BBChina
Master Program on Bio-Based Circular Economy

Course of Renewable Energy Technologies

Variable Renewable Energy curtailment level in China

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Co-funded by the Erasmus+ Programme of the European Union

Summary

BBChina

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Chapter 1 Variable Renewable Energy curtailment level in China

With the deepening understanding of the concept of sustainable development and the increasing attention to energy security, ecological environment and other issues, reducing fossil energy consumption and promoting the development and utilization of renewable energy have been generally recognized by all countries in the world. As early as the end of the 19th century, Denmark began to use wind energy for power generation, but it was not until 1973 that there was a worldwide oil crisis. The concern about oil shortage and environmental pollution caused by fossil fuel power generation made all countries in the world realize the importance of using renewable energy for power generation[1]. In 2015, the new installed capacity of renewable energy power generation in the world exceeded that of conventional energy generation for the first time, indicating that the construction of global power system is undergoing structural transformation. However, due to the randomness and uncontrollability of renewable energy, such as wind energy and solar energy, even if the generating unit can work normally, the power station has to be shut down due to the mismatch between the generating capacity and the consumed power, resulting in the waste of resources. The phenomenon of energy curtailment has seriously restricted the development of renewable energy.

Sub C1-1 Current situation wind energy curtailment

Because of the randomness and uncertainty of wind speed, the active output of wind turbines is uncontrollable. This has become a major obstacle to the development of wind power generation. The wind farm output is also greatly affected by the climate, even in the case of separate power supply, its stability needs to be improved. After the wind farm is connected to the grid, it will bring a series of impacts on the power system. With the growth of the total installed capacity of wind power generation and the increase of wind power penetration rate, these factors have a great impact on the reliability, security, economy and other indicators of the power system.

Due to the imbalance of the supply and consumption of renewable energy in the space-time distribution and the improper control of the coordinated operation of various energy sources, the consumption of renewable energy in China has been greatly affected, and the problem of curtailment has appeared since 2010. The so-called "wind curtailment" refers to the phenomenon that the wind farm is forced to suspend some wind turbine generators due to problems such as grid consumption under the condition of normal wind turbine equipment and good wind conditions[2]. From the data analysis, in recent years, the situation of wind curtailment in China has been good or bad, and the specific situation is shown in Figure 1.1[2]. In 2011, the national average wind curtailment rate reached 16%, with 12.3 billion kWh of electricity loss, equivalent to 6.6 billion RMB of electricity loss. In 2012, the wind power loss in China reached 20.8 billion kWh, and the wind curtailment rate reached a record high of 17%; in 2013-2014, under the active intervention of the government, the wind curtailment situation improved for a while, but in 2016, after the "rush to install" of wind turbine units in 2015 and the lag of superimposed grid construction, the average wind curtailment rate in China reached a historical high of 17%, again, compared with 2016 that of last year, it increased by 2%, and the wind energy consumption reached the highest value of 49 billion kwh in recent years.

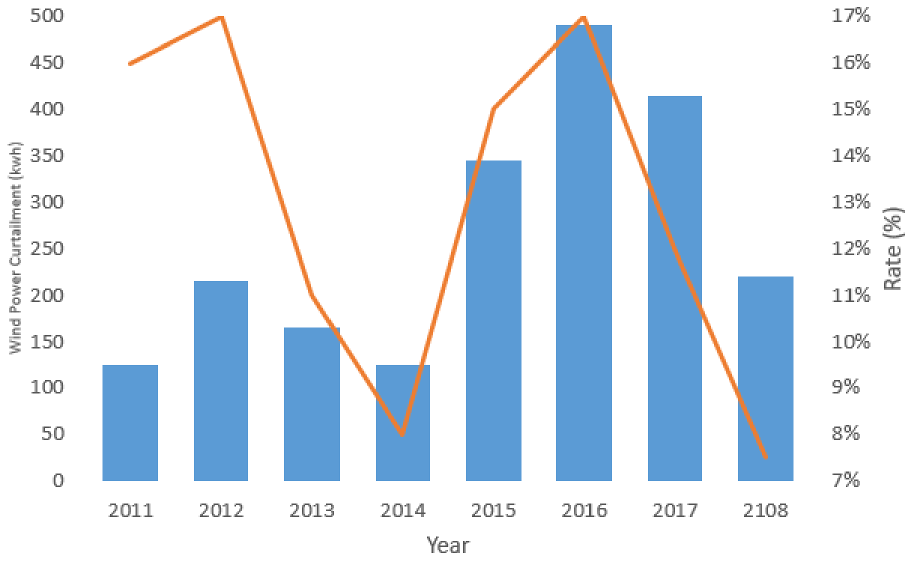

Fig. 1.1 The curtailment of wind power and curtailentment rate

in 2011-2018(first three quarters)

As far as the phenomenon of wind curtailment is concerned, the northern region is the place where the phenomenon of wind curtailment occurs most in China. The statistics of the average wind curtailment rate of key provinces in China in 2011-2014 and in the first half of 2015 are shown in Figure 1.2[3]. From figure 1.2, the top three provinces with the highest average wind curtailment rate in 2011-2014 are Inner Mongolia, Jilin and Gansu, with the average wind curtailment rates of 22.70%, 22.51% and 20.31% respectively. In the first three quarters of 2018, China's wind energy consumption was 22.2 billion kwh, while the total wind energy consumption in the northern region was 21.98 billion kwh, almost equal to the total wind energy consumption in the country. In addition, the average wind energy consumption rate in the northern region was 12.40%, far higher than the national average of 7.70%.

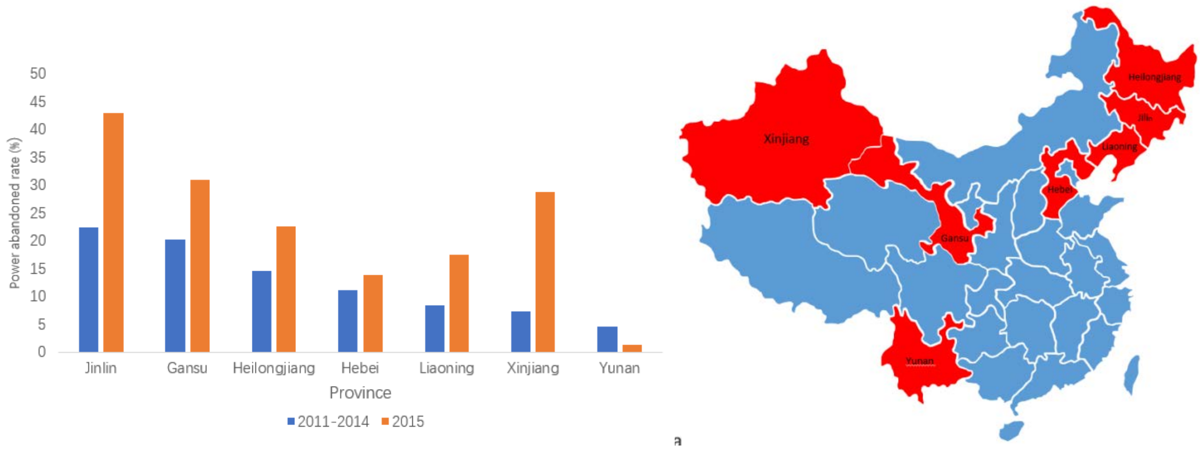

Fig.1.2 The statistics on wind power curtailment rate in

major provinces between 2011 and 2014 and 2015

According to the occurrence of wind curtailment in the northern region, the reasons can be summarized as follows: firstly, the wind energy resources and regional energy demand in the "Three North" area are inversely distributed, the local load level is not high, the economy is underdeveloped, the power consumption capacity is insufficient, and the wind power is far away from the southeast power consumption area, which makes the local consumption of wind power more difficult[4]; secondly, the wind power has a strong randomness, volatility and anti peak regulation make it more difficult for wind power to connect to the grid, which seriously affects the wind power consumption; thirdly, most of the "Three North" areas are located in the high cold area, and the energy consumption structure is still dominated by coal, so it is necessary to provide heat in winter to ensure people's normal life[5]. Because of the demand of heating in winter, the proportion of thermoelectric units in the northern region is too heavy, and there is a very serious phenomenon that thermoelectric units can not be decoupled. Therefore, in order to meet the demand of people for heating temperature, thermoelectric units must operate according to the demand of heat load, which will cause the serious shortage of peak regulation capacity of the system during the heating period in winter to ensure the balance of the active power between heating and power grid, a lot of wind has to be curtailed. Finally, the development speed of wind power is faster than that of power grid construction. At the same time, the power management system is not conducive to the development of wind power.

In 2017, the state began to vigorously rectify and improve the problem of wind curtailment, with considerable improvement results, realizing "double reduction" of wind curtailment power and wind curtailment rate. In 2018, the state increased its efforts to improve. In the first three quarters of the country, the wind energy consumption was 22.2 billion kw·h, a year-on-year decrease of 7.4 billion kwh, and the wind curtailment rate was 7.70%, a year-on-year decrease of 25%. Among them, the wind curtailment rate in Gansu Province decreased by more than 20 percentage points, that in Xinjiang and Jilin Province by more than 10 percentage points, and that in Heilongjiang Province by more than 5 percentage points[2]. Compared with 2017, the situation of wind curtailment continues to improve, but the wind curtailment rate is still at a high level. There is still a certain gap from the goal of reducing the wind curtailment rate to 5% proposed by the State Grid in 2020[6]. The phenomenon of wind curtailment is still serious, the form is still severe, and there is still a long way to go to solve the problem of wind curtailment.

Sub C1-2 Current situation solar energy curtailment

Since 2012, China's photovoltaic installed capacity began to grow rapidly, and by 2014, the problem of absorption caused by this high-speed growth began to appear, and the problem of solar electricity curtailment attracted the attention of the whole society. According to the "Information of Photovoltaic Power Generation Construction in 2015" issued by the National Energy Administration, from January to September in 2015[7], China's cumulative photovoltaic power generation was 30.6 billion kw•h, with a solar electricity curtailment rate of 10%. Solar electricity curtailment mainly occurred in Gansu and Xinjiang province. Among them, 1.76 billion kw•h in Gansu, 28% in solar electricity curtailment rate, 1.04 billion kw•h in Xinjiang, 20% in solar electricity curtailment rate. After wind power is curtailed, solar electricity generation in China is also in a dilemma of curtailment[3].

