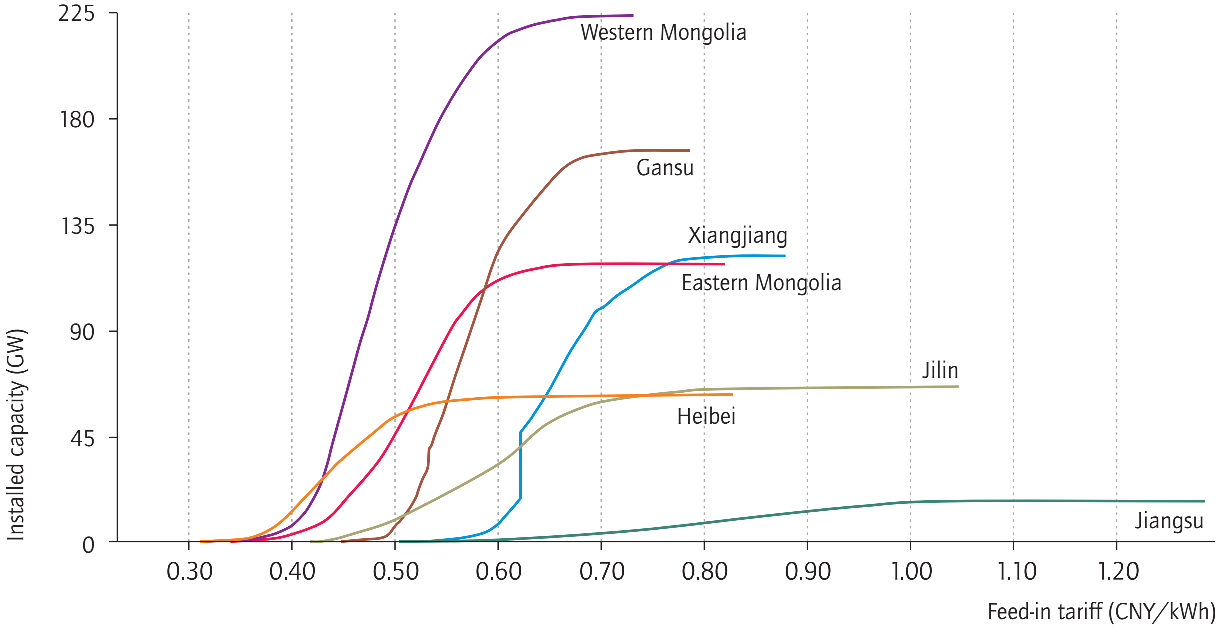
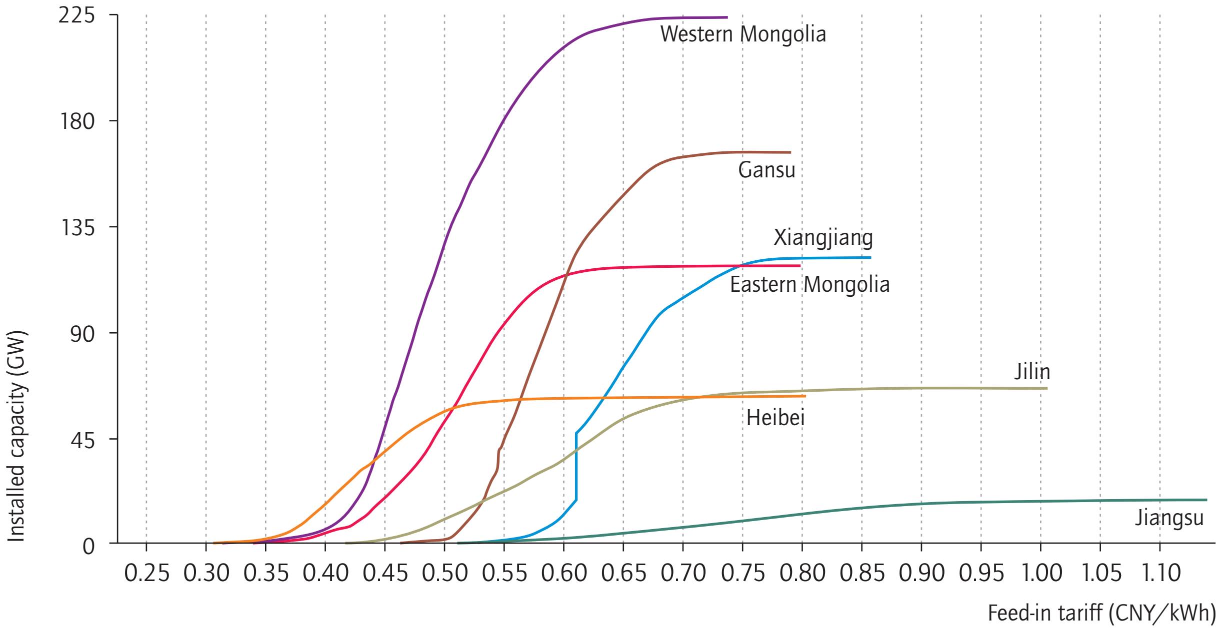


Figure 9. Supply curves of the seven large-scale wind power bases in 2030, including grid connection and transmission costs



Without considering grid access and transmission costs, the seven wind power bases' marginal and average costs have been calculated for 2020 (Table 8) and 2030 (Table 9).

According to these wind power supply curves, current wind resource assessments and current wind power technical conditions, if the maximum tariff level permitted is set at CNY 0.55/kWh or less (with the full cost price of wind power not higher than CNY 0.70/kWh), the economic wind power potential can reach 700 GW of installed capacity at China's seven large-scale wind power bases.

Table 8. Marginal and average costs for 200 GW target in five land-based wind power bases in 2020

	East Inner Mongolia	West Inner Mongolia	Jiuquan, Gansu	Hebei	Jilin
Marginal cost (CNY/kWh)	0.493	0.493	0.493	0.493	0.493
Average cost (CNY/kWh)	0.398	0.398	0.492	0.364	0.431

Table 9. Marginal and average cost for 400 GW target in seven wind power bases in 2030

	East Inner Mongolia	West Inner Mongolia	Hami, Xinjiang	Jiuquan, Gansu	Hebei	Jilin	Jiangsu
Marginal cost (CNY/kWh)	0.542	0.542	0.542	0.542	0.542	0.542	0.542
Average cost (CNY/kWh)	0.414	0.427	0.535	0.521	0.421	0.471	0.521

Vision for Wind Power Deployment and CO_2 Abatement

Strategic objectives

Strategic objectives for wind power development in China, including milestones, schedules and distribution, are determined by numerous factors. These include quantifying overall wind resources, potential technological progress, the scale of wind power development and the potential for cost reductions, combined with national energy and electricity demand, and long-term strategic goals.

Before 2020

By addressing grid infrastructure conditions and other possible constraints, the wind power market can be developed on a large scale before 2020. Establishment of a wind power industry with advanced technologies and standards will be a major goal. More than 15 GW of new capacity will be installed each year, with land-based wind power supplemented by offshore demonstration projects. By 2020, total installed capacity could be as much as 200 GW. Without taking into account transmission cost, wind power costs will fall to levels similar to those of coal power. At the end of 2020, wind power will contribute significantly to the energy system, representing 11% of total installed generation capacity and 5% of total electricity production.

2020-2030

From 2020 to 2030, without considering the cost of inter-provincial transmission, wind power is expected to be less expensive than coal power. If transmission costs are included, the full cost of wind power will still be higher than that of coal power, but if the environment and resource costs of coal power are considered, the full cost of wind power will be lower than that of coal power. The wind power market will be further expanded. Land-based and offshore wind power will both be developed, with new capacity of more than 20 GW added annually. Of the total installed power capacity added annually in China, 30% will come from wind.

By 2030, cumulative installed capacity could be over 400 GW. Wind power will meet 8.4% of the total electric power consumption and account for 15% of total electric power capacity. Wind power will play an increasing part in meeting China's electricity demand, improving its energy structure and supporting its economic and social development.

2030-2050

Between 2030 and 2050, wind power, power systems and energy storage technologies will continue to progress. Wind power will be better integrated in the national power system. China will further expand the scale of wind power, with co-ordinated development of land-based, near offshore and far offshore projects. About 30 GW of capacity will be added annually, accounting for about half of newly installed capacity. By 2050, installed capacity could reach 1 TW, about 26% of total power capacity. Wind power will meet 17% of national electricity consumption and become a major power supply, with a wide range of industrial applications.

Scenarios[3]

Before 2020

Before 2020, China's wind power development will focus on land-based and near offshore resources. Without considering transmission costs, when wind power development reaches 2 GW in 2020, the estimated tariff level will be CNY 0.36/kWh. This roadmap finds that in 2020, capacity that could be installed at this tariff level would be located in five areas: Jiuquan (85 GW), Hami (60 GW), East Inner Mongolia (9 GW), West Inner Mongolia (30 GW) and Hebei (8 GW).

When transmission costs are taken into account, the top-end grid-connected tariff would be CNY 0.49/kWh. Capacity installed at this tariff level could include: Jiuquan (3 GW), East Inner Mongolia (41 GW), West Inner Mongolia (100 GW), Hebei (51 GW) and Jilin (5 GW).

Finally, when the extent of the existing grid is taken into account, as well as plans to develop it over the next ten years and predictions of electricity demand growth, this roadmap finds that by 2020 China will see capacity development as follows: West Inner Mongolia (40 GW), East Inner Mongolia (20 GW), Northeast China (30 GW), Hebei (15 GW), Gansu (20 GW), Xinjiang (20 GW), and more than 10 GW will be developed in each of the Jiangsu and Shandong bases. Of the total wind power capacity of 200 GW, near offshore wind will contribute 30 GW (Table 10).

3. The roadmap scenarios are based on analysis from ERI.

2020-2030

From 2020 to 2030, both land-based and offshore wind power will be developed. Far offshore wind demonstration projects should also start. The same analysis is used for 2030 investment costs and feed-in tariffs. When total installed capacity reaches 400 GW, the top-end feed-in tariff (not including transmission costs) will be about CNY 0.39/kWh. Capacities installed at this tariff level would be: Jiuquan (130 GW), Hami (97 GW), East Inner Mongolia (36 GW), West Inner Mongolia (89 GW), Hebei (30 GW) and Jilin (18 GW).

If transmission costs are accounted for, the feed-in tariff would be CNY 0.542/kWh. At this tariff level, planned wind power bases and installed capacities would be: Jiuquan (40 GW), East Inner Mongolia (93 GW), West Inner Mongolia (186 GW), Hebei (58 GW), Xinjiang Hami (2 GW), Jilin (20 GW) and Jiangsu (1 GW).

Assuming significant improvement to grid infrastructure, as well as multiple additional energy storage facilities, and sufficient land resources, capacities could be as follows in 2030: West Inner Mongolia (100 GW), East Inner Mongolia (40 GW), Northeast China (38 GW), Hebei (27 GW), Gansu (10 GW), Xinjiang (40 GW) and 40 GW will be developed in the Jiangsu and Shandong bases together. Of the total capacity of 400 GW, near offshore wind will contribute 60 GW and far offshore 5 GW.

