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Electric power substitution for coal in China: Status quo and SWOT analysis

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ABSTRACT

In 2013, “haze-fog” became an annual buzzword in China; this “haze-fog” is primarily attributed to coal combustion. If coal continues to be used as it has been previously, China will suffer as a result of air pollution. Different from coal, electricity is a highly efficient energy source with no pollution emissions. Electric power substitution (EPS) for coal can reduce air pollution and transmit electricity to a load intensive area by an ultra-high voltage transmission project that can promote renewable energy accommodations in remote areas. However, EPS was proposed in 2013 and is still in the initial stage. The present paper studies the relationship between coal and haze-fog, proposes an EPS action mechanism, and summarizes the EPS market and policies. A SWOT model has proved to be an efficient tool to analyze the internal and external competitiveness of a system. Therefore, to fully study the current development status of electric power substitution in China, this paper adopts a SWOT model to analyze the strengths, weaknesses, opportunities and threats of EPS. The conclusion is drawn that EPS is a good substitution for coal, but increased interest and use of EPS in China still needs support, including energy price marketization, electricity price subsidy, UHV optimization, clean coal technology innovation, and so on. This research can promote optimization in the energy structure and provides policy makers with good references and a clear direction in EPS development.

1. Introduction

1.1. Background

“Haze-fog” was China's annual buzzword in 2013. The primary pollutant of haze-fog is $PM_{2.5}$, fine particulate matter whose aerodynamic diameters is less than 2.5 mm and is harmful to health. In 2013, haze-fog invaded 25 provinces and more than 100 large-medium cities in China [1]. In central and southern north China and northern Jiangnan, the days of haze-fog in 2013 increased from 50 to 100 [2]. $PM_{2.5}$ can penetrate deep in lungs because of its small size. Various chemicals are absorbed on its surface [3] and threaten transportation, safety and the environment. In China, nearly 71.6% of $PM_{2.5}$ is from fuel combustion; coal contributes the most to $PM_{2.5}$. In 2012, SO_2, NO_X and smoke-dust emission caused by the use of coal individually accounted for 93%, 70% and 67% of the total emission; $PM_{2.5}$ emission related to the use of coal accounted for 63% of the total emission [4]. If the consumption mode of coal continues, haze-fog in China will be more serious. In addition to the threat of air pollution, the energy structure in China is unreasonable. In 2014, the consumption ratios of coal and renewable energies accounting for the total energy consumption were 66% and 1.79%, respectively, while the values for America were 19.7% and 2.83%, respectively [5]. An unreasonable energy structure is a great threat to energy safety. Additionally, the coal industry in China has been in a depression since 2012. The demand and supply for coal has declined; the coal price has slumped; and the benefits of coal enterprises have shrunk. The tragedy is that this trend continues in 2016. The coal industry in China should find a new and sustainable way to transform itself. In addition, many provinces in China, such as Gansu and Xinjiang, are suffering from heavy wind curtailment [6] that needs to be solved in addition to the coal utilization situation. The future development of coal in China has to meet this great challenge, and a new mode of coal utilization should be explored in China.

Electricity is an efficient energy source with no pollution emissions. We consider that if electricity power is substituted for coal to meet the needs of daily life and production, problems such as air pollution and energy structure optimization can be solved. Therefore, the present paper provides detailed analysis regarding this issue.

1.2. Literature Review

Since the outburst of haze-fog in 2013, $PM_{2.5}$ has been of interested to large numbers of scholars. Guo L. et al. [7] analyzed the formation of long-lasting haze-fog. Kong [8] applied diagnostics ratios and principal component analysis, proving that the combustion of coal was the chief

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Nomenclature

Item

EPS	electric power substitution
$PM_{2.5}$	fine particulate matter
NRDC	Natural Resources Defense Council
SGCC	State Grid Corporation of China
CCT	clean coal technology
UCG	underground coal gasification
IGCC	integrated gasification combined cycle
UHV	ultra-high voltage
AC	alternating current
DC	direct current
EHV	extra high voltage
MEP	Ministry of Environmental Protection
NBS	National Bureau of Statistics
AQSIQ	Administration of Quality Supervision Inspection and Quarantine
SC	State Council
NDRC	National Development and Reform Commission
MOF	Ministry of Finance
SCIO	State Council Information office
NEA	National Energy Administration
MOFCOM	Ministry of Commerce
MIIT	Ministry of Industry and Information Technology
LPG	Liquefied petroleum gas
SEPB	Shanghai Environmental Protection Bureau
SMFB	Shanghai Municipal Finance Bureau
GAC	General Administration of Custom
BP	British Petroleum
COEA	China Oil Enterprises Association
SHDRC	Shanghai Municipal Development & Reform Commission

Unit

kWh	kilowatt hour
kJ	kilojoule
kcal	kilocalorie
CNY	China Yuan
Kg	kilogram
L	liter
m^3	cubic meter
Km	kilometer