Chapter 2 The current situation of Unbalanced power grid in China

Sub C2-1 Imbalance of power generation and electricity consumption in the eastern and western regions

Electric power is one of the most important basic industries for the development of national economy. Coal-fired power generation, as the most important type of power source since the founding of the People's Republic of China, has played an irreplaceable role. Meanwhile, due to China's energy structure and other conditions, it will also exist in the power system for a long time to come. Before 2006, China's power supply structure has been dominated by coal power, hydropower, and other types of power supply as an effective supplement. After the reform and opening up, China's electric power industry develops rapidly, and the installed power supply growed rapidly. The rapid economic growth has led to the continuous growth of electricity demand. Compared with the installed capacity, the average generating hours of equipment have been maintained at a relatively high level except for the decline around 1998. (In 1998, When China was relatively rich in electric power, the relevant government departments proposed that conventional thermal power should not be started for three years in 1999.) Since 2006, with the improvement of technology level and the enhancement of energy conservation and environmental protection awareness and requirements, new energy, clean energy, especially non-hydro renewable energy, has shown an exponential growth trend, and China's power supply structure has gradually changed greatly. From 2006 to 2016, the proportion of installed coal-fired power generation (including thermal power) in China fell by about 15%.

There is a big difference between the electricity generation and electricity consumption in the eastern and western regions of China. The eastern region is located in the coastal region with convenient transportation and developed economy, so the electricity consumption is relatively large. And the western region is more isolated, so its economy is poor, electricity consumption is not as good as the eastern region.

With the change of power installation ratio and energy demand, the electric power industry is quietly stepping into another new stage from the original steady state. The past decade (2010-2020) can be regarded as the transient process of the development of the power system, especially the power generation industry. With the gradual advancement of this process, the new roles played by various power sources are gradually changing [8].

Sub C2-2 Unbalanced transmission lines in the eastern and western regions of China's power grid

China is a vast country with long power transmission lines, high costs and high losses. There has been a lack of emphasis on renewable energy, and coal-fired power networks are better than wind and hydropower. The "West-to-East power transmission" policy implemented as early as the tenth five-year Plan has effectively alleviated the uneven situation of the power grid in the eastern and western regions, while the problem of the power grid dispatch of renewable energy cannot be underestimated. From the perspective of the "wind curtailment" and "solar curtailment" policies in recent years, the power loss caused by power saturation is largely due to the shortage of transmission lines, that is, the uneven degree of the national grid. The scheduling problem of State Grid has indeed brought many problems to the development of renewable energy.

Uneven transportation lines, not just between the east and the west, but also between renewable and fossil fuels. It will also have a big impact on the power electricity curtailment in China, so developing a "smart grid" is an effective measure. In fact, smart grid has been positioned as the goal and direction of grid development in China. In May 2009, State Grid Corporation of China proposed a development plan named "Strong smart grid" at the "2009 UHV Transmission Technology International Conference".

What is smart grid? State Grid China Electric Power Research Institute puts forward: " Based on the physical power grid, a new type of power grid is formed by highly integrating modern advanced sensor measurement technology, communication technology, information technology, computer technology and control technology with the physical power grid. It aims to fully meet the needs of users for power and optimize the allocation of resources, ensure the safety, reliability and economy of power supply, meet environmental protection constraints, ensure the quality of power, and adapt to the development of electricity market, so as to realize reliable, economic, clean and interactive power supply and value-added services for users."

For renewable energy, the traditional grid is difficult to access, and smart grid will change this situation. Smart grid will simplify the access process of renewable energy generation to the grid, and make all kinds of power generation and energy storage systems easy to access through improved interconnection standards.

Sub C2-3 Unbalanced China's power energy structure

Coal power still occupies the absolute dominant position of total power generation. China's surplus of coal and electricity is absolute, while its surplus of renewable energy is relative.[8] . Why is the surplus of coal and electricity absolute? Because, according to the general trend of the energy revolution, coal power should have been reduced and gradually withdrawn from the stage of history. However, due to a variety of reasons, China's coal power has developed rapidly, resulting in the structural deterioration of the entire power industry and overcapacity. The reason why renewable energy is a relative surplus is that the whole world is facing the serious threat of gradual depletion of fossil energy resources and excessive greenhouse gas emissions. If human society wants to achieve sustainable development, energy transition must be realized as soon as possible. So, from a macro and logical point of view, as long as we have to rely on and use fossil energy, there is no real surplus of renewable energy. From the point of causality, the absolute excess of coal power is the root cause of the excess capacity in the power industry, while the relative excess of renewable energy is a harmful consequence of the serious excess capacity in the power industry.

Fig.2.1 Coal power construction risk early warning

On April 15, 2016, the National Energy Administration issued the Notice on Promoting the Orderly Development of China's Coal power Generation (CAE) and the Development and Reform of Energy [2016] No. 565, which proposed to "establish the early-warning mechanism of coal power generation planning and construction", and released 33 provincial-level electricity in the next three years. Warning signals of coal power construction risks in the network area (including Eastern Mengxi And northern and southern Hebei).

The index system of coal power planning and construction risk warning mechanism is composed of three parts: coal power construction economy warning index, coal power installation abundance warning index and resource constraint index. The final risk warning rating is determined by the highest rating of the three indicators, with red, orange and green warning levels from high to low. Only Jiangxi, Anhui and Hainan are green, Hubei is orange and all other provinces are on red alert.

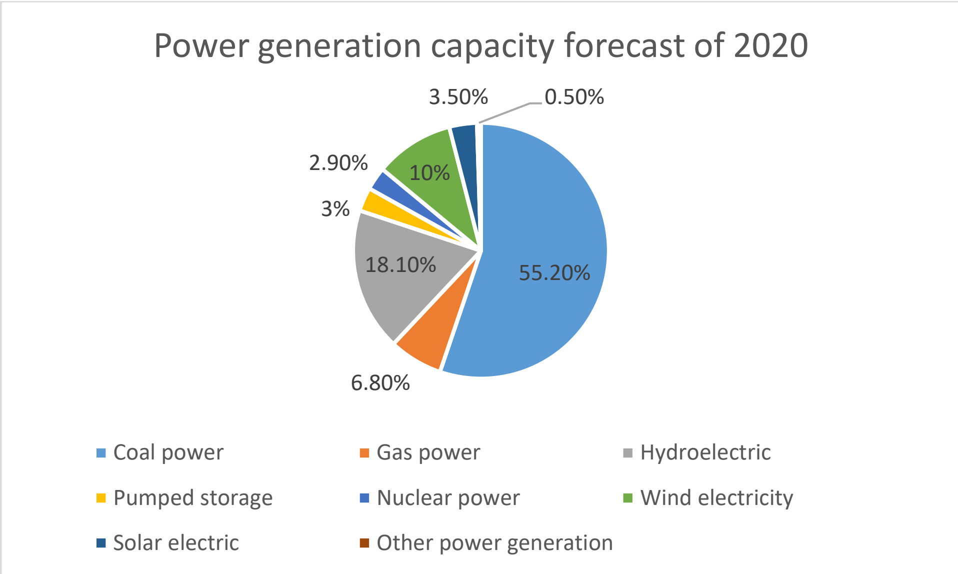

Fig.2.2 Power generation capacity forecast of 2020[9]

Fig.2.2 Power generation capacity forecast of 2020

From the point of view of the way to solve the problem, the development and construction of coal power must be strictly controlled, and create conditions to gradually make it out of the historical stage. In the long run, renewable energy must be developed vigorously and actively in spite of the need to slow down the speed of renewable energy in order to avoid greater harm to our development caused by increasing overcapacity. China's promulgated "13th Five-Year" electric power development plan also runs through and embodies such a spirit of principle[10]. During the 13th Five-Year Plan period, the development of coal power has been slowed down to a weak degree, which makes China's power development more polarized. Objectively speaking, coal power has always dominated the power industry's discourse power, so far, the fastest growth rate of China's power production capacity over the years has been coal power. Although China has always been determined to optimize the energy structure in the process of development, the optimization of China's energy structure has always been relative (and the deterioration has always been absolute). Including the 13th Five-Year Plan, China's energy structure can only be said to have slowed down the trend of deterioration, far from a real transformation [11].

For renewable energy, the growth rate is very slow compared with the 200 Gwh coal generated during the 13th five-year Plan period (only hydro, wind and solar have 43 Gwh, 79 Gwh). If we estimate the operating hours of various power sources (hydropower 4000 h, wind 2000 h, solar 1800 h), the total renewable energy production is increased by 452.4 TWh during the 13th Five-Year Plan period, which is not only much less than coal power, but also much less than the previous 12th Five-Year Plan period. While the designed operation hours of coal power can normally reach 5500 hours, the actual increase of coal power capacity in the 13th five-year plan can reach up to 1.1 trillion Kwh. In other words, during the 13th Five-Year Plan period, China's new coal-fired power capacity will account for 243% of all renewable energy growth. That's assuming we can successfully cut 150 million coal-fired power plants. Without the control of 150 million coal power generation, China's coal power capacity growth during the 13th Five-Year plan period will be 425% of that of renewable energy.

Sub C2-4 Summary

From high carbon to low carbon, then to no carbon is the inevitable logic of China's energy regulation development. The technological path of China's energy transformation has long been very clear. In the early stage, hydropower and nuclear power (high-density energy sources, etc.) are mainly used to replace coal power; in the later stage, low-density wind power and photovoltaic power are mainly used with the progress of technology. Although serious reasons for hydroenergy, wind and solar curtailment include the construction of renewable energy projects, line matching and power grid dispatch, the most fundamental problem is that the power market is crowded out by the expansion of coal power without control [12, 13]. Take into consideration Jiangxi province, which was originally planned by the state, as an example. Jiangxi province, insisting on its own coal power, has steadily refused to accept hydropower from the west. Without the guarantee of landing in the market, line matching, engineering construction, including power grid dispatching have become "castles in the air". Until now, has been written into the 13th five-year plan in the construction of DC power grid, is still a "pending case". Of course, it is understandable that local governments want to rely on coal power to drive the economy, and the energy revolution and the electric transformation depends on the development of renewable energy to replace coal power. How to deal with the contradiction between them in reality is really a very difficult problem.

Chapter 3 Improving measures for China's power grid imbalance

At present, the growth rate of electricity consumption in the whole society of China is slowing down, and the development of electricity has not yet gone out of the traditional growth mode of high input, high consumption, and low efficiency. It is urgent to solve the problems of uncoordinated structure and unbalanced development[14]. The key is to adopt Resource allocation and technological progress to improve total factor productivity

Take into account the construction of Liuzhou Power Grid in Guangxi, China as an example[15]. Prior to 2009, the layout of Liuzhou Power Grid can be described as "stressing the south to the north". Liuzhou Power Grid has six 220 kV substations in Yeling, Liubei, Yangliu, Liantang, Jinglan and Yueshan, and all of the six substations are located in and around Liuzhou City. In contrast, Sanjiang, Rongshui, and Rongan counties in the north, and Liucheng and Luzhai counties further south, do not have a 220-kV substation. The unbalanced power grid structure can be seen. A powerful power grid must first be a reasonable power grid. Liuzhou Power Supply Bureau deeply realizes that the weak northern power grid is a "short board" of the entire Liuzhou power grid, so it has increased the construction of the northern power grid. On August 6, 2009, the first 220-kV substation in the three northern counties, Rong'an Substation, was put into operation, which greatly improved the problem of uneven distribution of the power grid.