2030-2050

This roadmap assumes that development up to 2050 will also centre on these key geographical areas. The assessment is based on current investment and O&M costs, existing wind resource data, and transmission costs.

However, with continuing deployment, wind turbine and component manufacturing technologies will improve significantly, and offshore wind R&D will advance. These factors could greatly improve wind power technology and reduce deployment costs. Grid and system integration issues will gradually be resolved. Improved grid planning practices, extension and reinforcement will maximise local consumption of wind power, and transmission costs over long distances will decline.

By 2050, when total installed capacity will reach 1 TW, the wind power development strategy will need to be adjusted: wind farms will be developed in several additional areas. Inner Mongolia will have installed some 400 GW, based in several interconnected key areas. In Xinjiang and Gansu, more than 200 GW of capacity will be constructed. About 100 GW of capacity will be developed in Hebei and Northeastern China. With improved road access it will be possible to harvest the majority of the best resource.

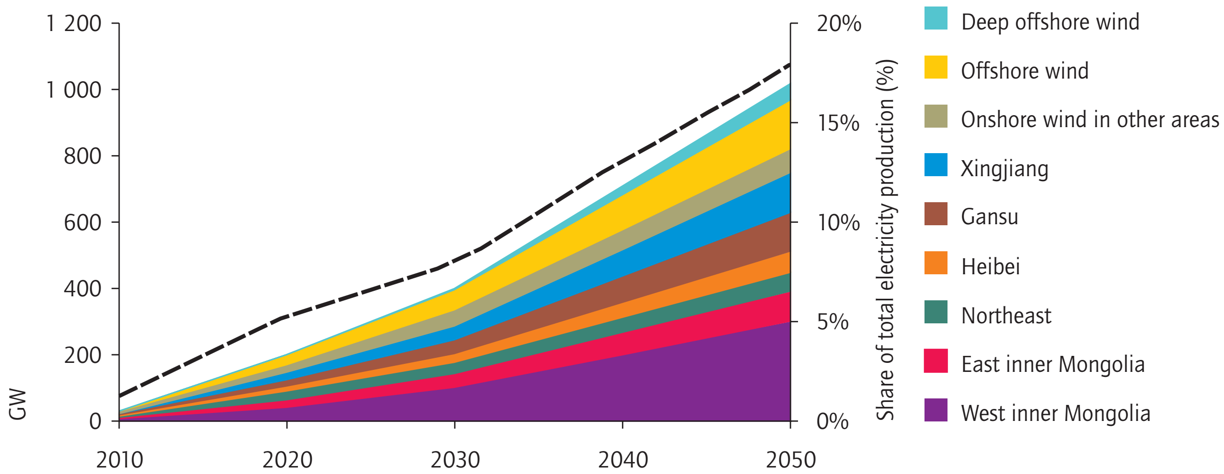
Offshore capacity will reach 200 GW, including 150 GW in near offshore areas. Several far offshore wind farms will be developed. Wind power applications will be expanded towards remote and desert areas and to far offshore. Technologies will be further improved, with power system upgrades and technology breakthroughs.

Wind power development targets and distributions have been calculated for 2020, 2030 and 2050 (Table 10 and Figure 10).

Table 10. Wind power development targets and distribution (GW)

Regions	*2010*	*2020*	*2030*	*2050*
West Inner Mongolia	6.50	40	100	300
East Inner Mongolia	3.62	20	40	90
Northeastern China provinces	7.31	30	38	60
Hebei Base	3.78	15	27	60
Gansu Base	1.44	20	40	120
Xinjiang Base	1.13	20	40	100
Distributed land-based wind in Eastern and Central China and other areas	7.43	25	50	70
Near offshore wind	0.10	30	60	150
Far offshore wind	0	0	5	50
Total	**31.31**	**200**	**400**	**1 000**

Figure 10. Targeted installed capacity and electricity share of wind power, 2010-50



Investment and subsidies

Investment

Accumulated investment in wind power will reach CNY 12 000 billion by 2050 (Table 11 and Figure 11).

Table 11. Expected wind power investment costs (in 2010 constant prices)

		2010	2020	2030	2050
Projected average tariff (CNY/kWh) without taking into account of transmission and storage cost.	Land-based	0.57	0.51	0.48	0.45
	Near offshore	0.77-0.98	0.77	0.60	0.54
	Far offshore	-	>2	2	1
Total investment in the year (CNY billion)		**123.4**	**136.2**	**298.2**	**427.6**
Total accumulated investment (CNY billion)		**313.1**	**1 777.3**	**3 833.8**	**12 096.2**

Figure 11. Total accumulated investment

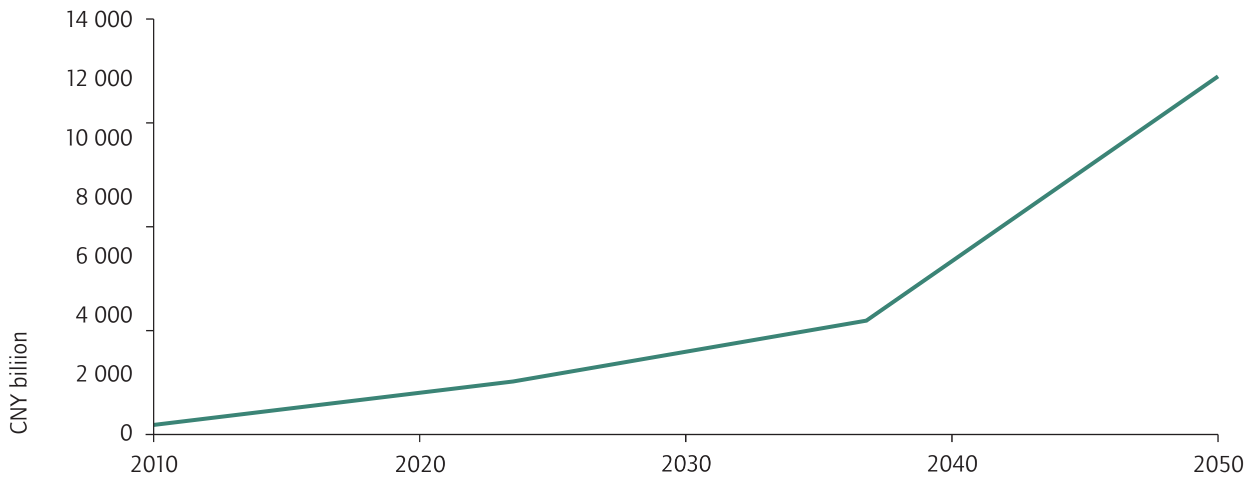
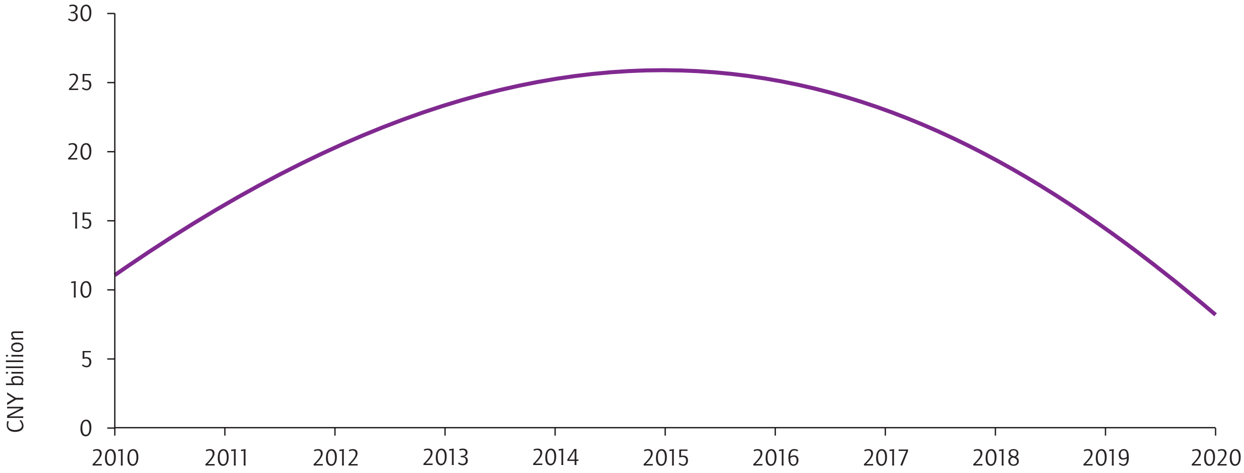


Figure 12. Expected subsidies for land-based wind power



Financial subsidies

Since 2006, China has implemented region-specific feed-in tariffs for wind power. Regulations stipulate that the incremental cost of wind power be higher than the feed-in tariff of desulphurised coal power be covered by a renewable energy surcharge on all end-users (or a renewable energy development fund in future). In addition, depending on the distance between power transmission lines and wind farms, subsidies of CNY 0.01/kWh to CNY 0.03/kWh will be awarded to help connect wind farms to the power grid. However, this subsidy does not take into account the costs of long-distance transmission of wind power.

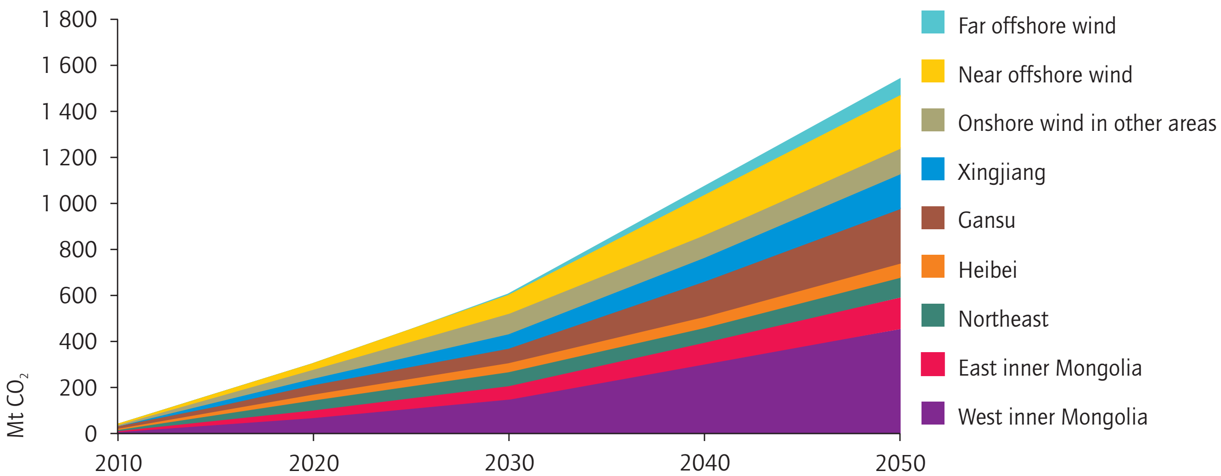
Assuming comparable costs for land-based wind and coal by 2020 and a continuation of current policies, required tariff subsidies are expected to increase smoothly to reach a peak around 2015 and then decline smoothly until 2020. Total wind power tariff subsidies will reach about CNY 210 billion (Figure 12).

After 2020, it is expected that the only subsidies required will be for offshore wind tariffs.