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culprit of $PM_{2.5}$ and polycyclic aromatic hydrocarbons. Ramya S.R. et al. [9] used a multiple linear regression model to assess the relationships between the $PM_{2.5}$ mass and its optical properties and meteorological parameters, verifying that the post-monsoon season explains over 88% of the variability in the $PM_{2.5}$ mass. Zhao [10] noted that wind speed and relative humidity greatly affect outdoor and indoor $PM_{2.5}$, and they further predicted $PM_{2.5}$ mass concentrations with an average relative deviation of 15%. Maria C.P. et al. [11] measured the concentrations of organics in $PM_{2.5}$ and found that a strong seasonality exists in organic concentrations. A Weather Research and Forecasting–Chemistry model was employed by Gao [12] in forecasting the $PM_{2.5}$ concentration; impacts on health and economics were further assessed based on this model. Takashi Y. et al. [13] analyzed the relationship between infant mortality and the $PM_{2.5}$ concentration. The results clarified that for a 10 $\mu g/m^3$ increase in $PM_{2.5}$, the odds ratios were 1.06 for infant mortality and 1.10 for post-neonatal mortality. These previous studies have focused on how haze-fog forms and how to monitor and forecast haze-fog, as well as the reason, influence and consequence of haze-fog. These studies are crucial and basic, but how to fundamentally solve haze-fog should now be the main focus of research. This paper considers that replacing coal with electricity is one of the solutions to reduce air pollution in China.

The electrification level can measure the modernization of a country and can be represented by an indicator, the ratio of electricity consumption of total energy consumption. Previous research [14] shows that a one percent rise in the electrification level can increase energy efficiency by 4%. In 2011, the domestic per capita electricity consumption in China was 3312 kWh [15]; this level is only approximately 25% of that in America and 42.2% of that in Japan. Electricity power substitution is one way to increase the electrification level. EPS, proposed by SGCC in 2013, is intended to substitute electricity power for primary energies (coal, oil, natural gas, etc.) for direct consumption in the processes of end use. EPS can improve fuel efficiency, as well as decrease pollution and rationalize the energy consumption structure. To analyze the influence of EPS on coal, the present paper focuses on the substitution of electricity for coal. The main content of EPS includes three aspects: clean electricity generation, UHV grid development, and reduced consumption of decentralized coal. These aspects are involved throughout the whole processes of power generation, transmission and consumption.

1.2.1. Clean electricity generation

This section focuses on the perspective of power generation, indicating advanced clean mining technology, CCT, among others. Advanced clean mining technology and CCT guarantee that the electricity generation process is clean and has low contamination.

Clean mining technology for coal mines is important to protect the environment and maintain balance among energy resources, consumption, and ecology. Water management is an integral part of clean mining. Efficient treatment technology during coal mining can minimize freshwater pollution and contribute to water recycling. Ramesh T. et al. [16] evaluated two water treatment technologies, forward osmosis and reverse osmosis, and drew the conclusion that the combination of the two technologies provides better performance in treating coal mining wastewater than individual technologies. Chang Q.L. et al. [17] studied paste backfill mining technology and demonstrated that paste backfill mining technology can effectively improve environmental protection, mining safety and surface subsidence.

CCT are technologies that are committed to coal washing, processing, conversion and pollution control to reduce pollution emission and increase the utilization efficiency. UCG is a clean coal technology that converts coal into gas; however, UCG has to overcome energy loss challenges. Shrivastava A. and Prabu V. [18] proposed a solar-UCG technology that can effectively compensate for energy loss by integrating UCG with solar energy. Ehsan M. et al. [19] proposed a new catalytic hydrogen production reaction integrated gasification technology. They extracted ash-free coal from lignite coal and then produced high-purity H_2 from steam gasification of ash-free coal integrated with CO_2 capture. In addition to coal gasification, higher parameter ultra-supercritical coal fired units and integrated gasification combined cycle power generation units are currently the two main innovations [20]. CCT is one of the best options for China to achieve higher efficiency and lower emissions. However, the main challenge faced by China in CCT is not only technical but also includes soft factors, including enterprises' low enthusiasm, unsound laws, detailed implementation requirements, incomplete effective government supervision, and competing subsidization and investment priorities [21].

1.2.2. Development of UHV grid

From the perspective of power transmission, thermal power, wind power, solar power and hydropower can be efficiently transmitted by UHV from remote areas to eastern China. The distribution of coal resources in China is concentrated in the central and western regions; this is in contrast with energy consumption-intensive regions. UHV not only replaces coal transportation by electricity transportation but is also a tool that is used to optimize the energy structure and environmental quality, as well as being an indispensable means of renewable energy allocation and accommodation [22]. As of January 2016, three AC and four DC UHV projects have been constructed, and four AC and six DC UHV projects are under construction.

Previous research regarding UHV mainly focused on the technology and economy. Since the 1960s, the Soviet Union, America, Japan, Italy and other countries have started to study the feasibility of UHV transmission. It has been shown that the technology is absolutely feasible. Regarding the selection of the UHV voltage, there are four levels that have been used: 1050 kV, 1100 kV, 1200 kV and 160 0 kV [23]. SGCC compared the four voltage levels [24] according to operation, loss, transmission capacity, insulation, cost, and so on. The result demonstrates that the 1100 kV level outperforms the other levels; 1100 kV is the IEC standard voltage. The key technologies in over voltage and insulation dependence, external insulation characteristics, electromagnetic environmental, UHV equipment manufacturing and testing [25] have been greatly improved; however, more efforts need to be made to further increase UHV security and stability [26].