China's power load is mainly distributed in the eastern region, and the main power resources, such as coal, hydropower, and wind energy, are mainly distributed in the western and northern regions. The reverse distribution of power load and power resources has created the necessity of China's cross-regional resource optimization. Based on the distribution status of China's power resources and the development trend of industrial structure adjustment, the center of energy production will be further shifted to the west and north, but the power load center will remain in the central and eastern regions for a long time, and the scale and distance of energy flow may further increase. From the perspective of transportation media, the cross-regional balance of power mainly includes two modes of coal transportation and power transportation. At this stage, the cross-regional allocation of China's power resources is still dominated by coal transportation. However, with the development of long-distance transportation technology, the proportion of power transportation is gradually expanding. The advantages and disadvantages of the coal transportation mode and the transportation mode are mutual benefits. Factors such as price and pollution. However, coal and power transportation are not a zero-sum relationship, and it is not necessary to choose one from the other. Coal transportation mode will remain an important way to optimize the cross-regional energy allocation in the country for a long period of time, and the power transportation mode can expand the efficiency of clean energy use in the western region and reduce pollution emissions in power receiving areas. It is an effective supplement to relieve coal transportation pressure. With the development of long-distance transportation technology, the proportion of transportation will gradually increase. All in all, coal and power transportation are complementary organic wholes. Only by coordinating the development of coal and power transportation can China effectively resolve the contradiction between the reverse distribution of energy and load in China. China is committed to building cross-regional transportation channels, strengthening the interregional power grid structure, optimizing the level of clean energy utilization through interregional power generation replacement, and alleviating the pressure of power generation and discharge in the receiving area[16] .

China's electricity production is dominated by thermal power, and there is a large difference between the electricity production structure and developed countries. Compared with more developed countries, China's electricity production structure is dominated by hydropower and coal power, with a relatively low proportion of clean energy generation. With the continuous depletion of fossil energy, rising mining costs, and increasing pressure on international environmental protection, the proportion of nuclear power and renewable energy generation (not considering hydropower) in China's power production structure will definitely further increase, and the proportion of coal power will decline in recent years. With the increase in coal prices and transportation costs, as well as the maturity of the power grid technology, the power grid architecture and transportation capacity have been greatly improved, and the economic transportation distance has been greatly improved. Considering safety, environment, economy, technology, people's livelihood, land resources, etc., large-scale power plants are established in coal-rich areas, and large energy bases are gradually moved westward and northward, farther away from load centers. For a long period of time, the construction and operation of China's power grid, large-capacity, long-distance transportation is imperative. Strengthen the construction of long-distance transportation facilities; vigorously develop electric vehicles to reduce exhaust emissions; strengthen energy cooperation with neighbouring countries, and vigorously develop electricity imports. These measures will optimize China's energy structure, save energy and reduce emissions, ease environmental pressures, and promote social and economic sustainability. Development is of great significance[17] .

Hydropower and nuclear power have always played a major role in the adjustment of China's power structure. The "13th Five-Year Plan" still needs to speed up development, especially nuclear power, to maintain a certain scale of construction during the "13th Five-Year Plan" period, and lay a solid foundation for subsequent development. Due to insufficient construction of hydropower and nuclear power during the "Twelfth Five-Year Plan", it was difficult to achieve the original planned goals. In order to achieve the target of 15% non-fossil energy in 2020 and the medium and long-term carbon emission target, it is necessary to continuously increase the contribution of wind power and solar power. Judging from the current situation, wind power is mainly faced with the problem of dissipation caused by planning disconnection, insufficient flexible adjustment capacity, and lag in cross-regional transportation. The solutions for the "13th Five-Year Plan" mainly include:

1) Moderately adjust the development layout and increase The intensity of decentralized development in the central and eastern regions has been adjusted from the original planned 30 GW to more than 60 GW;

2) Increase the construction of power transportation channels in the "Three North" region to expand the scale and scope of grid interconnection; Peak shaving potential, speed up the construction of pumped storage power stations. The main problem of solar power generation is that large-scale power stations are mostly located at the end of the power grid, the network is weak, and it is difficult to deliver. However, the uncertainty of distributed photovoltaics' expected returns is large, and the civilian photovoltaic market is difficult to activate.

The solutions are as follows:

(1) Establish a distributed power penetration management mechanism for the distribution network and guide the rational deployment of distributed photovoltaics;

(2) Improve subsidy policies to increase the competitiveness of the domestic photovoltaic power generation market;

(3) Strengthen the adaptation to photovoltaic power generation The system's flexible adjustment of capacity building, etc. Among the goal of 100 GW of solar power generation in 2020, large-scale power plants and distributed photovoltaics are expected to account for 60% and 40%, respectively. After 2020, depending on resource conditions and technological progress, continue to vigorously promote the development of solar centralized power generation and distributed photovoltaic power generation[18] .

To improve the development efficiency of China's power grid industry and achieve balanced and coordinated development, we should pay attention to three aspects[19] :

(1) Cultivate the innovation awareness and innovation ability of power grid enterprises, further optimize and perfect the innovation incentive mechanism and technology risk investment mechanism, and increase the R&D investment in core technology and key equipment, make full use of international and domestic scientific and technological

resources, and strive to promote scientific and technological progress in China's power grid industry.

(2) Pay attention to the transformation of scientific and technological achievements, accelerate the promotion and application of new technologies, new equipment and new strategies in the development of power grids, and continue to increase the technological progress of power grid companies.

(3) Combining regional development plans and carrying out grid investment according to local conditions, provinces, cities and regions should allocate resources reasonably according to the current status of grid development and their own characteristics, strengthen regional cooperation, focus on technological innovation, and promote the balanced development of inter-provincial and cross-region power grids. Continue to narrow regional gaps and achieve common progress.

Chapter 4 A solution to minimise the curtailment by using the electricity-based hydrogen

The wind energy offers lower marginal costs compared to fossil-based energy in the electricity market, while the dispatching dynamic can cause curtailment of wind energy because the intermittency of wind profiles, inconsistency with electricity load profiles, transmission congestions, and geographically sparse installment of wind turbines that tends to be far from the demand centers[20]

To overcome these challenges, there are several approaches to stabilize the electric grid, such as using dispatchable generator capacity, building transmission lines, introducing time-of-use prices for demand response, incorporating energy storage systems in the electric grid, and using excess electricity for resource production, which includes desalination to produce water, and renewable hydrogen production using wind or solar energy [21, 22]. In this study, I want to propose the way of using the wind power to produce the hydrogen.

So the basic idea to reduce the curtailment of the wind energy is to store the energy in the form of hydrogen. Due to the different of the electricity and hydrogen price, the system can determine whether electricity should be used to produce hydrogen or be sold to the grid.

Sub C4-1 Wind Power Coupling with Hydrogen-Production System

In this part, we perform an economic analysis on an on-grid wind power coupling hydrogen-production system.

4.1.1 Capacity design of electrolysis water hydrogen plant

For the wind-electricity coupled hydrogen production system, the production capacity of the hydrogen production plant should be determined first. We assume that the capacity of the electrolysis plant is a percentage of the nominal installed capacity of the generator (kW), expressed as f_{wf}, then the production capacity of the electrolysis plant P_{ELY} (based on the digested wind capacity) is calculated as followed.

$$P_{ELY} = f_{wf} \cdot P_{wf} \qquad (4.1)$$

The P_{wf} is the Wind power installed capacity.

4.1.2 Revenue analysis of wind power coupled hydrogen production system

The revenue from wind-power coupled hydrogen production system includes three parts: H_2 sales revenue, the reduction in the cost of adjusting the grid frequency due to the implementation of the wind hydrogen strategy, and the carbon emission reduction benefits from the use of renewable energy[23].

Capacity design of electrolysis water hydrogen plant

$$\mathrm{RS_t} = P_t \bullet Q_t \quad (4.2)$$

Assuming that the price of H_2 changes with the change in inflation rate in different years, RS_t represents the profit from selling H_2 in year; P_t represents the unit price of H2 in year; Q_t represents the sales volume of H_2 in year.

Increasing the grid-connected capacity of wind farms will cause deviations in system voltage and frequency, voltage fluctuations and voltage stability. In order to reduce the impact of wind farm power generation intermittently on the system, it is necessary to increase the rotating reserve capacity, thereby increasing the cost of grid frequency adjustment costs.

Hydrogen plants can use wind power that exceeds the capacity of the grid to electrolyze water to produce hydrogen when the wind power is in excess, thereby reducing wind power fluctuations incorporated into the grid and reducing the cost of adjusting the frequency of the grid.

The cost of grid frequency adjustment (without hydrogen plant):

$$\mathrm{CB_t} = 2 \cdot f_{ERR} \cdot CB_{XWH} \cdot E_{WT} \quad (4.3)$$

The cost of grid frequency adjustment (without hydrogen plant):

$$\mathrm{CB_t} = 2 \cdot f_{ERR} \cdot CB_{WH} \cdot (E_{WT} - E_W) \quad (4.4)$$

We substrate 3.3 and 3.4,we will get the reduced expenditure for adjusting the grid frequency is

$$\mathrm{CB_t} = 2 \cdot f_{ERR} \cdot CB_{XWH} \cdot E_{WT} \cdot [1-(CB_{WH} / CB_{XWH}) + (CB_{WH} / CB_{XWH}) \cdot (E_W / E_{WT})] \quad (4.5)$$

f_{ERR} represents the percentage change of actual wind energy generation relative to the estimated annual electricity generation of wind energy; CB_{XWH} represents the fluctuation of wind energy generation per unit (kW·h) when there is no hydrogen plant, and the annual increase in the expenditure for adjusting the grid frequency; CB_{WH} Represents the fluctuation of wind power generation per unit (kW·h) when there is a hydrogen plant. The annual increase in the cost of adjusting the frequency of the power grid; E_{WT} represents the total annual wind power generation; E_W represents the annual amount of wind power delivered to the hydrogen plant The amount of electricity for hydrogen production.