CO_2 emissions abatement

China's energy system is currently dominated by coal power, but once the targets in this roadmap are achieved, wind power can replace 130 million tce by 2020, 260 million tonnes of coal equilalent (mtce) by 2030, and 660 mtce by 2050 (taking into account improved thermal power technologies and lower coal consumption per kilowatt-hour of power). By replacing coal

Figure 13. CO_2 reduction potential of wind power development



power, clean, non-polluting wind power can have significant environmental benefits. Of course, its large-scale development may have some negative impacts on the environment, such as land use, noise, visual impact, bird migration and electromagnetic radiation, but compared with other conventional energy sources, especially coal-fired electricity generation, wind power's impact in these areas is much lower or even avoidable.

Annual CO_2 emission reductions are expected to amount to 300 million tonnes (Mt) by 2020, 600 Mt by 2030 and 1 500 Mt by 2050 (Figure 13).[4] In addition, annual SO_2 emission reductions are expected to be 1.1 Mt by 2020, 2.2 Mt by 2030 and 5.6 Mt by 2050.

Northwestern China wind development and employment

China's onshore wind energy bases are principally located in the north, where wind resources are abundant, population density is lower and the economy is less developed. Building and then managing these wind bases will boost the local economy and increase employment opportunities. In the meantime, the increased energy supply in these areas will encourage energy-intensive industry to relocate to the north, contributing to the development of these regions.

Investing in wind energy creates employment opportunities. According to relevant sampling statistics in 2009 and 2010 and average productivity in China's manufacturing sectors, about 15 jobs are created for every megawatt of installed wind power, including 13 to 14 jobs in the manufacturing industry. The service sectors in wind power installation, transportation and O&M could create 1.5 jobs for each megawatt.

Improvements in production efficiency will lower job demand in manufacturing, however, to 13 jobs per megawatt in 2020, 12 jobs in 2030 and 10 in 2050. Because of improved wind farm operation, maintenance and management techniques, as well as unmanned offshore wind and large regional management, the number of on-site wind farm jobs per megawatt is is expected to fall, to 1.5 by 2020, 1.1 by 2030, and 0.8 by 2050. The total number of field job opportunities will increase, however, as the scale of wind power development increases. Overall, wind power will bring jobs to 360 000 people by 2020, 600 000 by 2030 and 720 000 by 2050.

4. Coal generation CO_2 emissions are expected to be 751 g/kWh in 2020, 727 g/kWh in 2030, and 704g/kWh in 2050.

Table 12. Estimated job opportunities from wind power industry (Unit: 1 000 jobs)

Classification			2010	2020	2030	2050
Manufacturing industry	Turbine manufacturing	Production line	43.5	45	84	91
		Management, R&D, sales and marketing, after sales service	36	37	69	76
	Component	Blade, generator, bearing, gearbox, inverter, tower, flange, hubcap, main axe, etc	106	109	204	223
	Raw materials	Steel, polyurethane, fiberglass, magnets, other	48	50	93	102
Service sector	Installation and transportation	Installation, transportation	17	16.9	29	28
	O&M	Operation and maintenance	13	10	12	20
Total			**263.5**	**267.9**	**597**	**720**

Wind Technology Development: Actions and Milestones

This section explores the need and direction for research, development, demonstration and deployment (RDD&D) of key technologies and facilities for large-scale development of wind energy in China, with more emphasis on the mid term (before 2030) and a rough outlook for beyond 2030. Generally, RDD&D will not only learn from international experiences but also adapt to China's strategic goals, wind resources and power system development. Because R&D depends on many factors, including wind power targets, geography situation, local climate, wind resource characteristics, power load distribution and power grid distribution, this roadmap will need to be improved and adjusted as these factors change.

Wind energy resource assessment

This roadmap recommends the following actions:	*Milestones*
Set standards for advanced wind resource assessment	2020
Develop a national wind resource database	2020
Create a partnership of applied wind resource services	2020

Enhance wind resource assessment technical standards and technical capability

Technical standards for wind energy resource measurement need to be greatly improved, including advanced measurement techniques so that more measurements can be included in observations such as gradient temperature and climate parameters to forecast wind power.

Technical standards also need to be established for numerical computation and analysis of wind energy resources, focusing on normalised methods for resource assessment in hilly areas and of near offshore wind, wake effect measurement and wind farm power forecasting. Before 2020, as wind power is developed on a large scale, a complete package of numerical simulation methods needs to be established to assess resources for large-scale wind farms, including meteorological simulation, wake effect computation, and remote sensing data for near offshore wind. Between 2020 and 2030, complete numerical simulation of wind farm energy will be developed, including methods and standards for short-term forecasts and for medium- and long-term trends. Studies should be encouraged to evaluate high air wind resources.

Regional wind resource quality assessment standards also need to be developed, based on constraints in wind power development technologies, regional economic development and power grid infrastructures.

Develop wind resource database expand and application services

Measurement needs to be improved of China's wind resource conditions and environmental parameters, including temperature, lightning, sand and dust, and ice and frost. A national wind resource data platform and database need to be developed, covering national meteorological and wind power resource data, and wind measurement results from local government, enterprises and research institutes. Provincial fine-mesh wind resource simulations and regional wind quality information should also be included. A wind energy resource data co-sharing service platform needs to be built, to share available information as much as possible and encourage wider use of the database.

Processing and analysis of all kinds of integrated wind resource data needs to be strengthened. By summing up China's specific wind conditions and characteristics, International Electrotechnical Commission (IEC) standards on wind turbines and wind energy model applicability can be verified, so that international standards can be amended or supplemented to promote sound wind turbine design and testing. Through improved standards, domestic wind turbine design can be optimised for the local environment.

Wind turbines

This roadmap recommends the following actions:	***Milestones***
Develop and deploy 5 MW offshore turbine	2015
Improve performance of wind system components	2015
Secure reliable supply of key materials or develop alternatives	2020

China's wind power manufacturing industry grew quickly from 2006 to 2010. In future, advanced large-capacity turbine system R&D capabilities should be improved to meet the needs of the wind power supply chain and to ensure wind turbine quality and reliability (Figure 14).

Improved turbine performance

Market demand for wind turbines

From 2010 to 2015, China's annual installed capacity is expected to reach about 15 GW, including about 14 GW of land-based wind power and about 1 GW of offshore wind power. Between 2015 and 2020, as large-scale offshore wind power begins to be developed, wind turbine manufacturers need to reach 18 GW of installed capacity per year. This will include 13 GW from land-based turbines and 5 GW from offshore turbines, while older wind turbines with a total capacity of about 500 MW will need to be retired or transformed. From 2020 to 2030, 24 GW of wind turbines will be needed annually, 19 GW land-based and 5 GW offshore. Over the same period, a total of 39 GW of wind power units need to be retired or transformed. Between 2030 and 2050, average annual wind turbine needs will be about 50 GW, including 44 GW land-based and 6 GW offshore. About 400 GW of wind turbines will need to be retired or reconstructed over the period 2030-2050 (Figure 15).

Figure 14. Estimated additional wind power capacity and retirement, 2010-50

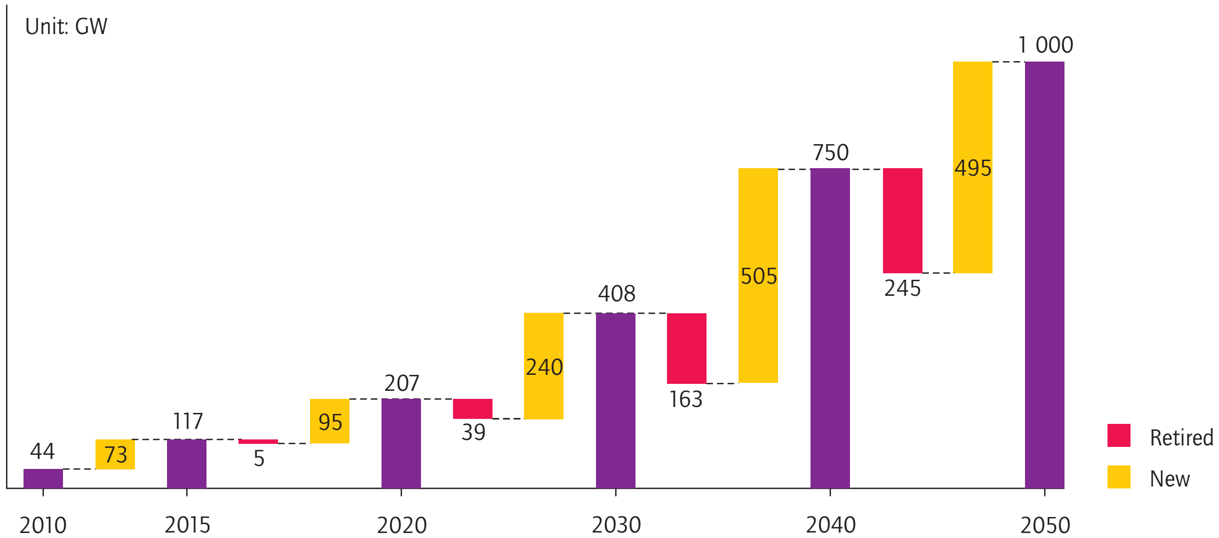
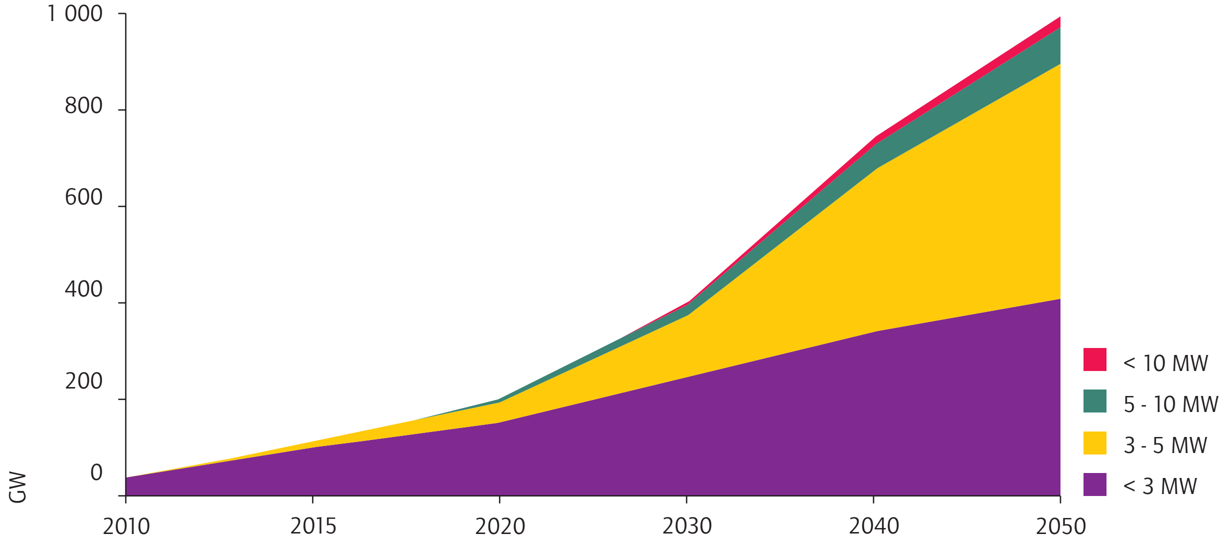


Figure 15. Megawatt-scale turbine system demand, 2010-50



As technologies improve and offshore projects are developed, large-capacity, diversified wind turbine systems will be the trend. From 2011 to 2015, turbines of 3 MW or smaller will be mainstream units; these will be supplied to the market in large batches to meet annual installation demand of 15 GW to 20 GW. Turbines of 3 MW to 5 MW are used for offshore and some land-based projects, with an annual demand for these of 8 GW. From 2015 to 2020, turbines 5 MW or larger will begin to be installed offshore, with an annual demand of 1 GW to 1.3 GW for turbines of this capacity. From 2020 to 2030, 5 MW to 10 MW units will be mainly used to meet the needs of large-scale offshore wind, with annual demand of 22 GW. From 2030 to 2050, many 3 MW turbines will be retired, so demand for wind turbines will usher in a new peak. Systems of 3 MW to 5 MW will replace the 3 MW turbines and become mainstream products, with annual demand for these of 30 GW to 50 GW. The demand for 5 MW to 10MW turbines will be 5 GW to 10 GW annually. Annual demand for 10 MW turbines will be 1 GW to 2 GW (Figure 16).