The economy is another issue receiving attention. The UHV economy will surpass that of EHV when the transmission capacity exceeds the economic capacity and the transmission distance exceeds the economic distance [27]. The economic transmission capacity is estimated to be approximately 2400 MW [28], and the economic distance ranges from 800 km to 1000 km [29]. The Soviet Union compared an economy of 1150 kV UHV and 7549 kV, and Japan compared an economy of 1100 kV UHV and 800 kV EHV. Both results verified that UHV outperforms EHV in economic terms [30]. The high economic efficiency of UHV power transmission technology means that power transmission over a long-distance, at a high-capacity, and with low pollution can be realized [31].

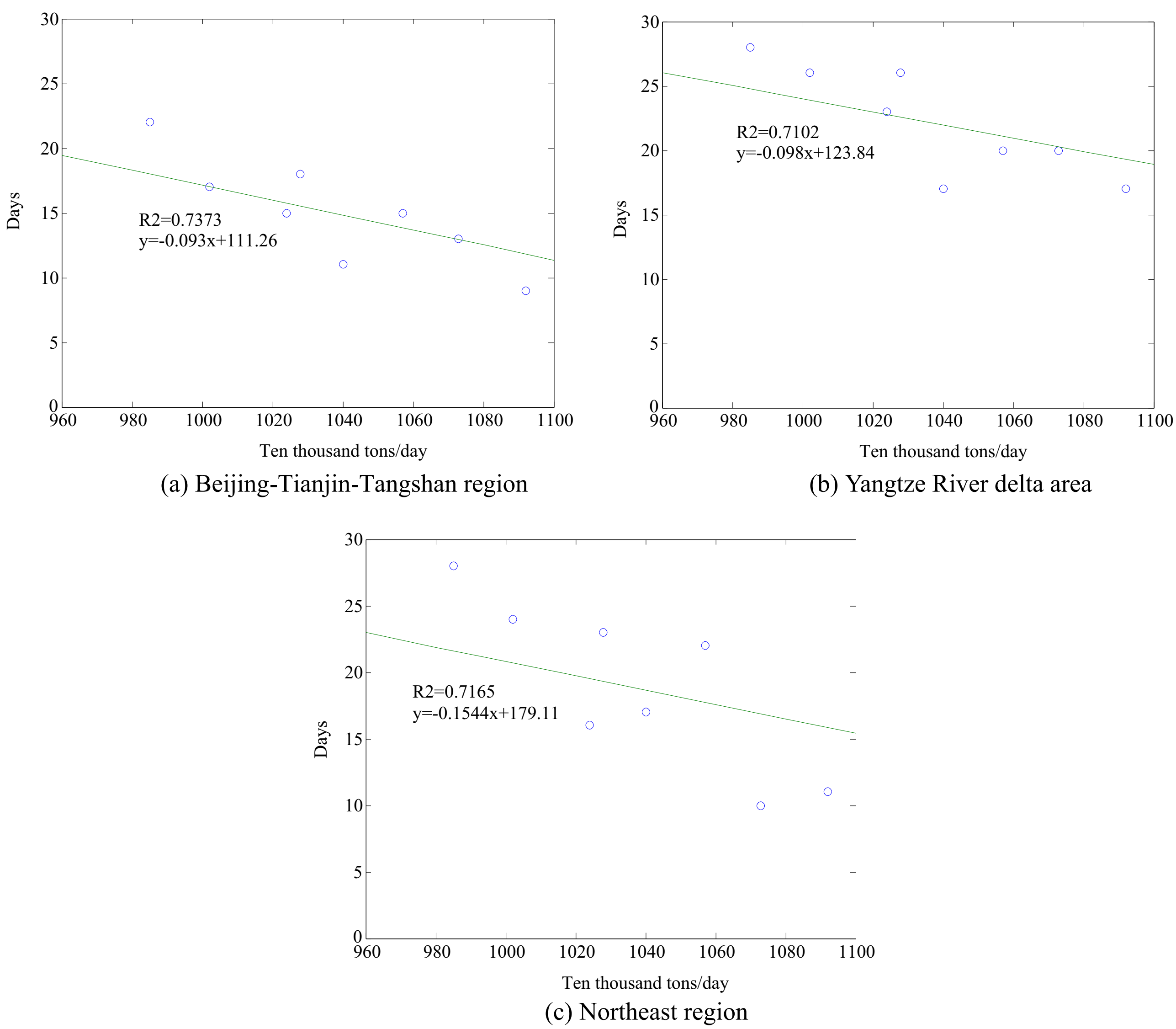

Fig. 1. Regression analysis between coal consumption and air quality. (a) Beijing-Tianjin-Tangshan region (b) Yangtze River delta area. (c) Northeast region.

1.2.3. Reduction in the consumption of decentralized coal

This section is from the perspective of consumption. Direct coal combustion gives rise to SO_2, NO_X and smoke-dust emission, accounting for 79%, 57% and 44% of the national total emission, respectively [32]. Decentralized coal is directly used for small boilers, domestic heating, and so on; it is the main source of direct coal combustion. In China, decentralized coal accounted for 41.6% (in 2012) of the total energy consumption, while the world's average level was 10.1% (in 2011). The levels in America and Japan were only 1.6% and 8.4% (in 2011), respectively [33]. In China, SO_2 emission from decentralized coal is nearly 10 million tons each year [34], paralleling that of thermal coal, while NO_X emission is more than 3.2 million tons [34], ranking next to that of thermal coal and vehicles. Replacing decentralized coal used in boilers, heaters and cookers with electricity can reduce the emission of harmful gas. Therefore, reducing the utilization of decentralized coal is an important method to reduce air pollution.