The benefits of carbon reduction

China's incentive policies for the use of new and renewable energy include subsidies for power generation and reductions in corporate value-added tax and consumption tax. For the wind power hydrogen production system, only the reduction and rebate obtained from the hydrogen production plant is considered as

$$RE_t = Q_{electronics} CTT_{electronics} \quad (4.6)$$

In the formula: $Q_{electronics}$ indicates that the amount of electricity annual wind power generation is used for hydrogen production ; $CTT_{electronics}$ indicates that the unit of electricity subsidies and tax relief.

4.1.3 Economic analysis

The cost of constructing a wind power hydrogen plant mainly includes capital expenditure (fixed asset investment), operating cost expenditure and variable cost expenditure in the process of hydrogen production.

(1) Capital expenditure mainly considers investment in fixed assets such as land and plant and investment in major equipment, and its annual amortization amount is recorded as CF_t

(2) The initial investment of the equipment is CCK0, and the equipment renewal expenditure is $CC_{Kt} - CC_{K0} \cdot FC_K$, CC_{Kt} is the cost for new equipment; FCK is the equipment residual value coefficient.

(3) The sum of operating costs is $C_{O\&M}$.

(4) The annual direct costs of a hydrogen plant include electrolysis, compression, storage, transportation, and water costs. According to the predicted annual hydrogen production of formula 3.1, it can be seen that the annual total direct cost of the hydrogen plant is

$$AP_t = CE \cdot E_{ELY} \cdot Q_t + CE \cdot E_C Q_t + MS \cdot CS + CT \cdot Q_t + CW \cdot Q_t f_{wa} \quad (3.7)$$

In the formula: CE is the price per unit of wind power; CW is the price per unit of water; E_{ELY} is the power consumption per unit of hydrogen produced by electrolysis equipment; E_C is the power consumed by the compressor compression unit H_2; f_{wa} is the production unit of the amount of water consumed by H_2, $f_{wa}>1$; CS is the annual operating cost of a storage unit; M_S is the number of storage units; CT is the labor and material cost of the transportation unit H_2.

(5) The tax payable by the project according to law mainly includes value-added tax, sales tax surcharge and income tax. The sum of the above three taxes is recorded as C_{total}.

Sub C4-2 Case Studies

In this paper, we take Zhangjiakou wind farm in Hebei province as an example, based on the comprehensive consideration of climatic conditions, market application and project economics.[5]

The total installed capacity of Zhangjiakou Wind Farm is 25 MW. According to historical statistics, the Actual hours of wind power utilization is 2324 hour, cumulative wind power on-grid for the whole year is 58 GWh. Assuming that the wind power used for hydrogen production is equivalent to 20% of the cumulative on-grid wind power for the whole year, it can be used for The amount of wind power for hydrogen production is 58 × 20%=11.6 GWh.

According to actual data, the energy consumption for producing 1 $m^3 H_2$ (standard state, the same below) is 4.5×1.1=4.95 kW·h. The coefficient 1.1 in the formula is due to the fact that the electrolysis equipment cannot always work at the rated power, resulting in the energy of the electrolysis equipment correction caused by reduced power consumption) to compress 1 $m^3 H_2$.

The average energy consumption of the compressor is 0.2 kW·h (according to the compressor output working pressure of 20 MPa), then the total energy consumption of the wind power producing 1 m^3H_2 is 5.15 kW·h. According to the effective hydrogen production wind power and unit hydrogen production energy consumption, the annual H_2 output of the hydrogen production plant is $11.6\times10^6/5.15$ = 2.25 million m^3. According to the H_2 sales price of USD 0.427/m3, it can be seen that the current annual H_2 sales income is about 964 thousand dollar.

The reduced power grid adjustment frequency expenditure is calculated according to formula, but at present, power companies still lack relevant data collection in China, so the RBt item in the case is calculated as 0.

The benefits of REt carbon emission reductions are subsidized electricity prices and tax incentives, which are calculated according to the following conditions:

(1) According to the "Zhejiang Provincial Price Notice on Wind Power on-grid Electricity Price" promulgated by the Zhejiang Provincial Price Bureau, there are 5 wind power plants according to USD 0.0014 - 0.0042/(kW·h) for subsidies, due to lack of relevant data in Shanghai, this article takes USD 0.0028/(kW·h) for calculation;

(2) Subsidies for tax incentives are in accordance with the new energy industry VAT halving policy, and income tax is implemented The preferential policy of "three exemptions and three reductions" means tax exemption for the first 3 years, halving for the next 3 years, and 25% tax rate after 6 years. The environmental benefit of the project is USD 532 thousand/year.

The reduced power grid adjustment frequency expenditure is calculated according to formula 3.5, but at present, Chinese power companies still lack relevant data collection, so the RBt item in the case is calculated as 0.

The benefits of REt carbon emission reductions are subsidized electricity prices and tax incentives, which are calculated according to the following conditions:

(1) According to the 0.02 dollar/(kW·h) for subsidies,

(2) Subsidies for tax incentives are in accordance with the policy of "three exemptions and three reductions" means tax exemption for the first 3 years, halving for the next 3 years, and 25% tax rate after 6 years. The environmental benefit of the project is USD 74,000 /year.

To build a hydrogen plant on the basis of an existing wind farm, due to the low requirements of the hydrogen plant's mechanical equipment for the plant, the initial cost of the hydrogen plant, constraction and supporting infrastructure is 700 thousand dollar.

According to the capacity of the electrolytic plant, the cost of electrolytic equipment, compression equipment, storage equipment and system integration is estimated to be 5.36 million dollar. Assume that the cost of CO&M (operation and maintenance) during the hydrogen plant is 10% of the equipment investment, that is, the annual operation and maintenance cost is 535 thousand dollar.

The total energy consumption for producing 1 m^3H_2 is 5.15 kW·h, the annual H_2 output of the hydrogen plant is 2.25 million m^3, and the price of wind power is calculated at USD 0.02/(kW·h), the annual electricity cost of the hydrogen plant is 700 thousand dollar.

On the other hand, the electricity price varies between day and night, in the daytime, the electricity fee is USD 0.098 / kWh, while in the night, the electricity fee is USD 0.The / kWh. As the results,the city can use the electricity at night to produce the hydrogen and sell the electricity by day[24].

In the entire process of producing, storing, and compressing hydrogen energy, the largest cost consumption comes from electricity bills. Therefore, changes in electricity costs

It is bound to significantly affect the economics of the entire project and will directly affect the investment analysis and decision-making of the project itself due to the electricity required for hydrogen production. By taking the curtailment of wind power with coupled hydrogen production, the electricity price is relatively high, which may be much higher than the on-grid electricity price of the thermal power unit at night. In actual operation, this part of wind power may also be provided to the hydrogen plant for free. When the unit electricity cost is less than USD 0.07 /(kW • h), the investment of the project will enter a profitable stage, and the electricity price is very sensitive to the profitability of the project.

The reason why I want to investigate the curtailment of the wind power coupled with the hydrogen is based on the research of some Japanese researcher. They put great enthusiasm in the hydrogen produced by the wind power. And with the development of the heat-electricity coupled device such as family fuel cell, they've take great efforts to make the idea of wind power coupled with the hydrogen generation work. I've also done some rough economic analysis on the same reasearch in Japan, the economic value of this project works better in Japan because the high electricity price (about USD 0.16 / kwh), as the result, the wind power coupled with hydrogen production is profitable in Japan. Because the time limitation, I've only done some rough calculation on the curtailment difference between the two countries, but this is an interesting idea that occurs to me and I want to share.

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Master Program
on Bio-Based Circular Economy

Course of Renewable Energy Technologies

Variable Renewable Energy curtailment level in China

Students: Zibo Zhao Hengzhao Wu Bowen Xu Jiaxu Pan

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Agreement number - 2017-2984/001-001 - Project reference number - 586083-EPP-1-2017-1-IT-EPPKA2-CBHE-JP

Variable Renewable Energy curtailment status

Reasons for Chinese grid unbalances and actions already adopted

Solutions to minimise the curtailment

Variable Renewable Energy curtailment status

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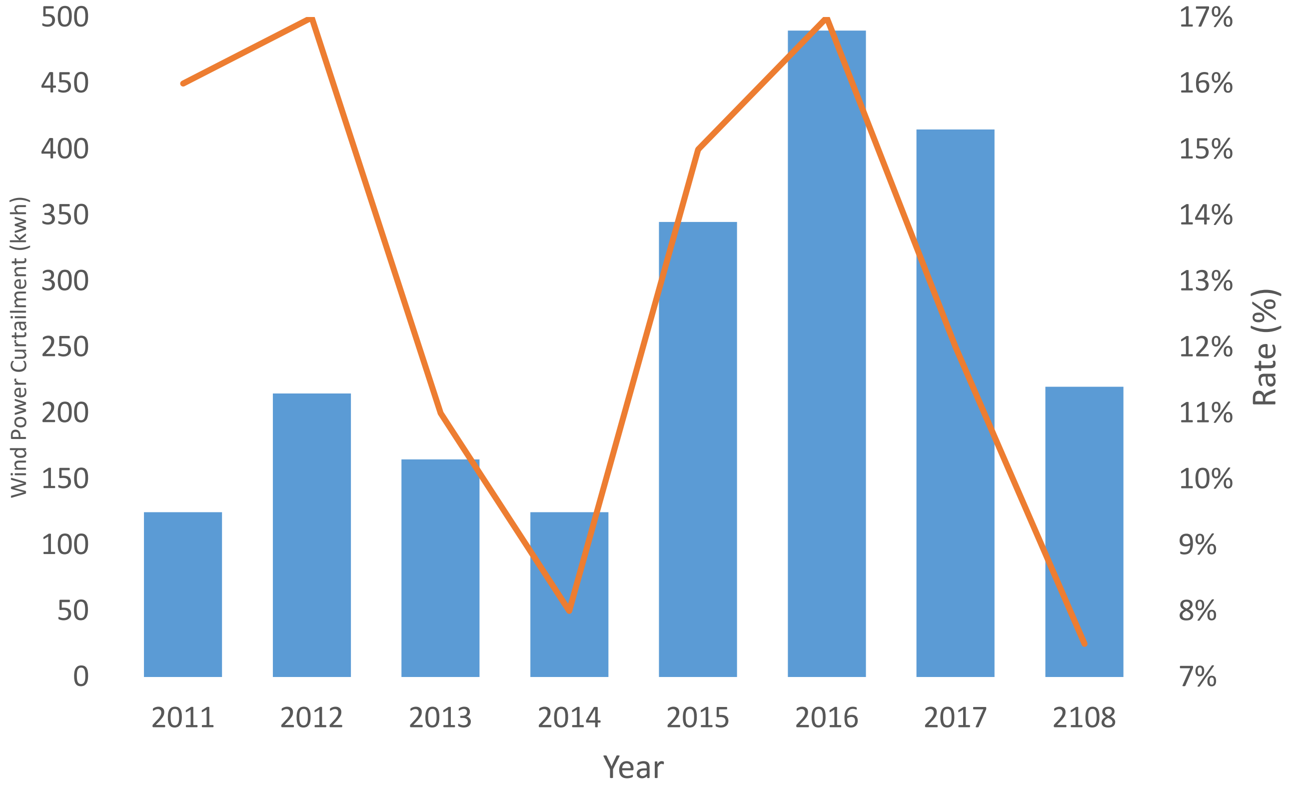
What is Energy curtailment

Energy curtailment refers to a phenomenon of wasting resources caused by the randomness and uncontrollability of renewable energy, especially to the wind and solar energy.