Wind turbine R&D

China currently has 10 major manufacturers supplying 2.5 MW to 3.6 MW advanced wind turbine systems using batch production. Some 5 MW offshore turbine prototypes have been delivered. Some manufacturers and research institutes have initiated R&D programmes for 10 MW systems, prototypes of which will be available in about 2020.

Following trends toward large-capacity wind turbines, basic research should be strengthened to master the design methodologies and technology advances needed to develop advanced large turbines based on China's wind farm characteristics. Light and environmentally friendly turbines, 3 MW or smaller, need to be developed and deployed. The design of 3.5 MW turbines needs to be optimised, and conceptual design and critical technologies developed for 5 MW to 10 MW offshore turbines. Before 2020, 5 MW turbiness will be commercially deployed and prototype 5 MW to 10 MW offshore systems completed. Conceptual design and key technology development will be completed for offshore turbines of 10 MW or larger. From 2020 to 2030, it is expected that 5 MW to 10 MW offshore systems will be commercially deployed. Prototype certification is expected to be completed for super-large (deep water) offshore systems (10 MW or larger).

Improving turbine performance to meet strict requirements for grid integration is a critical challenge. Before 2015, China should strengthen basic research programmes to optimise performance, especially of doubly fed induction generator (DFIG) turbines. Fault ride-through capacity and reactive power support capacity need to be further improved. From 2015 to 2020, new turbine controlling systems and grid-friendly turbines should be developed and deployed. After 2020, grid-friendly turbine technologies should be mature and widely deployed in China.

Offshore technology development will focus on reliability; cost-effectiveness; environmental integrity; ease of transportation, installation and maintenance; and greater resistance to typhoons.

Critical wind system components

As wind turbines continue to increase in size, technology R&D needs to be enhanced to supply advanced blades, mechanical systems, control systems and large capacity inverter technologies. Quality assurance and quality control should be strengthened in the production process.

Blades

As turbine size increases, blades need to become longer. Reducing load and weight, improving environmental integrity and friendliness, and ensuring transportation convenience will be key technology directions in the next 10 years. R&D needs to be strengthened on blade performance monitoring techniques, using new designs and new materials, (such as carbon fibre and high-intensity fibre glass). For offshore wind applications, higher tip speed (120 m/s) blades need to be developed. To prevent retired blades from having a higher environmental impact, new technologies using recyclable materials are likely to become an important development.

Gearboxes

China still lacks experience in advanced gearboxes, so there is a need to strengthen research to achieve technological breakthroughs in structure, materials and techniques, particularly to improve bearing life, bearing capacity and reliability.

Generators

The main direction of generator technology is to improve grid integration performance and reduce weight. With technology advances and cost reductions in full power conversion, full power inverter grid-in generators will be widely used, such as permanent magnet synchronous generators (PMG) or electrical excitation synchronous generators. As technology breakthroughs are made and superconducting materials become less costly, generators 10 MW or larger that incorporate HTS (high-temperature superconductor) technology are expected to be used in next 10 years. High-voltage generators are another technology direction; while 3 MW to 5 MW turbines will use mid-voltage generators, higher-capacity turbines will support widespread use of high-voltage generators.

Inverters

The increasing capacity of wind turbines requires larger inverters. In addition, some wind farm conditions requires turbines with high reliability and easy maintenance, which necessitates modular converters. As wind power's share of total generation increases, the larger number of inverters will require studies and control of possible negative impacts on the grid.

Tower

Tower height, currently 60 m to 80 m, is likely to continue to rise, increasing the revenue from generating capacity. Higher towers will require more careful load computation as well as other adjustments. In addition, with wind power development in the intertidal zone and offshore, corrosion resistant towers will be a greater challenge. Current anti-corrosion technology solutions, imported from Europe, cannot meet the actual geographical and climatic conditions in China. Anti-corrosion technologies need to be improved to extend the service life of offshore wind farms to 20 years or longer.

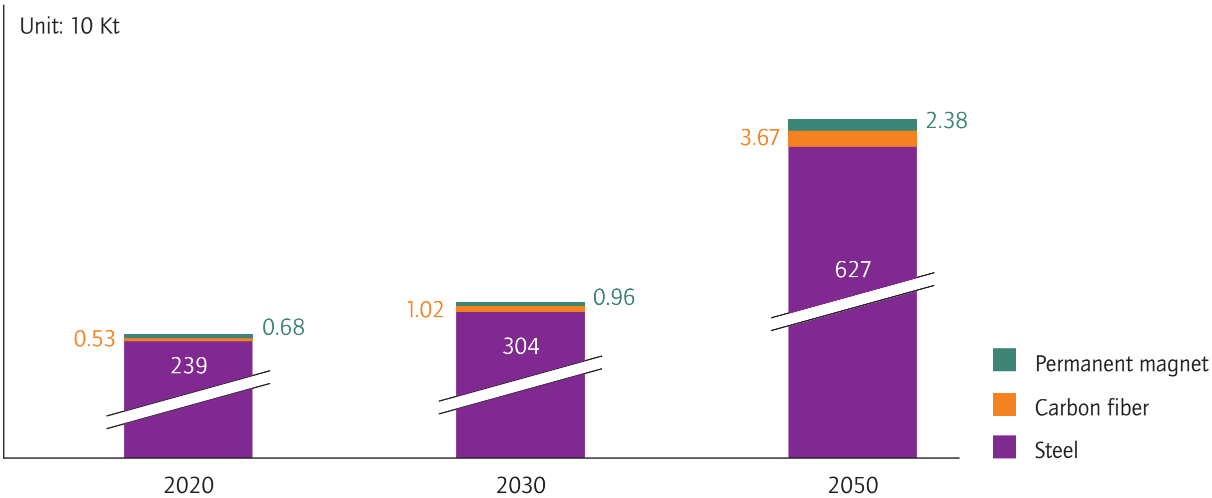
Critical raw materials

Wind turbine manufacturing uses raw materials such as steel, aluminum, copper, concrete, glass fibre, carbon fibre, epoxy and permanent magnetic materials. Steel currently accounts for about 90% of the weight of a turbine unit. Carbon fibre composite materials represent the future development direction of main blade materials. Demand for permanent magnetic materials will increase as the direct-drive turbine market expands. More attention should be paid to securing the supply of these three materials. Other materials are used in smaller amounts, so do not affect the development of the wind power industry.

Steel

In 2009, when 13.8 GW of installed wind capacity was added in China, the amount of steel used by the wind power industry was about 1.75 Mt, only 0.38% of crude steel production in China. According to rough projections, the total steel needed for future wind turbine manufacturing will be 2.39 Mt in 2020, 3.04 Mt in 2030 and 6.27 Mt in 2050. China's steel output will be sufficient to support the wind power industry for the foreseeable future.

Figure 16. Estimated annual demand for major raw materials in 2020, 2030, and 2050



Data source: CWEA

Note: Annual demand for raw materials (t) = use of raw materials per unit capacity (t/MW) × annual additional installed capacity (MW).

Carbon fibre

As turbine blades become larger and lighter, more carbon fibre will be used to manufacture them. For a blade 50m long installed in a 4 MW turbine, for example, 1.2 tonnes of carbon fibre is required per megawatt. It is estimated that carbon fibre demand for Chinese wind turbine blades will be 5 300 tonnes in 2020, 10 200 tonnes in 2030 and 36 700 tonnes in 2050. China's level of carbon fibre production is far behind that of the developed countries, which cannot themselves meet domestic demand, so the supply gap is huge. R&D efforts should be made to accelerate China's production and supply of carbon fibre.

Permanent magnetic materials

It is estimated that for every megawatt of wind turbine capacity, about 0.75 to 0.8 tonnes of the rare-earth permanent magnetic material neodymium-iron-boron (NdFeB) will be used. In 2009, China's new direct-drive permanent magnet wind turbines demanded NdFeB materials of about 1 920 tonnes, which was only 2% of China's total neodymium-iron production of 94 000 tonnes. Demand for rare-earth permanent magnet materials in the wind power industry will be about 6 800 tonnes in 2020, 9 600 tonnes in 2030, and 23 800 tonnes in 2050. Based on China's proven reserves of rare earths (about 90.3 Mt) and output growth, supplies for the wind power industry in China seem assured. The price of permanent magnetic materials will increase, however.

Wind farm development and construction

Land-based wind farms

Land-based wind farm technology is relatively mature, but efforts should be made to develop micro-siting techniques to continuously improve planning, design and operation of wind farms, especially in complex terrain. Improved wind power system simulation and design software packages should be developed and used, particularly for hilly,

This roadmap recommends the following actions:	***Milestones***
Optimise the design and operation of land-based wind farms in complex terrains	2015
Build full Capacity for design, construction and operation offshore wind farms	2020
Secure port, transport vehicle and installing facilities	Through 2020

mountainous and other complex terrain. Before 2015, the system should be developed and used to optimise the layout of wind power bases and turbines. By 2020, optimal design and operation of complex terrain wind farms should be fully realised.

Offshore wind farms

Offshore wind power, especially deepwater wind farm development and construction, still lacks maturity. R&D and demonstration activities need to be enhanced, based on China's specific planning and construction conditions. Project demonstrations should be accelerated to work out technical systems for far offshore and deepwater wind farms.

Design and construction

Before 2020, China's offshore wind farms will mostly be sited no deeper than 25 m, especially in beach and intertidal zones in Jiangsu province. Some pilot intertidal wind farm projects have been developed. It is expected that by 2015, China will have completely addressed technical problems concerning the foundations, construction, operation and maintenance of intertidal wind farms, and that shallow water offshore wind farm techniques will be fully mastered by 2020. In 2020, wind farms will be started in waters 50 m to 200 m deep, using floating turbines. R&D is expected to start before 2015, including conceptual studies, simulation, model testing, real machine tests, and actively promoting turbine design changes.