Although EPS has only recently been proposed, the technologies used in UHV and clean coal have led to a breakthrough, providing a basic platform for EPS. EPS is theoretically feasible. However, studies regarding the economy and EPS practice are insufficient and unsatisfactory. To examine whether electricity is a good substitute for coal in China, this paper focuses on the comprehensive feasibility of EPS and applies SWOT to analyze the strengths, weaknesses, opportunities and threats of EPS. This paper is organized as follows: Section 2 elaborates the status quo of pollution, action mechanism, potential and effects, in addition to describing the policy and summarizing the integrated planning roadmap of EPS. The SWOT model is employed to analyze the strengths, weaknesses, opportunities and threats of EPS in China in Section 3. Lastly, Section 4 discusses the issues that need to be faced when substituting electricity for coal, proposes support suggestions and concludes the paper.

2. Status quo

2.1. Relationship between coal consumption and air pollution

Nationally, the average haze days in 2013 was 35.9 days [35], reaching a peak since tracking began in 1961. Haze-fog is primarily distributed in the Yangtze River delta area, Beijing-Tianjin-Tangshan region and northeast region. In 2012, $PM_{2.5}$ emitted from coal direct combustion accounted for 31% of total human emissions [4]. The national average daily commercial coal consumption [36] and days of air quality that meet the standard [37] in the Yangtze River delta area, Beijing-Tianjin-Tangshan region and northeast region were collected. To observe the relationship between coal and air quality more intuitively, this paper applies regression analysis to quantify the relationship.

Regression analysis shows that the slopes of the regression lines are negative and the correlation coefficients (R^2) are greater than 0.7 in three regions, indicating that a negative but significant relationship between coal consumption and air pollution exists. (Fig. 1).

2.2. EPS

2.2.1. Action mechanism

In view of China's coal industry, there are four main coal-intensive industries, namely, the electricity industry, steel industry, building material industry, and chemical industry. The coal used in the four industries accounts for 53%, 18%, 14% and 3% of total coal consumption, respectively. Twelve percent of coal is used in other fields and is mainly consumed as decentralized coal [38]. The coal flow in the coal industry chain is presented in Fig. 2. In EPS mode, the flow of decentralized coal is cut and coal used in heaters, boilers and residences will be replaced by electricity generated from the electricity industry. This is a large difference between the traditional action mechanism and EPS action mechanism; Fig. 3 presents the comparison

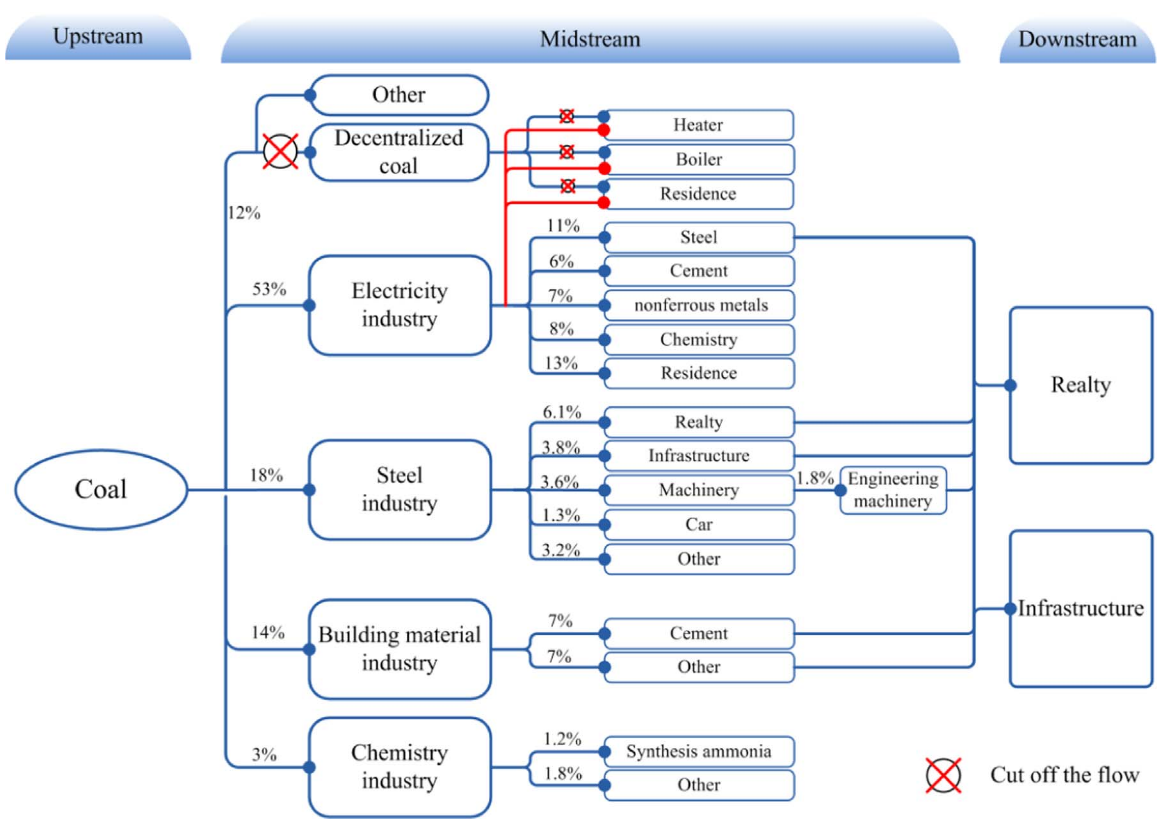

Fig. 2. Coal flow in the coal industry chain.