Current situation of Energy curtailment
Wind Energy



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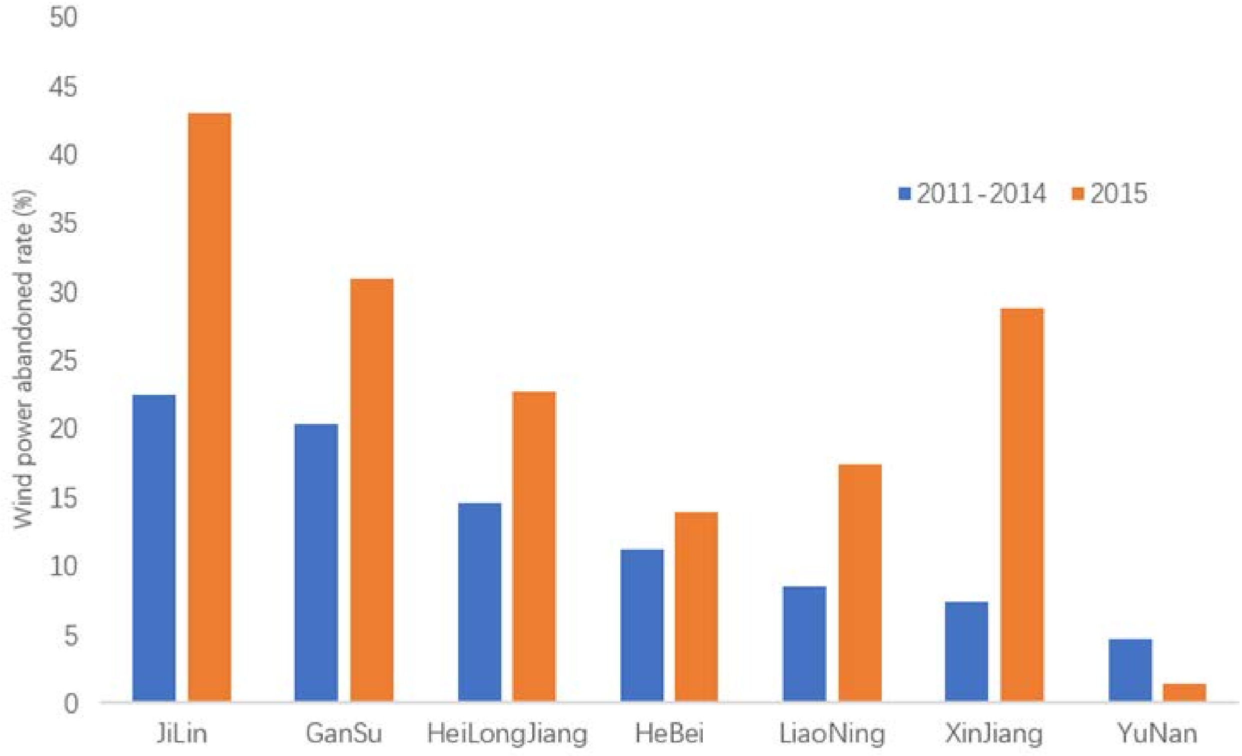
Current situation of Energy curtailment

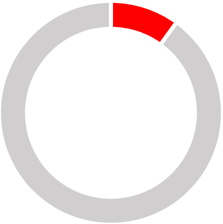
Wind Energy



Current situation of Energy curtailment
Solar Energy

From 2014

Total 3 billion kW·h



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Current situation of Energy curtailment

Solar Energy

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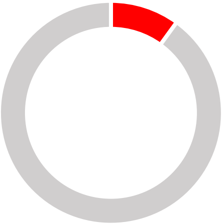
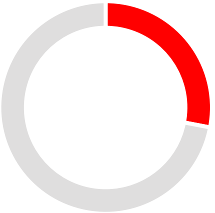
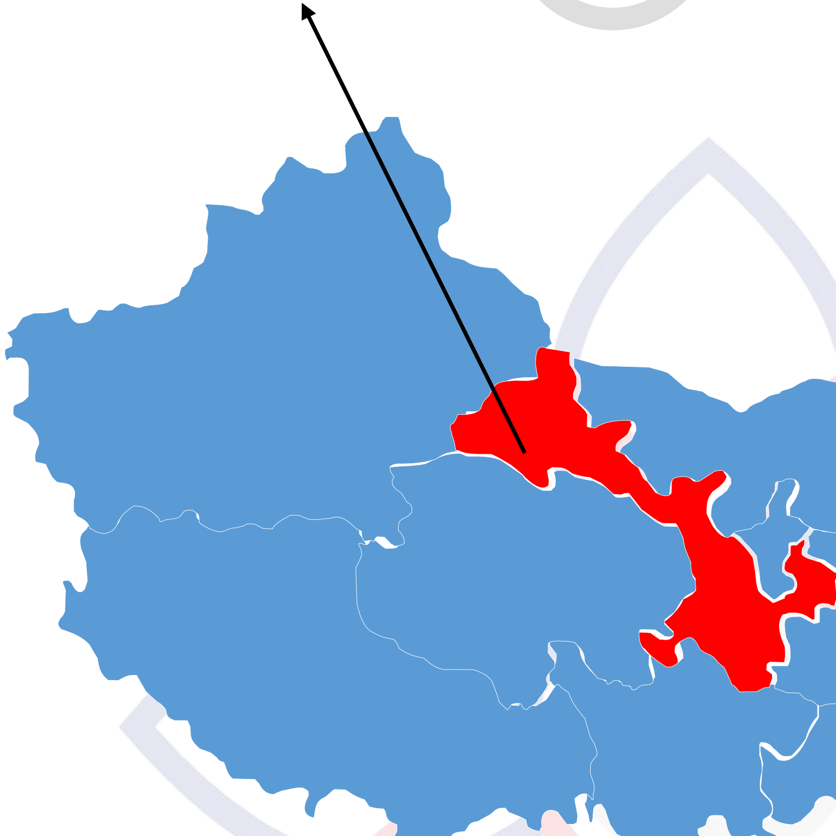
Total 3 billion kW·h



Gansu Province 17.6 billion kW·h





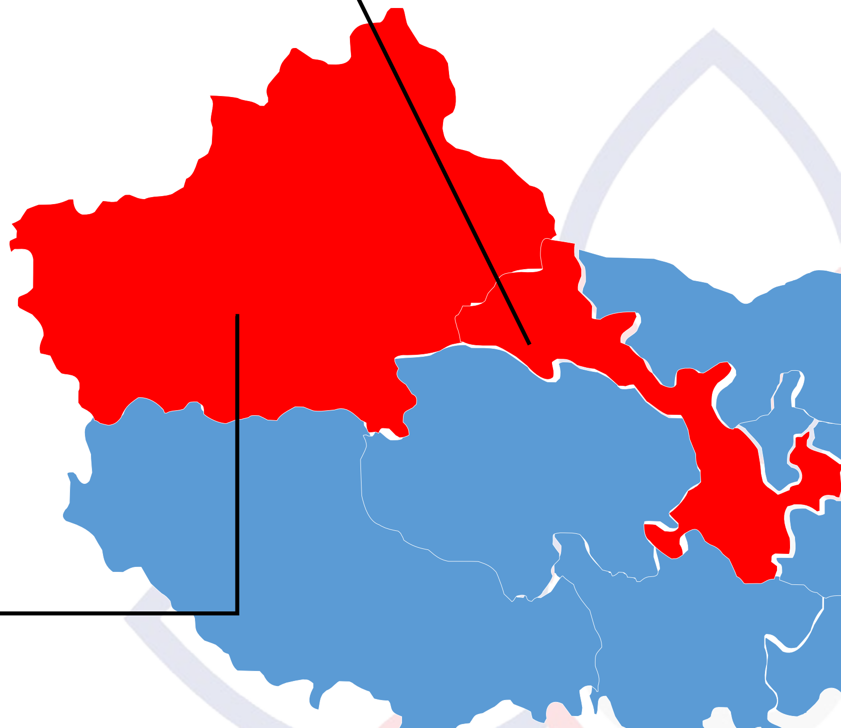
Current situation of Energy curtailment
Solar Energy