Port construction

Given the current configuration of China's coastal ports and terminals, three options for turbine transportation and installation can be identified, with costs from lowest to highest: co-ordination and configuration of existing ports and terminals; renovation and expansion of existing ports and terminals; building dedicated new ports and terminals.

Before 2015, existing ports and terminals will meet the basic needs of small offshore projects, but services to offshore wind power projects need to be co-ordinated with other port functions. After 2015, about 20 offshore projects are expected to start each year, which will require the construction of special ports and terminals. After 2020, transport of large-scale equipment will put further demands on ports, which will need transformation, expansion or new construction. When technological advances make deepwater wind power development a reality, after 2020, then the distance from the coast of offshore wind farms will increase greatly. Some islands will be suitable for building distribution bases for wind power equipment, thus reducing uncertainty of transport and installation due to weather conditions.

Transportation and installation

Despite the late start of China's offshore wind power, many traditional marine engineering and port construction companies have already started some R&D activities, focusing on how to use large-capacity ships for turbine transport and installation. In recent years, special ships for offshore wind development and construction have been under preparation.

Given China's shallow coastal waters and specific intertidal environment, until 2015 offshore equipment transport and installation will continue to depend on ships combined with floating crane barges and a small amount of specialised equipment. From 2016-2020, with the expansion of installed capacity offshore, large track-type multi-carrier vessels and amphibious equipment will be developed, with greater carrying capacity, higher stability and safer high-tech equipment. After 2020, when far offshore deep-sea projects may start, traditional marine engineering and transportation vessels will be needed, along with large floating crane barges, using more advanced control systems suitable for severe weather conditions.

Wind power integration

In response to demand for flexible and efficient grid integration of large-scale wind power, considerable efforts will be made to develop and deploy grid-friendly technologies, including wind power forecasting techniques, optimal scheduling technology, long-distance transmission technology and large-capacity storage technology, along with power system reform (Figure 17).

Wind turbines and wind farms

Before 2020, wind turbine technical specifications, network testing and model certification will be used to develop grid-friendly wind turbines and wind farms that are more suitable to power networks with capabilities of active and reactive power rate control, reactive power adjustment, low-voltage ride through (LVRT), frequency control and anti-jamming. Before 2030, control systems, storage devices and auxiliary equipment will be

This roadmap recommends the following actions:	*Milestones*
Set up centralised and distributed wind power output forecast systems	2015
Wide application of advanced power transmission and power grid operation technologies for wind power	2015
Automation of wind power priority dispatch	2020
Scale up utilisation of advanced power storage facilities	2020

developed and deployed so that wind farms can be controlled and adjusted like conventional power systems. By 2030, when large-scale energy storage technology is widespread, wind farms are expected to match the performance of conventional electricity generation, supplying electricity through distributed systems to end-users or working with other power generation technologies to become a hybrid power supply source.

Forecasting

As the installed capacity of wind power increases, better wind power prediction becomes vital. Accurate forecasts support reliable operation of the power system, effective management of electricity markets and maximum integration of wind power, while reducing system operating costs and the requirement for capacity margin.

Before 2020, R&D will focus on sophisticated statistical techniques, providing forecasts ranging from 3 hours to 72 hours ahead of the time of delivery. A centralised and distributed wind power forecast service will operate jointly with power grid dispatch, weather departments and wind farms to provide effective dispatching support. From 2020 to 2030, there will be a need to continue to improve the accuracy of wind power forecasting, with R&D on forecast applications for monthly, quarterly, annual and long-term scales. Offshore wind power forecast services will need to be improved. After 2030, more extensive wind power forecasting will support intelligent scheduling systems.

Integration and long-distance transmission

Alongside improvements in power grid infrastructure and operation techniques, and traditional AC transmission for large-scale wind farms and long distances, more flexible DC, high-voltage DC (HVDC), superconductive and low-frequency transmission technologies will need to be improved, especially for offshore wind farm electricity.

Before 2020, while the super-high-voltage grid infrastructure has not been established, advanced technologies including dynamic reactive power compensation, series compensation/TCSC, controllable high resistance, and automatic voltage control (AVC) will be applied to improve wind power output and energy quality, as well as enhancing safe operation of the power system. For small capacity and near offshore wind farms, AC transmission will be used, but as capacity increases and far offshore wind farms are installed, flexible HVDC technology will be developed at a faster pace. After 2020, as effective solutions are found to HVDC power transmission constraints, efficiency and economic advantages will be maximised, enabling high-voltage transmission to provide effective protection to the development of large-scale wind power programmes. After 2030, superconducting technology will be used for grid access and long-distance transmission in China's wind power industry.

Dispatching techniques

Dispatching control, a key part of power system construction, will play an important role in optimal allocation of power resources. The volatility of wind power and large-scale development of renewable energy technologies will increase the need for smart dispatching techniques. Wind turbine operational statistics and data analysis should be strengthened in order to gain accurate knowledge of wind power operational characteristics. Scheduling techniques and strategies should be studied to continuously improve more refined wind power scheduling. Smart grid technology will be integrated in dispatching control.

Before 2020, an integrated wind turbine/wind farm data collection and dispatching control system will be established to centralise forecasting, control and automatic wind power dispatching. By 2030, with initial smart grid construction, the integration of distributed co-ordination and control technologies will be developed, with control scope extended to the whole power system and intelligent wind power dispatching. Operational control of large-scale variable power sources and of the overall system will be improved. Wind power and other renewable energy generation will be flexibly connected, transmitted and used.

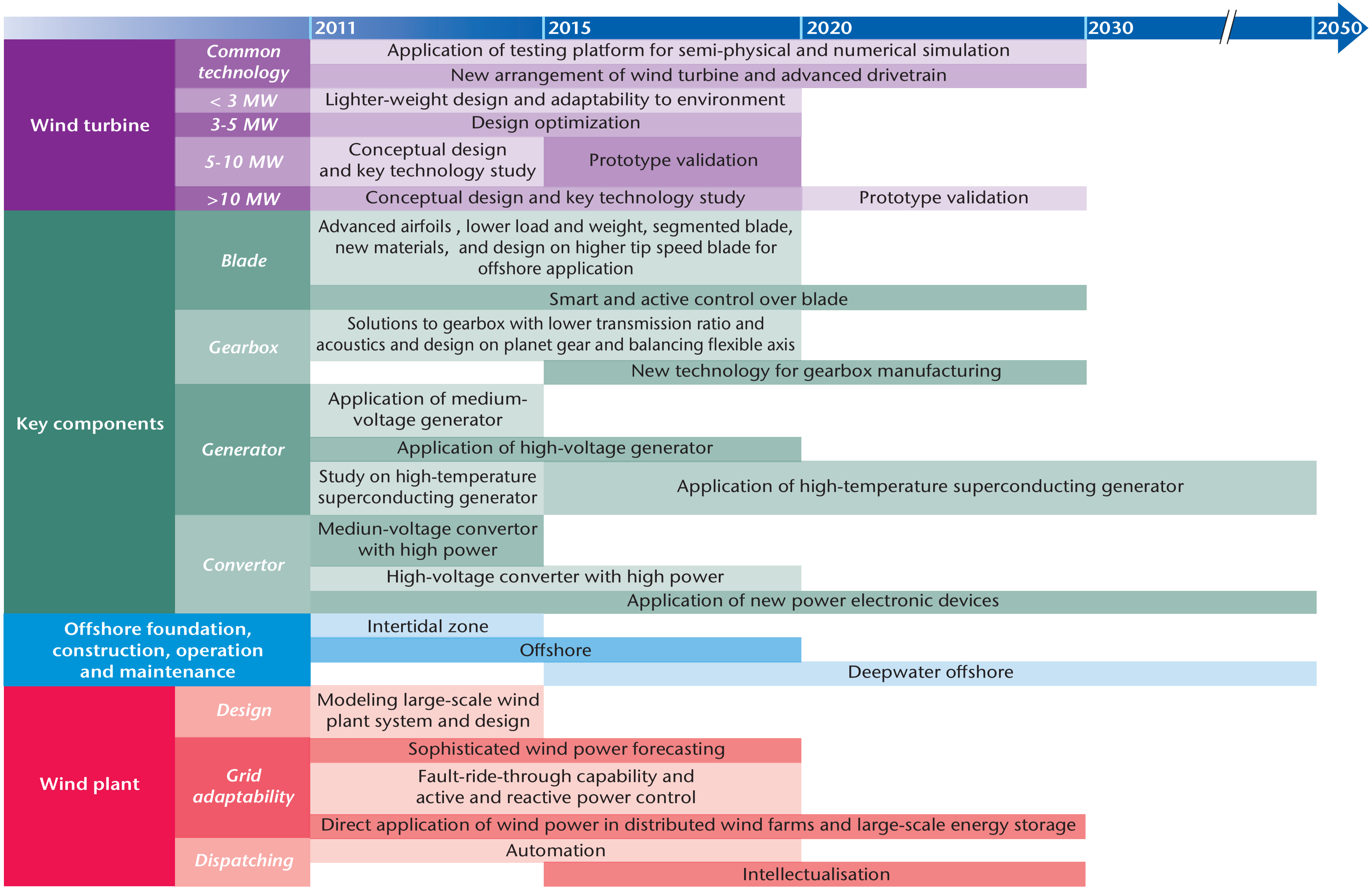
Large-capacity energy storage technology

Integrating large-capacity storage devices into the power system is an important potential measure to deal with renewable energy fluctuations. Such devices can reduce the impact of wind power variations on the power system, improving consistency of forecasted output with actual output and ensuring the credibility of power supply. They can also reduce the requirement for flexible reserves when wind output is not available, improving the economics of the power system while increasing acceptance of wind power.

More attention should be paid to energy storage system functions, technical options, planning and uses. Storage systems should be incorporated in the load side and the power source side. Available storage devices have not been widely used so far, because of their small scale, high cost, inadequate technical performance and small market. So far, pump storage techniques have been used most widely, while chemical battery storage is progressing the fastest. Liquid flow battery and lithium ion battery technologies should be encouraged with priority.

Before 2020, large-scale energy storage should depend on pumped storage technology. After 2020, battery storage technology is expected to achieve breakthroughs in technology and cost, enabling large-scale application of liquid flow, lithium ion and sodium sulfur batteries. Around 2020, large-capacity chemical energy storage, including lithium ion, sodium flow and liquid flow batteries, will be installed on a scale of dozens and hundreds of megawatts, with a conversion efficiency of 90%. They will be widely applied for centralised peak adjustment, frequency adjustment, emergency load management and distributed load management. By 2030, chemical energy storage and compressed air energy storage systems will be competitive in cost-effectiveness to pumped storage units, and will be widely applied. By 2050, high-capacity battery storage technology is expected to exceed performance of water energy storage technology.

Figure 17. Key milestones for wind power technology RD&D



Delivery and Network Integration: Actions and Milestones

This roadmap recommends the following actions:	***Milestones***
Estimate local consumption of wind energy produced at provincial and regional levels; plan inter-regional transmission and integration of wind energy production	According to the 5-Year Plan, and through to and beyond 2020
Demonstrate and deploy smart grid technology	Through 2020
Promote electricity market reform	2020
Enlarge the application of distributed power generation	2020 and beyond

China's greatest wind resources are in the north, far from load centres and the power grid framework. In addition, wind power fluctuates significantly, making generation uncertain and difficult to control. As a result, grid integration and accommodation is a major challenge in the large-scale development of China's wind power.