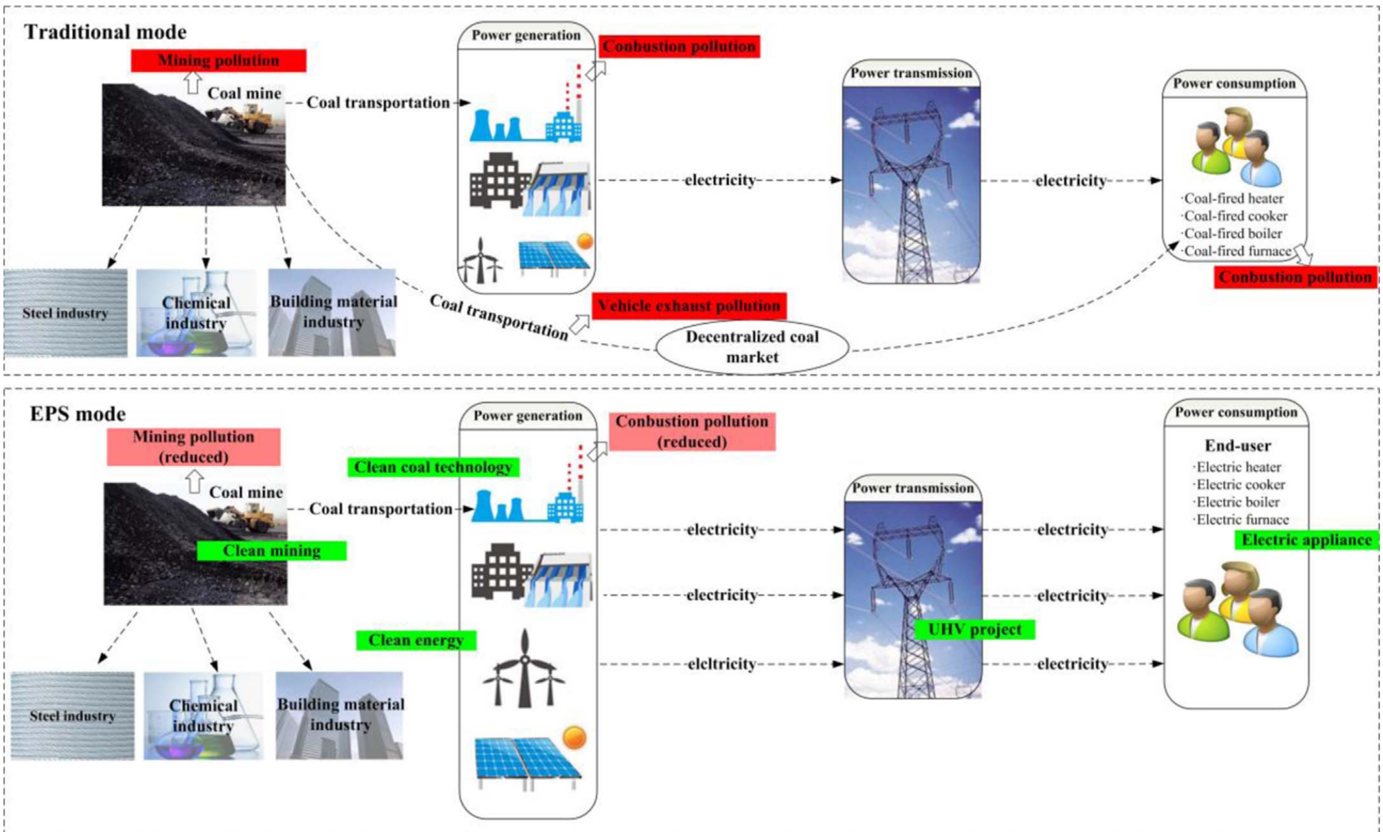

Fig. 3. Comparison between the action mechanism of the traditional mode and EPS mode.

between them.

In the traditional utilization mode, coal produced in mines is transported to thermal plants, where electricity is generated and then transmitted by transmission projects to end-users. Coal also flows to the steel industry, chemical industry, building material industry and decentralized coal market. Mining and combustion of coal are the two main sources of pollution, including mining, electricity generation and decentralized coal burning. However, the action mechanism of EPS is different to a great extent. Advanced clean mining technology reduces pollution during mining [16,17]. Clean coal technology can greatly reduce combustion pollution during power generation; this has been proven in numerous studies [39–42]. UHV proposes replacing coal transportation by electricity transmission, impelling the consumption of power generated by renewable energy, such as wind energy and solar energy, in remote areas and reducing the exhaust pollution generated by transport vehicles. In addition, the decentralized coal market shrinks and coal-fired equipment is replaced by electric appliances. There is no doubt that coal combustion pollution is reduced significantly in EPS mode.