From 2014

Total 3 billion kW·h

Gansu Province 17.6 billion kW·h

Xinjiang Province 10.4 billion kW·h



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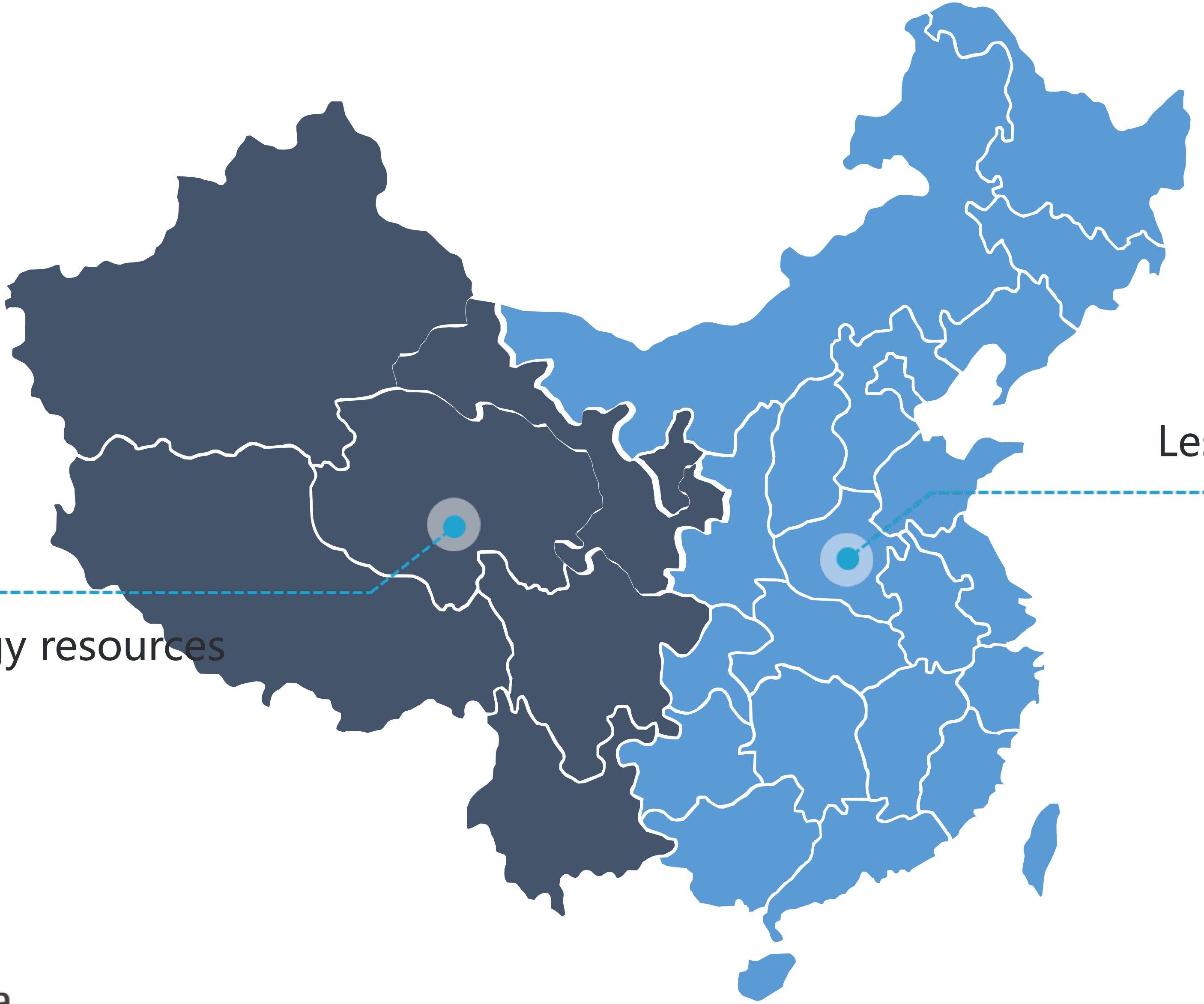
Reasons for Chinese grid unbalances and actions already adopted

1. Imbalance of power in the eastern and western regions
2. Unbalanced transportation lines in China's power grid
3. Unbalanced China's power energy structure

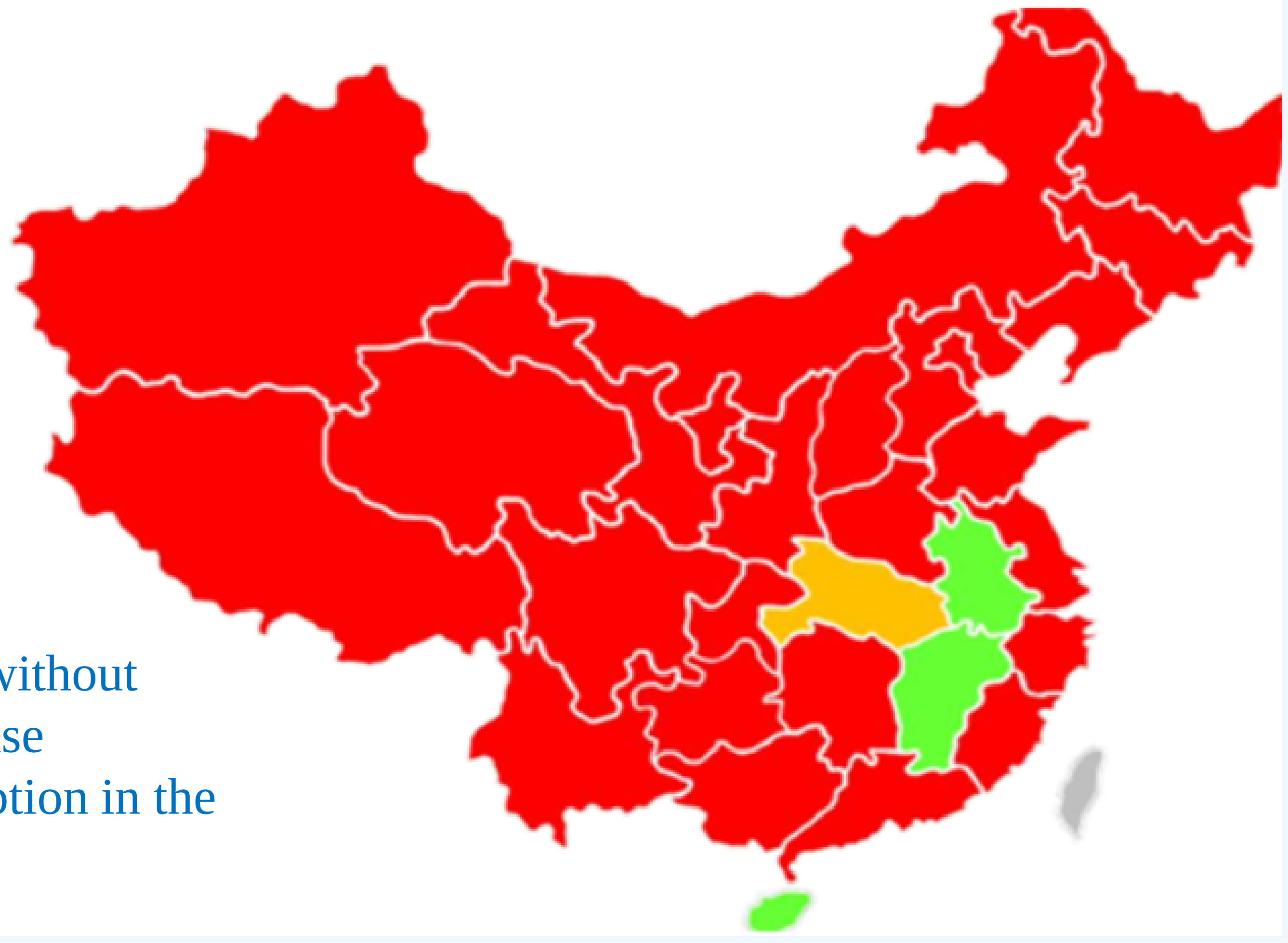
1. China has a vast territory and abundant resources unevenly distributed

Unbalance power grid in China



Unbalance power grid in China

Unbalance power grid in China



Electrify the west without electricity to increase electricity consumption in the west

Coal power construction risk early warning

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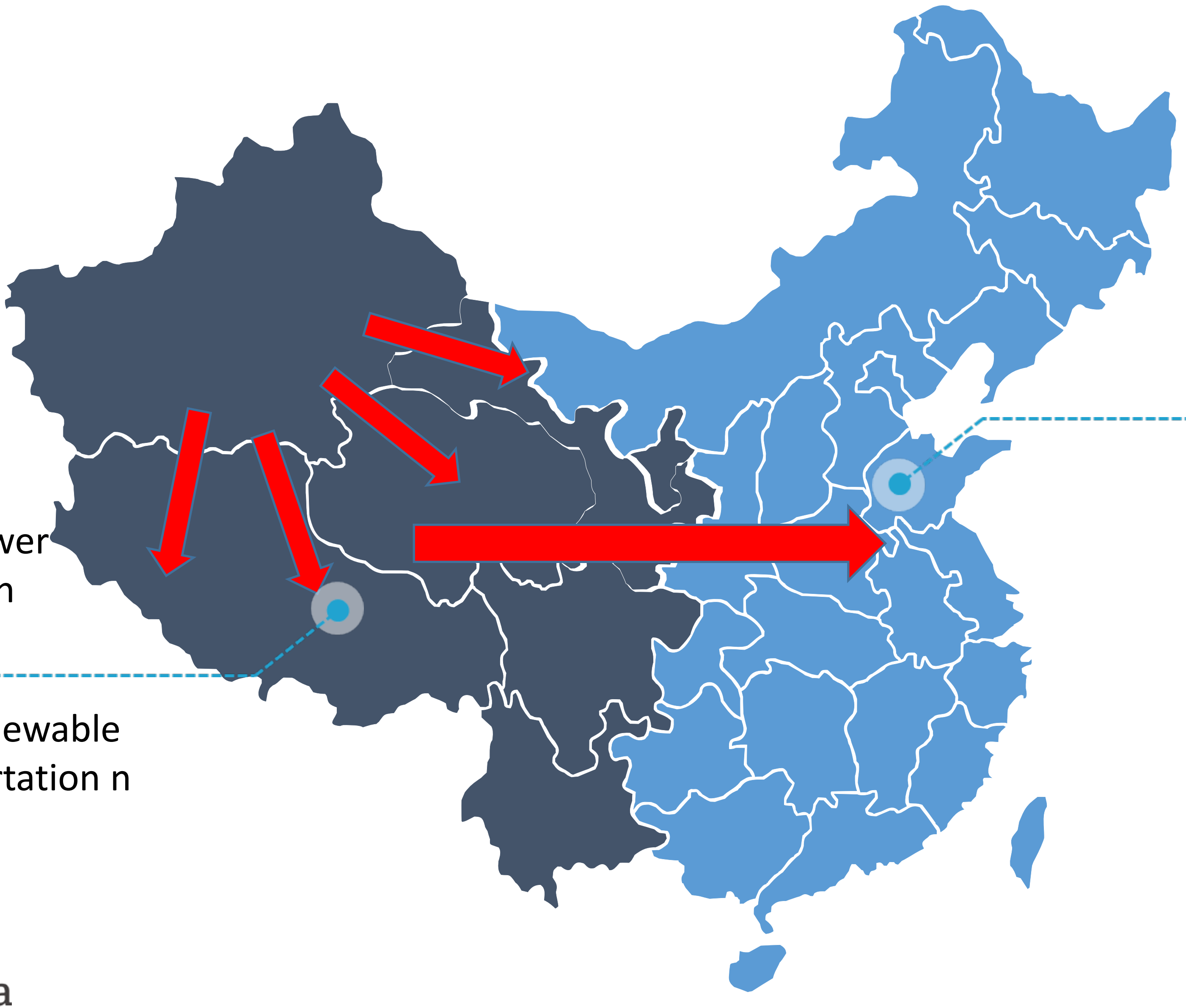
2. Unbalanced transportation lines in regions and resources