Power system development trends

Characteristic of electricity demand

China will continue to develop wind power at a rapid pace for many years. To understand the part that wind power will play in China, it is necessary to consider the characteristics of the overall power system.

Given the structure and distribution of China's primary resources, power generation bases in the west will be increasingly important, but load centres will remain in the east, so electricity transmission from west to east will remain vital in the mid term and long term.

At present, coal generation is the dominant power supply source. At the end of 2010, thermal power contributed 73.4% of total power generation capacity. Electricity supply is mainly balanced within provinces, with supply designed to meet the demands of the local power load. Although the different regional power grids are interconnected physically, trade among them is weak, with low inter-regional grid exchange and transmission capacity.

Without an extremely critical technology breakthrough in energy system, it is expected that coal-fired power and hydropower will be the main sources of electricity in the coming 40 years. Nuclear power, as well as wind and solar power in central and western China, will be increasingly important sources, with natural gas generation and pump storage stations serving as supplementary and regulating power sources. Until 2020 and even 2030, coal generation and hydropower capacity will steadily increase, with a focus on western regions, while wind and solar power will contribute more to total installed power generation capacity. Between 2030 and 2050, hydropower capacity will remain stable, thermal power installations will be decreased marginally, and nuclear, wind and solar power will amount to a significant share. By 2050, power generation technologies will be more optimised and diversified. Coal-fired electricity's share of total installed capacity will fall to 35%, while wind power's share is expected to rise to 25% to 30%.

China's geographical imbalance of electric load and energy resources results in the key characteristics of transmission from west to east and mutual support between north and south grids. The Northeast China grid, covering the eastern Inner Mongolia region, can meet local electricity demand and export electricity, using coal, nuclear and renewable energy sources. The North China grid is a major load centre; consumption relies on local thermal power, and electricity received from the Northeast and Northwest China grids. The areas covered by the Northwest China grid have abundant coal, hydro, wind and solar resource but limited load, so electricity can be exported. The Central China grid depends on the new power capacity developed in western China, and acts as hub linking western and eastern power systems. The Eastern China grid, a major load centre, receives a large amount of electricity from the west, including thermal, hydro, wind and solar power. The Southern China grid receives electricity from hydropower in western China and, in the long term, from Tibet and from surrounding countries.

Inter-regional electricity transmission will be gradually enhanced in the coming 20 years.

Transmission capacity from west to east is expected to increase to 300 GW by 2020 and to 400 GW by 2030, remaining steady at around 400 GW in 2050.

Power network infrastructure

After sustained reforms of power infrastructure and the power market, China has established an interconnected grid network of regional grid infrastructures, with provincial grids as the major operators in practice.

Before 1989, grid development was focused on building provincial and large regional grids. After that, inter-regional grids were strengthened and a system of six regional grids was developed. As of the end of 2010, all of China — except Xinjiang, Tibet and Taiwan — is covered by an AC-DC interconnected grid with a synchronised grid pattern of five grids: North-Central China, Eastern China, Northeast China, Northwest China and South China (Figure 18). Its super-high-voltage transmission grid structure and advanced power network technology applications have made China a leader in this field, but the three northern regional power grids are still not strong enough. Their capacity to exchange electricity is still relatively limited, making it difficult to meet the needs of large-scale wind power development.

Two different possibilities exist for future development of China's power network: a nationally interconnected regional power grid configuration or an ultra-high-voltage (UHV) grid-based configuration. In the first scenario (Figure 19), China would keep the current six large regional grids and enhance interconnection by establishing a 500 kV backbone grid (with 330 kV and 750 kV backbone transmission lines in the Northwest Grid). The 500 kV/750 kV transmission grid would be further developed to increase the potential and improve the efficiency of existing transmission infrastructures. At the same time, the 500 kV grid would be upgraded with flexible transmission techniques to significantly improve the power transmission capacity, long-distance transmission capacity and the capacity for fault control.

In the second scenario (Figure 20), a UHV grid would be constructed, with ultra-high AC synchronous grids connecting the North China, Central China and Eastern China Grids. Through DC connections to the Northeast, Northwest and South China grids, four interconnected synchronous power grids would be established, connecting thermal, hydro, nuclear and renewable power bases to load centres. These two configurations involve different technology development orientations. Although differing assessments exist of the feasibility, economy and safety of the two configurations, ultra-high-voltage DC technology will be a feasible technical choice for long-distance power transmission in China’s future grid development.

Figure 18. Grid connections in China as of the end of 2010

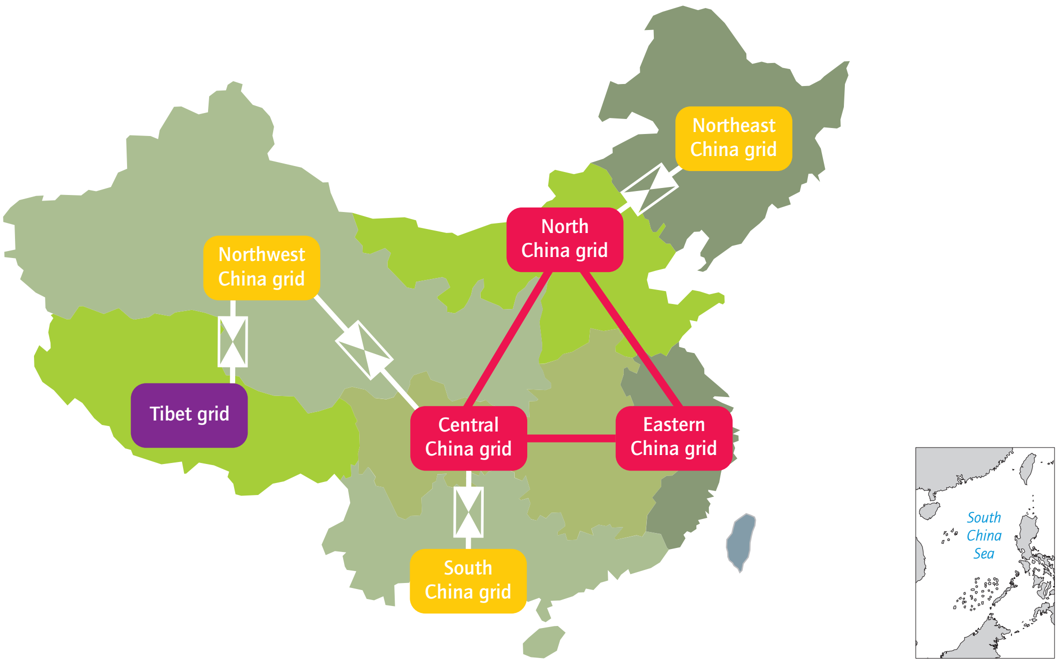
This map is for illustrative purposes and is without prejudice to the status of or sovereignty over any territory covered by this map.
Source: ERI.

Figure 19. Future grid configuration based on regional grids

This map is for illustrative purposes and is without prejudice to the status of or sovereignty over any territory covered by this map.
Source: ERI.

In the 12th Five-Year Economic and Social Development Planning Guidelines for 2011-15, UHV power grid development is encouraged. But many factors remain unclear, including technical routes, configurations, scale and contribution to the large-scale consumption of wind power.

Figure 20. Future grid configuration based on ultra-high-voltage infrastructure



This map is for illustrative purposes and is without prejudice to the status of or sovereignty over any territory covered by this map.
Source: ERI.

Preferential dispatch

Power dispatch in China has moved from a mode based on average operating hours to an energy conservation mode, which is favorable to wind power and other renewable energy sources. In 2007, the *Trial Regulation on Energy Conservation Power Generation Dispatching* was issued. By ranking the priority of power plants according to their levels of energy consumption and pollutant emissions, optimal power plant dispatch is used at provincial, regional and inter-regional grid levels to minimise total energy consumption and pollutant emissions.

Dispatch is prioritised in the following merit order: first, wind, solar, ocean energy, hydropower and other renewable energy plants; followed by adjustable hydropower, biomass, geothermal and other environmentally friendly renewable energy generators, (such as municipal waste generators), and finally other fossil fuels and nuclear power. However, due to lack of appropriate market incentives, implementation of preferential dispatch is still at an early stage. In the medium to long term, preferential dispatch must be paired with economic incentives, including the establishment of market-based power pricing.

Challenges of wind power integration and consumption

By 2030, China will develop several large wind power bases, with capacities in the tens of gigawatts, in Gansu, Xinjiang, west Inner Mongolia, east Inner Mongolia, Jilin, Hebei, Jiangsu and Shandong. By 2050, 100 GW wind base groups will be developed in west Inner Mongolia and other regions.

Integration and accommodation of wind power in the power network depends on many constraints, however, such as wind power output, system load, power source structure, regulation capability, power transmission scale and operation methods. These factors, which will continue to change, pose major challenges to the integration and accommodation of wind power.

Wind farm development before 2020 will be concentrated mainly in the three northern regions and near offshore wind bases. However, the northern regions will still be far from load centers and have a low power load in the near term. In addition, as China's power system is mainly based on coal generation, power grid development and construction is needed, and there is little scope for system balance dispatching. Integration and accommodation of a large volume of wind power from northern wind bases will be a challenge. Insufficient peak adjustment capacity and limited transmission capabilities give the north an overabundance of wind power.

Existing support policies for large-scale wind power integration are inadequate, focusing mainly on wind farm tariffs, grid access subsidies and cost sharing, rather than on obligations and conflicts of interest. The power grid system is still vertically managed, with transmission, distribution and power sales controlled by the same companies, preventing diversity among market players. In addition, transactions are far from being market-oriented; in the absence of improved inter-market transactions and inter-provincial exchanges,[5] markets are not playing their full role in optimising resource configuration. With power system and market reforms not in place, there is a lack of the necessary mechanisms in market operation, independent dispatch to promote wind power accommodation, free market trade, flexible tariffs, service systems, demand-side response and cost sharing.

After 2020, China will continue rapid development of wind power, expanding the scope of deployment areas and paying more attention to distributed wind power systems. By 2050, total installed wind power capacity will be as much as 1 TW, comprising more than 26% of total power capacity and 17% of power generation.

By then, the high proportion of wind power consumption will become a national challenge, which calls for prominent system restructuring and institutional innovation.

5. 2011.NER. Considerations on current power system and inter-provincial electricity exchanges.

Grid connection, transmission and consumption of wind power

Accommodating wind power in the national power system requires not only technical solutions but also reforms in management, policies and regulations. Wind power and power system development plans need to be co-ordinated, along with technology roadmaps, system standards and arrangements for power grid scheduling, dispatch and operation strategy. The implementation of flexible, well-developed electricity market mechanisms and incentives is required in order to optimise system operation and eliminate institutional barriers in the near and midterm. In the long term, the power system should be comprehensively transformed by technical and institutional innovation.