2.2.2. *Substitution potential and effect*

In China, the amount of decentralized coal used in middle- and small-sized boilers, furnaces and other end coal-fired equipment is approximately 800 million tons [43], accounting for 41.6% [33] of the total energy consumption in China. The ratio is far higher than that of other developed countries, such as America, Russia and Japan. Small coal-fired boilers account for more than 65% of industrial boilers. As shown in Fig. 4, a coal-fired boiler with a capacity of less than 10 t of vapor per hour accounts for 80% of the coal-fired industrial boilers, and the ratio of boilers with a capacity less than 35 t of vapor per hour accounts for 96% of the total [44]. China has a large potential for electricity power substitution for coal. In addition, the *Action Plan on*

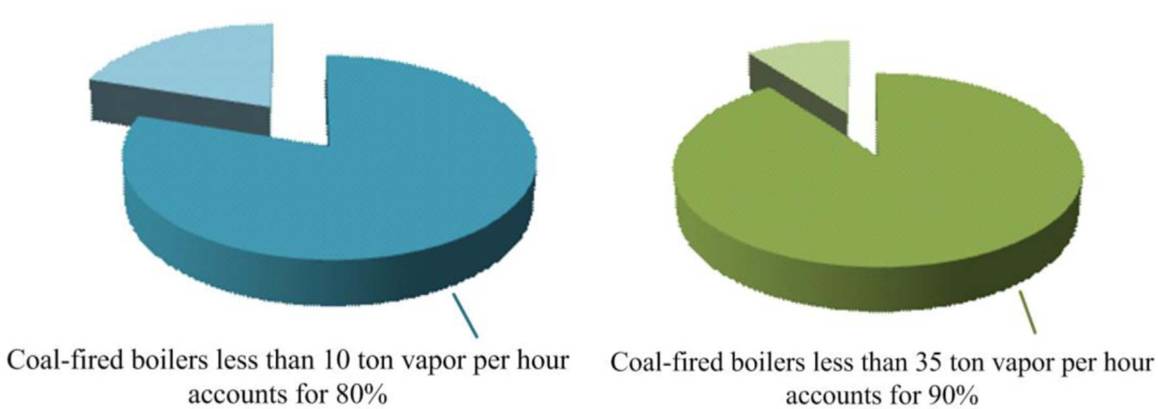

Fig. 4. Percentage of boilers less than 10 and 35 t of vapor per hour.

Prevention and Control of Air Pollution issued by the State Council [45] intends to “eliminate coal-fired boilers with less than 10 and 20 t of vapor per hour in prefecture level and above cities and forbid construction of coal-fired boilers less than 10 t of vapor per hour”. This policy guarantees the realization of EPS.

Under the drive of policies, EPS has attained phased achievements. From January to September in 2014, 6121 EPS programs had been carried out, realizing 29.7 billion kWh of electricity substitution, 14.22 million tons of reduction in decentralized coal and 25.32 million tons of reduction in CO_2 [46]. In the first quarter of 2015, 20.3 billion kWh of electricity substitution was realized, accounting for 31.23% of the yearly plan. For the whole year of 2015, 17.2 thousand EPS programs were completed; electricity substitution was 76 billion kWh, 1 billion kWh above the target [47].

2.3. Policy

Appropriate policies play important roles in guiding and impelling change. Since 2012, the government of China has enacted a series of policies in air pollution control and EPS development.

2.3.1. Support for air pollution control

From 2012–2015, NDRC, NEA and other administrative departments issued policies to control atmospheric pollution in China (Table 1). In 2012, concentration limits of $PM_{2.5}$ were added to the *Ambient Air Quality Standards* (GB3095-2012) [48]. The State Council set the upper limit of SO_2 and NO_X emissions in 2015 and the rules to eliminate backward mines were first proposed. In addition, the targets to control air pollution were set by MEP, and $PM_{2.5}$ was first listed as a regular monitoring object in *Progress in China's Human Right* in 2012. The decomposed goals are detailed in the *Action Plan on Prevention and Control of Air Pollution, Clean Coal Utilization Action Plan* (2015–2020) and other supported polices.

Many scholars have published studies on the implementation effect and impact of the above policies. Guo X.P. et al. [56] summarized the air pollutant emission policies in recent years and applied a system dynamic model to simulate the impact of these policies on the coal supply chain member enterprises. According to their simulated results, air pollution reduction policies can significantly improve air quality by promoting power structure adjustment and improving energy efficiency. Based on energy-saving policies, Tan Z.F. et al. [57] proposed a joint optimization model for the generation side and user side to optimize the energy efficiency of the power industry chain. Wen Z.G and Li H.F. [58] used three scenarios to simulate technological policies and analyzed potential energy conservation and CO_2 reduction in the non-ferrous metals industry. Momoe K. et al. [59] analyzed the long-term impacts of the air pollution policy in Japan and suggested that preventive actions and local-scale compliance enforcement tools contribute to the successful implementation of policies over the long-term. This study provides good references for policy executors in China to effectively implement the policies. Many other publications [60–63] have also contributed to the implementation effect and impact tracking of air pollution control policies in China.