Unbalance power grid in China



Transmit the electricity from western areas to East China

Unbalanced power transportation in western region

Unbalanced renewable energy transportation n

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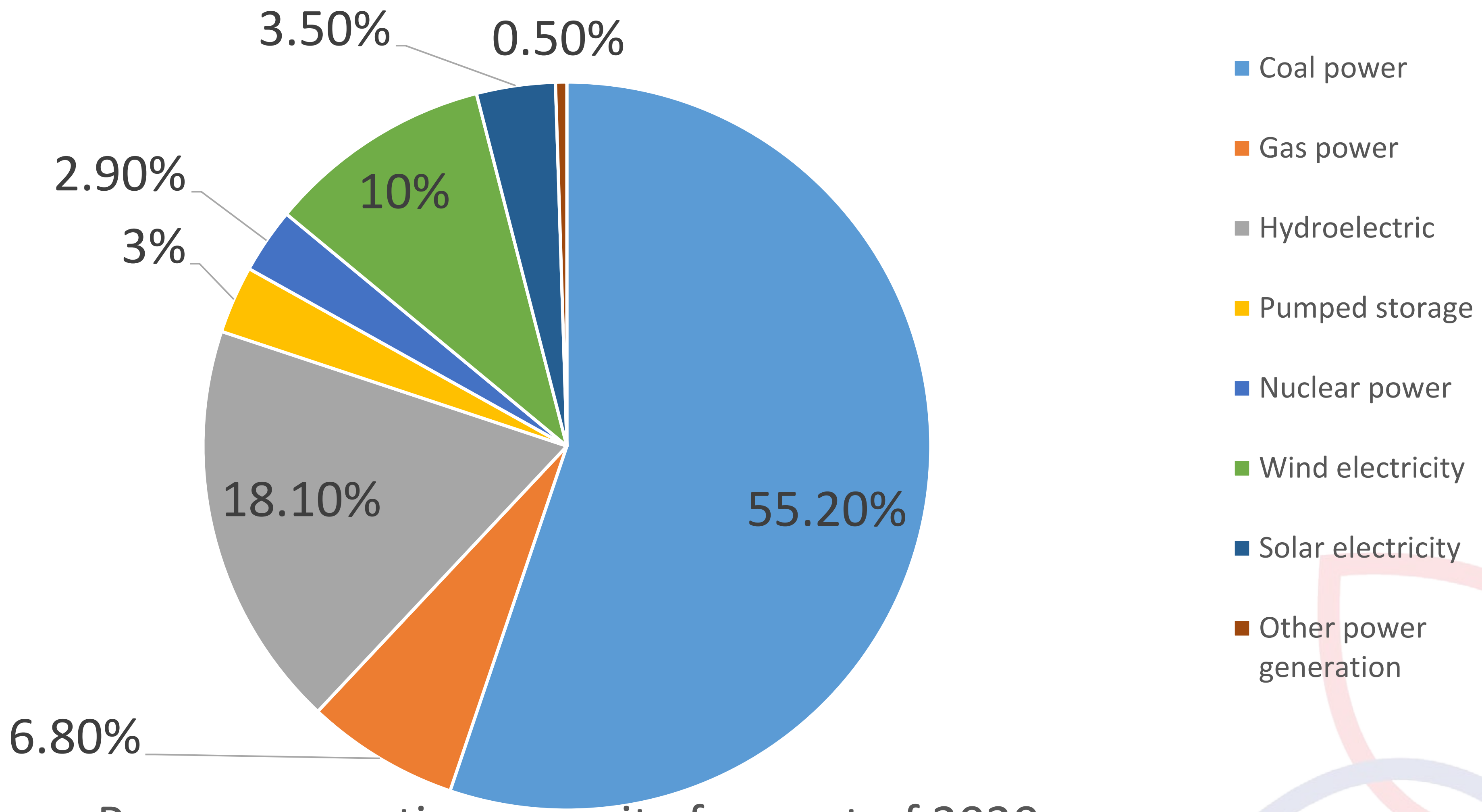
3. Unbalanced China's power energy structure

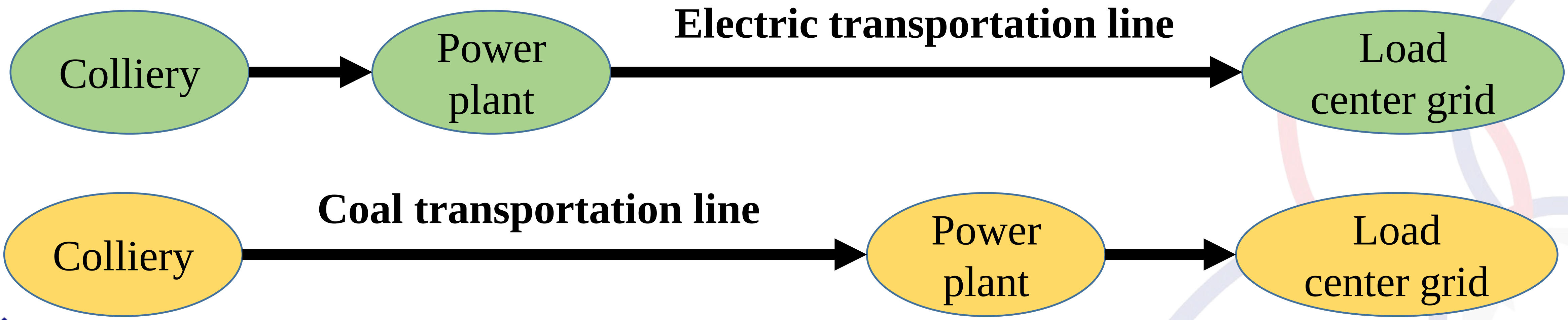
Unbalance power grid in China



Power generation capacity forecast of 2020

The actions already adopted for Chinese grid unbalances

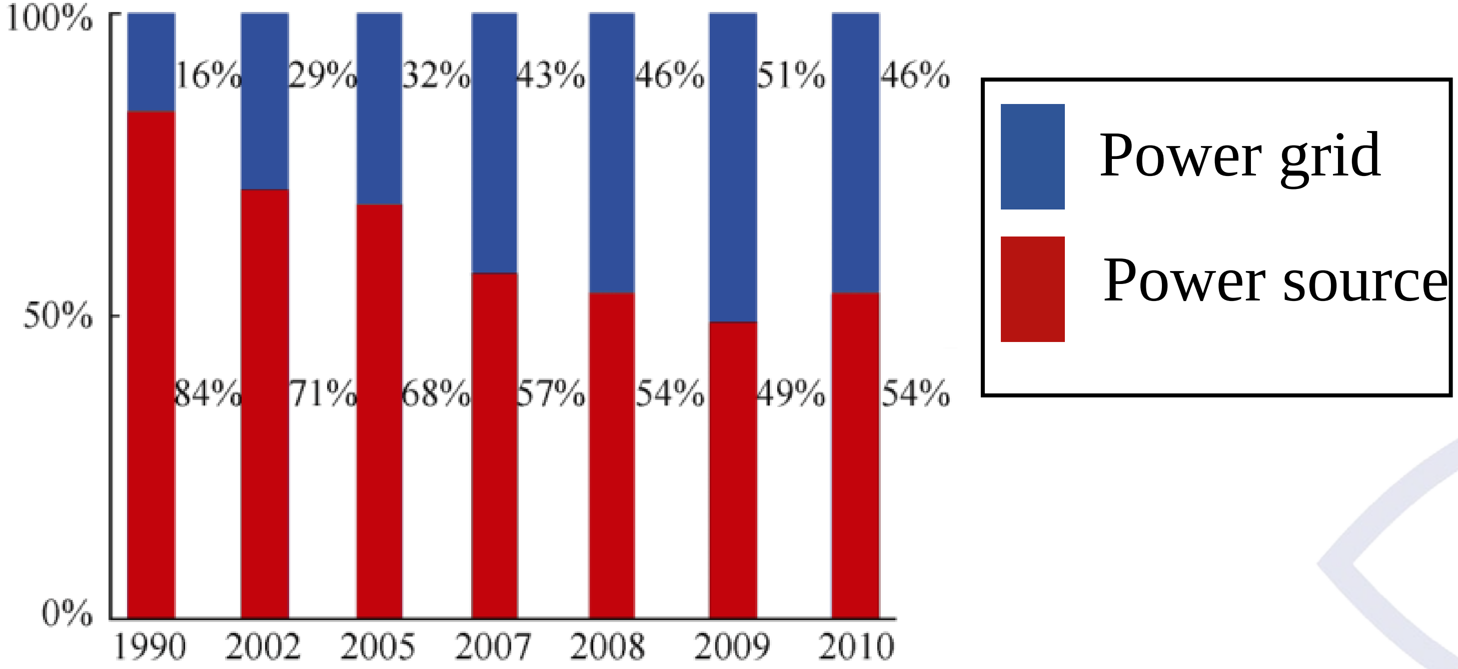
- The cross-regional balance mode of power in China mainly includes electric and coal transportation
- Coordinating the development of coal transport and power transportation can solve the imbalance of power distribution



The actions already adopted for Chinese grid unbalances

- At the end of the 20th century, China focused on generating electricity rather than supplying it, which result power grid unbalanced
- Now, China pays attention to the construction of power grid and adjusts the investment proportion of power grid year by year