Before 2020: strengthen management and co-ordination

According to studies and practice in the leading wind power countries, power systems can integrate and accommodate up to 20% wind power with modest incremental cost through: innovative utilisation of existing technologies;technical systems and management systems; improved transmission system planning and construction; optimised market operation; and a greater scope for power balance dispatch.

Over the past few years, China has constructed the most powerful grid system in the world, with advanced technologies and technical facilities. The National Energy Administration initiated a wind power grid integration and accommodation study in 2010, which shows that China could achieve a wind energy economic potential of 160 GW to 200 GW by 2020, by optimising systematic power development plans, encouraging appropriate deployment of pump storage capacity and gas power peak adjustment, as well as rational development of inter-province power transmission.

To achieve this potential, administrative co-ordination needs to be strengthened to increase the provincial capacity of wind power accommodation and promote long-distance inter-provincial and inter-regional transmission of wind power.

Start wind power integration at provincial level.

Given the costs of long-distance transmission and the fact that the power market management system is dominated by provincial government and grid companies, wind power accommodation should take place at the provincial level first, before being addressed at the regional, inter-regional and national levels.

Enhance overall planning and co-ordination of wind power and other power plants, and construction of power grids.

The management of wind power projects needs to be strengthened and the speed of wind power development controlled so that it keeps pace with overall power system development. Dispatching capacity should be increased by: accelerating hydropower development in western China; expanding large-capacity pump storage systems and natural gas power stations for peak adjustment; balancing distribution of coal-fired power plants; and increasing dispatching capability of thermal power plants. Wind power development should be incorporated into grid construction programmes with wind farm connection projects optimised and co-ordinated, and backbone grid construction well planned ahead of time for better provincial and regional interconnections, including ultra-high-voltage DC transmission from northern China wind bases to power load regions. Studies should be carried out on wind power transmission from northern to eastern regions. A cost return mechanism should be established for transmission system operation.

Optimise operational dispatch of wind power and accelerate reform of the power market.

The power system's capacity to respond to supply variability needs to be improved through formulation and implementation of grid codes and standards for wind turbines, and as well as research, development and wider deployment of an advanced and reliable short-term wind power forecasting system. The balancing area needs to be expanded to lower the net load variability by connecting a wider geographical spread of wind power, thus reducing the need for balancing power sources. The use of hydropower and thermal power should be optimised within provincial areas for peak balancing, and inter-provincial power grid interconnection enhanced. Abandoning wind output should be allowed in extreme cases to reduce overall system cost. Ancillary plants should be made available and financially incentivised.

Strengthen demand-side management in response to load variability.

Retail prices should be adjusted for peak and valley load in the light of the characteristics of wind power output and power load. This would encourage electricity consumers (especially large industrial consumers) to take appropriate administrative and technical measures to enhance the load transfer capability to match the wind power generation curve around wind power bases. All self-service coal-fired power plants should be encouraged to reduce generation when necessary. Combined heat and power (CHP) plants should study the possibility of using surplus electricity for heat supply via electric heat pumps and heat storage.

Establish price policies and market regulations for grid integration and accommodation of large-scale wind power.

To encourage grid-friendly wind power projects, pricing policies could include performance-based incentives or ancillary service cost-sharing. National directives should be strengthened on inter-provincial/inter-regional power exchange. Intra-province wind power transmission cost could be shared through local power tariffs. Inter-provincial and inter-regional UHV transmission costs should be covered by purchase prices and sale prices in the target province or region. In addition, mutually agreed quota systems and liberalised market mechanisms should be explored and implemented to promote inter-regional power exchange.

By 2030 and 2050: energy and power system structural reforms

After 2020, and especially after 2030, with the rapid increase in electricity demand in western China, increased pumped storage and natural gas power generation capacity, as well as widely deployed smart grid and advanced energy storage technology, wind power integration capacity in northern China will increase significantly. However, because of the continued scale-up of wind power, demand for inter-regional wind power integration will remain large for a long time, so advanced technologies and operation management will to need be applied widely in order to encourage energy structure and power system reforms to expand wind power integration within and between provinces and regions. This require three key actions.

(1) Continued efforts should be made to expand integration of wind power within provinces in western China. Smart grid technologies, smart power devices, energy storage facilities and electric vehicles should be deployed to enable flexible regulation of load to match power demand and greatly increase the capacity for integrating wind power and other fluctuating power sources.

(2) Transmission from west to east should be improved and optimised through widespread adoption of flexible transmission technology, especially ultra-high-voltage DC transmission and superconductive transmission. Transmission system cost recovery mechanisms need to be improved to maximise transmission line capacity and cost-effectiveness.

(3) Wider deployment of smart distribution network technologies and micro-networks should be encouraged, to improve decentralised wind power integration and accommodation potential in eastern and central China.

Policy Framework: Actions and Milestones

The previous sections of this roadmap analysed resource potentials, grid access and consumption, and technology development routes to reach the goal of 1 TW of wind power capacity by 2050. This section provides a clearly defined policy scenario for the future development of wind power in China.

As wind power technology progresses through the stages of research, design, testing and demonstration to large-scale market deployment, a stable and gradually expanding wind power market could be critical. However, there is a very complex relationship between large-scale deployment and market forces. The gradual expansion of the market could attract investment and reduce technology costs, and thus make wind power more economically competitive. With the increasing scale of wind power deployment, however, problems may emerge with regard to the pattern of development, grid access, consumption and subsidies, resulting in deeper institutional and mechanism issues. To prevent such problems, appropriate policy measures are necessary.

Policies should be transparent, stable and predictable so that investors face minimal uncertainty, and also flexibly adapted to different stages of technology maturity. When wind power becomes fully competitive, policies should be easily adjusted or canceled to avoid dependence on incentives.

Develop a national strategy to transform China's energy structure

China's continued economic development depends on a sustainable and clean energy supply. If the country continues to depend on fossil fuel energy, it will face a more challenging future. In the coming 20 to 30 years, as energy demand increases, the government faces the challenge of securing supply while reducing fossil fuel consumption. The only solution is a cleaner, low-carbon energy structure, taking advantage of the 21st century's energy revolution and innovation. Renewable energies are clean energies and among these, wind energy is the most promising as it has almost reached the mature technology development stage and has the greatest potential to be deployed commercially. During the current Five-Year Plan period (until 2015), China needs to develop a national strategy to transform the its energy structure, with wind energy being the central element of that transformation.

Accelerate transformation of the power system and promote reform of the electricity market

Grid infrastructure, operation and dispatch are the core of the power system. Currently, China's power system is not keeping up with the demand for wind power development and needs to evolve to be able to manage greater shares of variable wind power. Future power systems will need to feature more flexibility on the demand side as well as on the supply side if they are to benefit from the full range of non-polluting, low-carbon energy sources, while maintaining security and reliability. This flexibility is essentially the ability to compensate for periods of low wind output, or to manage highs, using a portfolio of flexible generators, trade, storage and demand-side response.

Germany's energy strategy and Denmark's 2050 Energy Strategy, which plan for independence from fossil fuels, provide blueprints for accommodating renewable energy within the overall power system. To meet the demand for large-scale renewable energy development, China needs to accelerate power system reform in the 12th Five-Year Plan period, and develop a system capable of integrating a large share of renewable energies by 2020, which will be an essential condition for China's wind energy development through to 2050.

Support incentives and regulatory framework

The wind power market should at first be supported by government at first and then developed to maturity by market mechanisms.

Wind power development objectives can be set according to the national energy strategy, with a 50-year or longer term. A well-designed Implementation plan will be vital to achieve the objectives. Rolling five-year wind power development plans should be developed by the central government of China. Each plan should include five-year targets and expected goals for the following five-year horizon. The plans should include specific development programmes, regional focuses, priority projects, implementation schedules, the supporting grid infrastructure development, technical service systems and safeguard measures.

This roadmap recommends the following actions:	Milestones
Implement mandated market system for renewable power	2011/2012
Establish rules for wind power priority on grid integration and consumption	Through 2020
Establish sustainable incentive policies	Through 2020

Developing and implementing management regulations on renewable portfolio system and protective purchase of renewable energy

National mandatory laws and regulations should be enforced to ensure scale-up of wind power deployment and wind power market competition. Based on overall renewable energy targets proposed by the central government, grid companies' full purchase of renewable electricity should be regulated as renewable obligations. Provincial renewable power objectives should also be proposed. Grid companies, generation enterprises and local government will follow the implementation procedures in regional dispatching. The policy measures and regulations should be followed starting in 2011. The implementation period could be set at 10 years, to 2021, based on the development of the renewable energy market.

Establishing rules for wind power priority in grid integration

China's power system should be adapted to utilise the maximum amount of wind power through cost-effective co-ordination among provincial, regional and inter-regional power grids.

On the principle that renewable energy, including wind power, should be given priority, power grid enterprises should focus on the 2050 goal of installing a total of 1 TW of wind power capacity and develop a long-term power development strategy with five-year rolling plans. Specifically, by 2015, inter-province and inter-region transmission obstacles should be overcome. By 2020, transmission problems within and among regions should be resolved, as should difficulties with energy storage and smart grids. By 2030, China should complete a nationwide, interconnected smart grid.

Providing incentives for investment

Incentives should be designed based on a market system. Eventually, wind power should compete equally in the market and develop sustainably without depending on government incentives.

Currently, China's wind power market still lacks fair competition. For example, determination of the power tariff and the power grid regulating and scheduling rules cannot reliably reflect the roles of different power installations. Base load, peak adjustment, standby power sources and other equipment typically cannot be operated using its full function and value. External environmental impact cost is not included in the internal cost structure. The scarcity of resources has not been reflected in the development costs. Unfair competition for wind power is a common obstacle.

Supporting policies and measures proposed in this roadmap should be concentrated on tariffs and tax incentives, by considering environmental costs, resource costs and other factors, to achieve the development objectives at minimum cost.

By 2015, peak and valley tariffs in the electricity market should be implemented first in order to let peak adjustment power be the most powerful competitor and profitable. Later, environmental tax, carbon tax and other tax policies should be studied, with the aim of creating a fair competitive environment for wind power and other clean energy technologies as soon as possible. In addition, the pricing mechanism for wind power should be improved and detailed feed-in tariff regulations established to provide reasonable profit opportunities for the wind power industry. By 2020, a comprehensive, fair and competitive electricity market should be set up in China.

Market facilitation and transformation

This roadmap recommends the following actions:	*Milestones*
Continuously release detailed information on wind resources	2015 and update regularly
Improve standard system	Through 2020

Releasing detailed information on wind resources

Before 2020, a detailed wind resource investigation and assessment roadmap should be developed and implemented. Efforts should also include establishing a national database of wind energy resources and a database of wind farm projects. Mechanisms for providing access to information on wind energy resources should be developed to support wind farm preparation activities.

Principal activities should include:

(1) A large, specialised wind resource observation network should be established in wind resource rich areas and some special zones, based upon available wind resource surveys. The wind resource data should be used to work out simulation and medium- and micro-scale distribution maps, and detailed wind resource assessment. A national-level wind resource database should be developed.