2.3.2. Support for EPS development

In the past four years, China has made progress in impelling the development of EPS (Table 2). In 2012, a differentiation subsidy was introduced for the replacement of coal-fired boilers in Shanghai. In 2013, SGCC proposed an ambitious target that the accumulative substitution of electricity will reach 100 billion kWh by 2015 and 1000 billion kWh by 2020. NDRC set a target that the utilization ratio of clean coal in Beijing, Tianjin and Hebei province will reach 90% by 2017, and the plans for UHV and construction of clean energy bases were proposed by NEA and SC.

After the release of the EPS policies, many researchers focused on the benefits of EPS emission reduction, renewable energy accommoda-

Table 1
Support policies for air pollution control.

Policies	Data	Issuers	Main contents
Ambient Air Quality Standards (GB3095–2012) [48]	February 29th, 2012	MEP AQSIQ	• Add concentration limits of $PM_{2.5}$
12th Five-year Plan for Energy Saving and Emission Reduction [49]	August 6th, 2012	SC	• Restrict CO_2 and NO_X emissions within 23.476 million tons and 20.462 million tons, respectively, in 2015. • Restrain the development of industries with high consumption and emission and accelerate the elimination of backward enterprises.
12th Five-Year Plan on Air Pollution Prevention and Control in Key Regions [50]	December 29th, 2012	MEP NDRC MOF	• Reduce the annual average concentrations of PM_{10}, SO_2 and NO_X in key regions by 10%、10%、7%、and 5% by 2015.
Progress in China's Human Right in 2012 [51]	May 14th, 2013	SCIO	• Add $PM_{2.5}$ as a regular monitoring indicator of air quality.
Action Plan on Prevention and Control of Air Pollution [45]	September 10th, 2013	SC	• Impel construction of centralized heating, coal-to-gas and coal-to-electricity. • Rectify small coal-fired boilers and accelerate the construction of desulphurization, denitration and dust removal projects in key sectors. • Reduce the coal consumption ratio to 65% by 2017. • Try to achieve negative growth of total coal consumption by improving the outside power supply, natural gas consumption and non-fossil energy utilization in Beijing-Tianjin-Hebei Province, the Yangtze River Delta and the Pearl River Delta. • Increase the selective ratio of raw coal to 70% and ban imported coal with poor quality by 2017.
Work Plan on Strengthening Prevention and Control of Air Pollution in Energy Industry [52]	May 16th, 2014	NDRC NEA MEP	• Intensify quality supervision of coal products.
Provisional Measures on Commercial Coal Quality Management [53]	September 3ed, 2014	NDRC MEP MOFCOM	• Restrict the selling and usage of decentralized coal with ash content (Ad)≥16% and dried base total sulfur content (St,d)≥1% in the Beijing-Tianjin-Tangshan region, Yangtze river delta region and Pearl river delta region.
Clean Coal Utilization Action Plan (2015–2020) [54]	April 27th, 2015	NEA	• Increase the raw coal preparation ratio to 80% by 2020. • Increase the consumption ratio of thermal coal to 60% by 2020.
13th Five-Year Plan [55]	March 18th, 2016	MIIT	• Increase gas utilization to 45 trillion m^3, and replace coal-fired boilers with 1890 thousand tons of vapor. • Decrease the days of heavy pollution at the prefecture level and above cities by 25%.

Table 2
Support policies for EPS.

Policies	Data	Issuers	Main contents
Notification on Coal-fired Boiler Clean Energy Substitution Work Plans and Fund Support Implementation [64]	May 15th, 2012	SHDRC SEPB SMFB	● Offer a subsidy ranging from 80 thousand CNY per ton of vapor to 200 thousand CNY per ton of vapor to boiler users according to the difference of districts, substitution methods, fuels and facilities. ● Reward 107 users who possess 189 boilers with a fund of 71.79 million CNY.
Electric Power Substitution Implementation Scheme [65]	August 15th, 2013	SGCC	● Realize accumulative electricity substitution of 100 billion kWh by 2015. ● Realize accumulative electricity substitution of 1000 billion kWh by 2020.
Work Plan on Strengthening Prevention and Control of Air Pollution in Energy Industry [52]	May 16th, 2014	NDRC NEA MEP	● Increase the utilization rate of clean coal in Beijing, Tianjin and Hebei province to 90% by the end of 2017.
2014 Guidance on Energy Works [66]	January 20th, 2014	NEA	● Strengthen power transmission from west to east, and plan to construct 12 transmission lines to optimize the energy spatial layout and increase efficiency of energy allocation.
Energy Development Strategy Action Plan (2014–2020) [67]	June 7th, 2014	SC	● Construct 14 large coal-fired power bases of 100 million tons. ● Increase the ratio of non-fossil energy in primary energy consumption to 15% by 2020. ● Construct 9 large modern wind power bases as well as the matched transmission project. ● Increase the installed wind capacity to 200 million kW and the feed-in-tariff of wind energy will reach as much as that of coal power by 2020. ● Increase the installed solar capacity to 100 million kW and the feed-in-tariff of solar energy will reach as much as that of coal power by 2020.

tion and electric boilers. Zhang L.H. et al. [68] established an EPS reduction benefit model at the system level to calculate emission reductions. The research concluded that a 20% percent rise in thermal coal consumption can reduce the emission of SO_2 by 11%, and a 20% percent increase in electricity consumption can reduce the emission of SO_2 by 18%, verifying that EPS can effectively reduce air pollution emission. EPS promotes the consumption of renewable energies and encourages the utilization of electric boilers. Electric boilers can directly consume excess wind power to supply heat during low load periods. Zhang N. et al. [69] proposed an idea that employs electric boilers and pumps hydro for energy storage in reducing wind power curtailment. Liu D. et al. [70] optimized the electric boiler capacity configuration of a regional power grid based on various constraint conditions for a wind power accommodation scenario. Numerous studies involving EPS will be followed up in the near future.