China's power, power grid investment in the proportion of electricity investment



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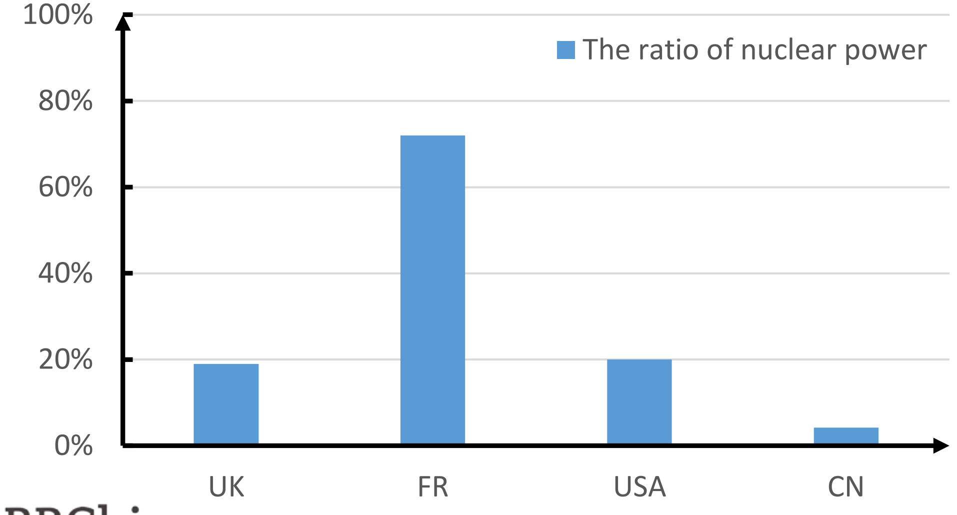
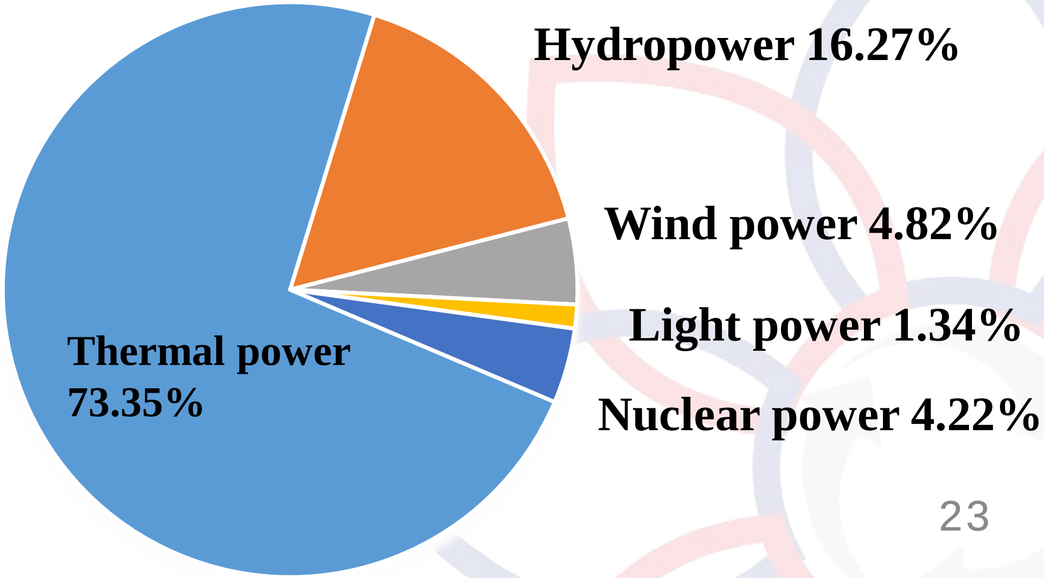
The actions already adopted for Chinese grid unbalances

- China's power generation mode is mainly thermal power, the power generation mode is unbalanced
- During the 13th Five-Year Plan period, China vigorously developed the way of generating electricity from clean energy and established relevant scientific research incentive mechanism

The ratio of nuclear power of UK, FR, USA, CN



Type and proportion of Power generation in China



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A solution to minimise the curtailment by using the electricity-based hydrogen

A solution to minimise the curtailment by using the electricity-based hydrogen

The wind energy offers lower marginal costs compared to fossil-based energy in the electricity market, while the dispatching dynamic can cause curtailment of wind energy because the intermittency of wind profiles,inconsistency with electricity load profiles, transmission congestions, and geographically sparse installment of wind turbines that tends to be far from the demand centers.

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Wind Power Coupling with Hydrogen-Production System

Capacity design of electrolysis water hydrogen plantthe electrolysis plant is a percentage of the nominal installed capacity of the fan (kW), expressed as fwf, then the production capacity of the electrolysis plant PELY (based on the digested wind capacity) is calculated as followed.

$$P_{ELY} = f_{wf} \cdot P_{wf} \qquad (3.1)$$

The Pwf is the Wind power installed capacity.

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Revenue analysis of wind power coupled hydrogen production system

Capacity design of electrolysis water hydrogen plant

$$\mathrm{RS}_{\mathrm{t}} = P_t \bullet Q_t \qquad (3.2)$$

The cost of grid frequency adjustment (without hydrogen plant):

$$\mathrm{CB}_{\mathrm{t}} = 2 \cdot f_{ERR} \cdot CB_{XWH} \cdot E_{WT} \qquad (3.3)$$

The cost of grid frequency adjustment (without hydrogen plant):

$$\mathrm{CB}_{\mathrm{t}} = 2 \cdot f_{ERR} \cdot CB_{WH} \cdot (E_{WT} - E_{W}) \qquad (3.4)$$

We substrate 3.3 and 3.4,we will get the reduced expenditure for adjusting the grid frequency is

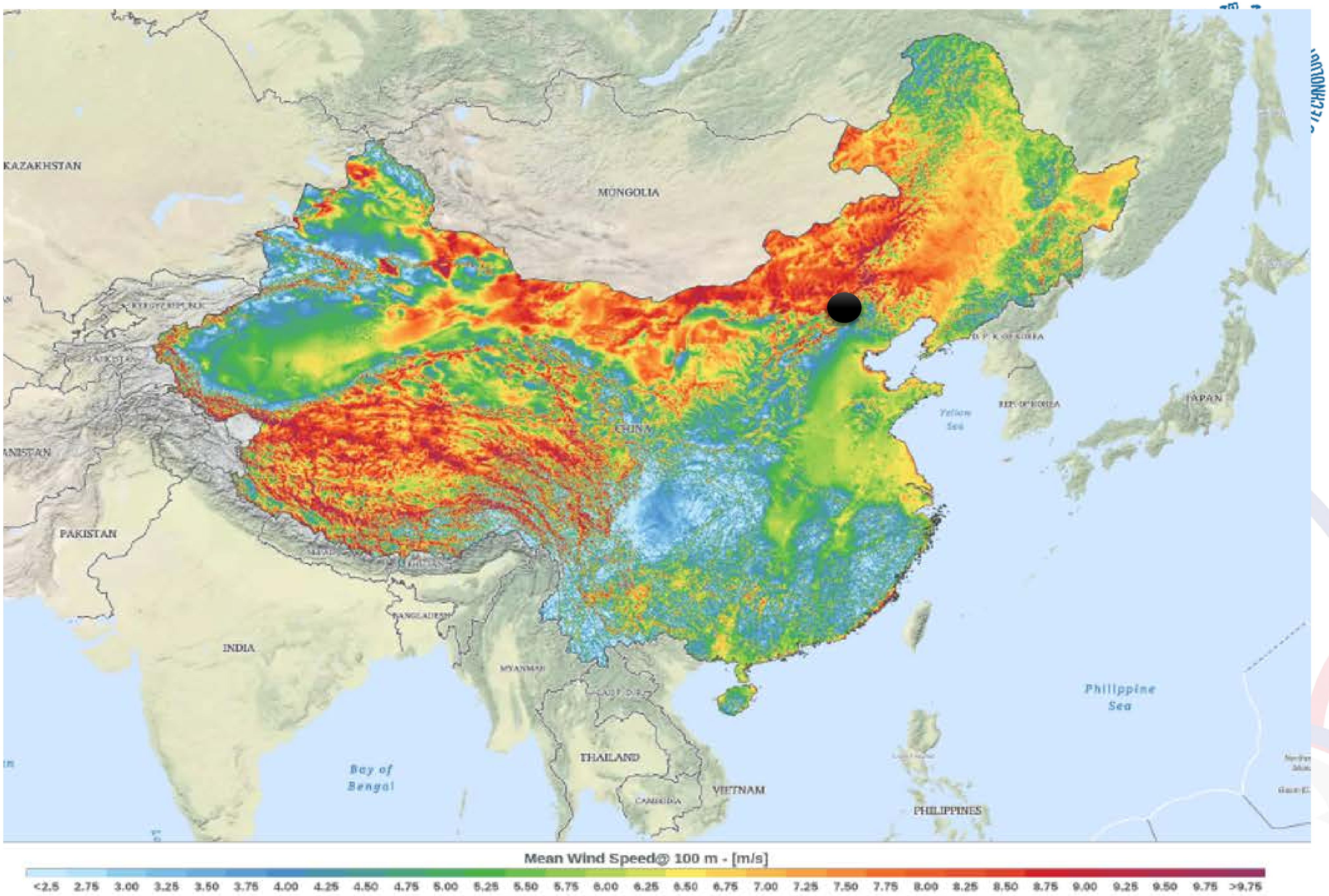
$$\mathrm{CB}_{\mathrm{t}} = 2 \cdot f_{ERR} \cdot CB_{XWH} \cdot E_{WT} \cdot [1 - (CB_{WH} / CB_{XWH}) + (CB_{WH} / CB_{XWH}) \cdot (E_{W} / E_{WT})]$$

The benefits of carbon reduction

China's incentive policies for the use of new and renewable energy include subsidies for power generation and reductions in corporate value-added tax and consumption tax. For the wind power hydrogen production system, only the reduction and rebate obtained from the hydrogen production plant is considered as

$$RE_t = Q_{electronics} CTT_{electronics}$$

Case Studies



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Case Studies

we take Zhangjiakou wind farm in Hebei province as an example, based on the comprehensive consideration of climatic conditions, market application and project economics.

The total installed capacity of Zhangjiakou Wind Farm is **25 MW**. According to historical statistics, the Actual hours of wind power utilization is **2324 hour**, cumulative wind power on-grid for the whole year is **58 million kW·h**. Assuming that the wind power used for hydrogen production is equivalent to 20% of the cumulative on-grid wind power for the whole year, it can be used for The amount of wind power for hydrogen production is **58 × 20%=11.6 million kW·h**

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Case Studies

According to actual experience, the energy consumption of producing 1 m3H2 (standard state, the same below) is 4.5×1.1=**4.95 kW·h** (the coefficient 1.1 in the formula is due to the fact that the electrolysis equipment cannot always work at the rated power, resulting in the energy of the electrolysis equipment Correction caused by reduced power consumption), compression 1 m3H2 .

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Case Studies

The electricity price of the built wind power is USD **0.07 / kWh**.

On the other hand, the electricity price varies between day and night, in the daytime, the electricity fee is USD **0.098 / kWh,** while in the night, the electricity fee is USD **0.044 / kWh.** As the results,the city can use the electricity at night to produce the hydrogen and sell the electricity by day.

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Case Studies

It is bound to significantly affect the economics of the entire project and will directly affect the investment analysis and decision-making of the project itself. Due to the electricity required for hydrogen production.

By taking the curtailment of wind power with coupled hydrogen production, the electricity price is relatively high, which may be much higher than the on-grid electricity price of the thermal power unit at night.

In actual operation, this part of wind power may also be provided to the hydrogen plant for free. When the unit electricity cost is less than **USD 0.07 /(kW·h)**, the investment of the project will enter a profitable stage, and the electricity price is very sensitive to the profitability of the project.