(2) Based on a comprehensive consideration of regional wind resources, grid infrastructure, climate conditions and geological land forms, wind farm resource measurement and assessment activities should be completed and a national wind farm project database should be established. The information should be utilised for government development planning, macro site selection and project development.

(3) The government should release updated wind resource information to the public every three to five years so that information on wind farm development and investment costs are transparent to all investors. A market competition mechanism should be established to attract capital investment for wind power development.

Improved industry regulations and technology standard systems

To encourage R&D activities, reduce deployment costs and promote efficient technology development in the market, a complete set of wind power management and market rules should be developed before 2020.

Industrial management system

A complete system of wind power regulations needs to be established by 2015. An improved standards, testing and certification system, authoritative and consistent wind power programme management, and effective inter-agency co-ordination among grid, power generation, meteorology, technology R&D, codes and standardisation, and manufacturing sectors will help create a favorable institutional environment for wind power development. In addition, effective integration of wind power technology, resource, grid, and the market should be demonstrated in each five-year-plan issued by the government.

Technical standards and regulation system

An improved Chinese wind power standards, testing and certification system will be developed. Wind turbine standardisation, testing, and certification regulations will be continuously improved. By 2015, all wind turbine systems must be tested and certified by qualified organisations. Current IEC standards used in China will be amended to be suitable for China's wind and environment constraints. As manufacturing of new, larger wind turbines progresses, product quality standards need to be upgraded and renewed. In addition, relevant technical standards, design and certification guidelines should be made to match the standards. Detailed implementation methods will be provided for wind power manufacturing, R&D and certification activities. A national wind power equipment testing and certification centre should be established. Whole system and critical component mandatory testing and certification should be enforced gradually.

Research, development and demonstration support

This roadmap recommends the following actions:	Milestones
Establish national wind power technology and innovation system	2015
Improve wind power training programmes	Through 2015

Supporting technology progress to continuously reduce cost

R&D and innovation capabilities will be critical success factors for wind power technology upgrading. Through establishment of a national wind energy technology R&D centre and integration of resources, basic energy research and common technology research should be carried out to solve some technical difficulties faced by Chinese manufacturers. The comprehensive research results will help strengthen co-operation among wind energy developers, manufacturers, project technical service providers and grid enterprises. The best efforts of national basic research institute and business application research organisations should be integrated to provide technical support for innovations for the whole wind power industry. To this end, the following activities shall be carried out:

(1) a national wind power technology and innovation system should be established by the end of 2015. Basic research and common technical service capabilities should be improved. The focus should be on a common testing platform and certification service for blades, mechanical systems and other wind power components. Experimental wind farms will be developed at Xinjiang Dabancheng, Inner Mongolia, and southeastern China's coastal areas to provide testing and certification service support for wind turbine systems and wind power connection to the power grid. Government financial support, stock share and power sales approaches can be used. The international practice of "national investment and site rental" can also be used for service operation.

(2) before 2020, an improved wind power industrial service system should be established, to provide a comprehensive technical consulting, strategic research, transportation and installation, operation and maintenance, and testing and certification service for scaled development of the wind power industry in China.

(3) R&D activities should be encouraged through incentives such as renewable energy development funds and national technology programmes. For example, the support could be provided to R&D on advanced large-capacity wind turbine systems and low-speed turbine systems, wind farm output forecast and prediction, energy storage technologies, smart access to power grids, distributed power generation, end-user technologies (such as electric vehicle charging facilities), and wind farm environmental impact assessment methods.

Improving wind power training programmes

China should accelerate its wind energy training programmes. By using national R&D capacities, public experiment facilities, and testing and certification capacity-building programmes, training capabilities in technical consulting and industrial service should be strengthened.

The government of China should increase its support for human resource development and institutional capacity-building activities. Personnel training and selection mechanisms should be improved to develop an adequate number of much-needed wind power industry professionals and senior R&D experts. Wind power curricula should be developed at key educational institutions to offer professional wind power training programmes under the national education system.

A group of universities with sound science foundations and strong research and teaching abilities should be chosen to establish wind power curricula for master's and PhD courses. Post-doctoral programmes should also be developed. Joint training programmes should be encouraged between universities and enterprises. Internships and post-doctoral positions should be encouraged at companies. Visiting scholar and overseas study programmes should include wind power. Universities, research institutes and enterprises should be encouraged to attract talented people returning from overseas.

Conclusions: Roadmap Action Plan

This section summarises the actions needed to achieve the objectives proposed by the roadmap. Implementation organisations include government agencies, the wind power industry and power system actors. The public should also be involved in implementation. Some aspects of the action plan should be jointly implemented, so co-ordination between the wind power industry, government and the power system is vital.

Actions led by governments

Government agencies include central and local government departments. Their major tasks are establishing and implementing incentive policies, developing national and local projects, co-ordinating stakeholder relations, and promoting international collaboration to overcome obstacles to large-scale wind power development, to encourage diversified and integrated wind power and power system development.

R&D	***Milestones and participants***
Increase support for wind power technology R&D efforts. Set up renewable energy development fund to support R&D on key technologies of wind power and common technical service platform, including experimental wind farm and testing platform, as well as standards and certification activities.	By 2015, improved technology R&D and common service platform will be established. By 2020, effectively co-ordinated R&D capacity should be established. Implementation organisations include NEA, MOF, MOST, National RE center, testing and certification organisations.
Training and employment	***Milestones and participants***
Wind power specialty and curricula shall be provided at universities, technical training programmes in industry will provide more job opportunities and capacity-building for technical personnel.	Complete by 2015. NEA and national education and employment departments.
Market incentives	***Milestones and participants***
National demonstration projects of advanced wind power technologies, designs, and commercial applications.	Sustained progress of stages. NEA, MOF, and MOST.
Improve pricing system for wind power development, including grid access, integration and transmission. Develop scaled wind power market.	Complete by 2020. NEA and price department.
Power system reform	***Milestones and participants***
Actively promote power system reform for a competitive and fair power market. Optimise power resource dispatching for an equal service. Wind power integration with power system.	Progress by 2015, and complete by 2020. NEA and Electric Power Regulatory Commission.
Public participation	***Milestones and participants***
Outreach programme of wind power technologies and social and environmental impact Series of RE Week programmes	Complete by 2015. NEA, etc.
Wind power planning and project management	***Milestones and participants***
Rolling plans for wind power development. Improved project management regulations and rules towards independent market investment decisions.	Sustained progress. NEA, etc.
International collaboration	***Milestones and participants***
International co-operation through international exchange, technical collaboration, mutual standard recognition, fair trade activities, to encourage global wind power development.	Framework complete by 2015. NEA, MOST, MOC, and Standardisation Department.

Actions led by the wind industry

Wind energy sector players include universities, national and enterprise wind power research institutes, wind power manufacturers, wind farm developers and operators, the wind energy association, and various wind power investor organisations.

Major objectives of the wind power sector players include wind power technology progress, promotion and applications, sufficient investment, and co-ordination to encourage large-scale wind power development in China.

Resource assessment	***Milestones and participants***
Enhance and improve wind resource assessment technical standards, measurement procedures, numerical computation and analysis regulations, and wind resource evaluation methods.	Progressing, complete by 2015. CMA and other research institutes.
Improve measurement and statistical analysis of local wind conditions and environment information (especially temperature, lightning, sand and dust, and frost).	Progressing, complete by 2015. CMA and other research institutes.
Offshore wind resource measurement and detailed investigation.	Not yet start, initial result by 2015 and complete by 2020. CMA and other research institutes.
Establish wind resource data sharing platform.	Complete by 2020. CMA and other research institutes.
Develop more accurate, long-term and variable scale wind power output forecast models.	Initial result by 2015 and complete by 2020. CMA, wind power developers and utility companies.

Technology development	***Milestones and participants***
Improve wind power technologies for 5 MW or larger wind turbine systems. Improve onshore wind farm development and O&M technologies. Advance offshore wind farm planning and construction techniques.	Complete an advanced technology system by 2015. Operation of 5 MW large wind turbine systems. Technologies of near offshore wind farm development mastered. By 2020, international advanced wind power technology system established for 10 MW wind turbine system demonstration. Near offshore wind technology matured. Demonstration of far offshore wind farm started by 2030. Wind power manufacturers, wind farm developers and wind power technical service providers.

Supply chain and supporting equipment	*Milestones and participants*
Develop series and models of wind power supply chain for different resource conditions, land forms, wind turbine system manufacturing, integrated into the global wind power supply chain.	Ongoing. By 2015 wind energy equipment supply chain completed, international advance level by 2020. Wind power equipment manufacturers.
Accelerate offshore wind manufacturing and installation capacity, *e.g.* port configurations, offshore installation and flexible offshore wind infrastructure.	Ongoing. Wind farm developer companies and service provider enterprises.
Public participation	***Milestones and participants***
Introduce wind power technologies and impact to public. Consult public during wind farm development. Improve public awareness of wind power.	Ongoing. Wind farm developer companies.

Actions led by power system actors

The power system includes power grid companies and electric power regulator organisations. Their key functions include integrating large-scale wind power into the power system, cost-effective power system operation and reducing the impact of fluctuating wind power generation.

Grid construction and transmission reliability	*Milestones and participants*
Construction of regional interconnected smart grids.	Complete by 2020. Power system operators and grid companies.
R&D of grid-consistent low-cost energy storage systems.	Complete by 2030. Power system operators and grid companies.
Power system and power market development	***Milestones and participants***
According to power system reforms, develop detailed regulations and technical procedures to ensure wind power grid access, power purchase, and wind power transmission.	Implement along with power system reform process Grid companies at all levels.

Next Steps

This roadmap describes a perspective for development of wind power in China based on the fast growth of recent years. It also describes the efforts that will be required in terms of resources, technology, industry and policies to reach the proposed objectives and targets. The roadmap is intended for government decision makers, research institutes, wind power enterprises and investor organisations.

Along with continuous improvement of wind energy technologies, industrial growth and policy making and implementation, this roadmap should be further improved and progress on the roadmap closely monitored. Implementation and close monitoring of progress against the roadmap goals will help encourage sustainable large-scale development of wind power in China.

Appendix: References, Acronyms and Abbreviations

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Acronyms and abbreviations

AVC	Automatic voltage control
AC	Alternating current
BAU	Business as usual scenario
CHP	Combined heat and power
CMA	China Meteorological Administration
CWEA	China Wind Energy Association
DC	Direct current
DFIG	Double fed induction generator
ERI	Energy Research Institute
EU	European Union
GIS	Geographical information system
GSC	Gross supply curve
HVDC	High-voltage direct current
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEJ	Institute of Energy Economics of Japan
IRR	Internal rate of return
LVRT	Low voltage ride through
MOC	Chinese Ministry of Commerce
MOF	Chinese Ministry of Finance
MOST	Chinese Ministry of Science and Technology
Mt	million tonnes
NDRC	National Development and Reform Committee
NEA	China National Energy Administration
O&M	Operation and Maintenance
PMG	Permanent magnet synchronous generator
R&D	Research & development
RD&D	Research development & deployment
RE	Renewable energy
tce	tonnes of coal equivalent
toe	tonnes of oil equivalent
UHV	Ultra-high-voltage
WERAS	Wind energy resources assessment and simulation

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