2.4. Integrated planning roadmap

Based on the progress achieved in the past few years, EPS will be further developed from 2015 to 2020. In the coming five years, EPS technology, such as heat pumps, electric heating, electric boilers, cooling and heating storage systems, will be vigorously promoted in

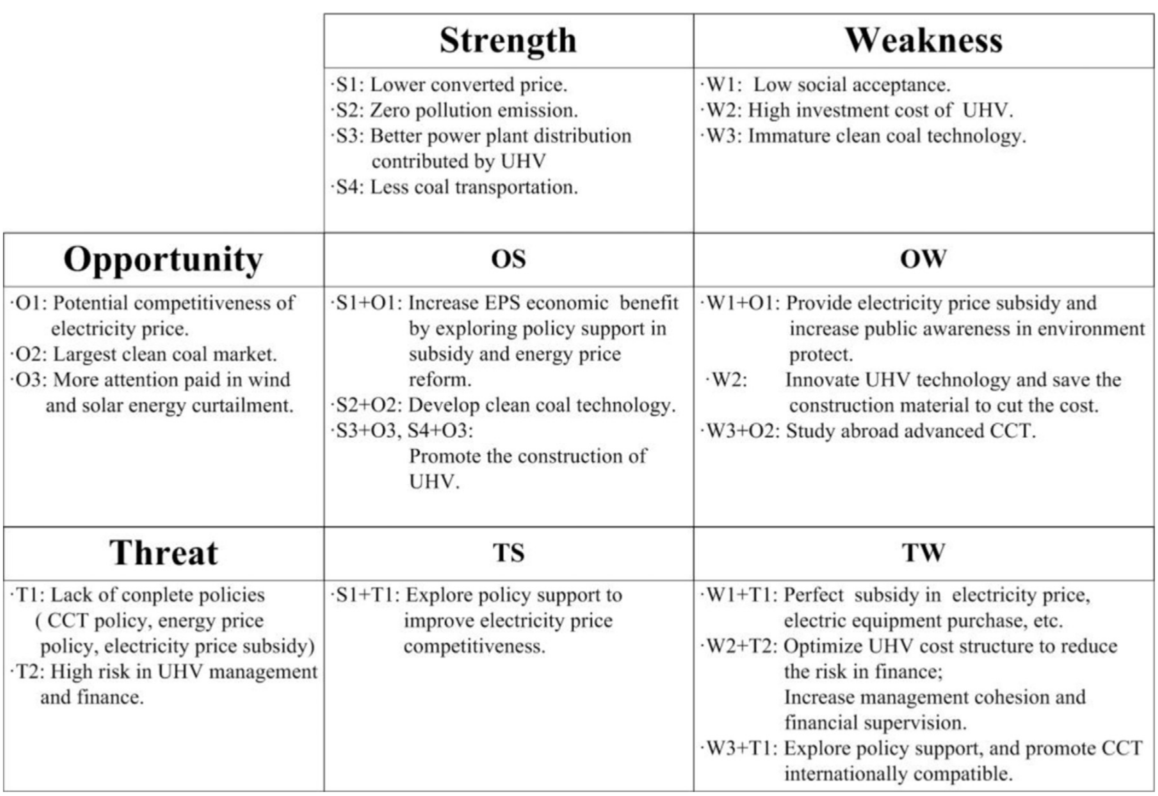

Fig. 5. SWOT analysis.

the fields of central heating, commerce, agriculture, residences, and so on. The planned accumulative substitution of electricity power by 2016 will reach 153 billion kWh, an amount equal to the annual power generation of 18 thermal plants producing 1000 MW. By 2020, the accumulative substitution of electricity will reach 1000 billion kWh, and 187 million kWh of electricity power will be transmitted to the east, contributing to 850 million tons of reduction of decentralized coal [71]. Additionally, by 2020, the annual reduction of SO_2, NO_X and $PM_{2.5}$ will be 320 thousand tons, 260 thousand tons and 130 thousand tons, respectively [72].

3. SWOT analysis for EPS

Currently, EPS is still in the initial stage and the support policy is still incomplete. The SWOT model has proved to be an efficient tool for analyzing the internal and external competitiveness of a system [73,74]. To evaluate the development of EPS in China, this section adopts the SWOT model to analyze the strengths, weaknesses, opportunities and threats of EPS (Fig. 5).

3.1. Strength

3.1.1. Lower converted unit price

The end-user is the electricity consumer; thus, this paper assesses the economic benefit from the end-users' perspectives. To compare the economics of different energies according to a unified standard, this paper calculates efficient heating values (kJ/unit) for all energies and then obtains the converted unit price (10^{-4} CNY/kJ) and ranks them (Table 3).

As shown in Table 3, the heating value of electricity is the lowest, but it has the highest thermal efficiency of 95%. The converted unit price of electricity ranks third, with a value of 1.429×10^{-4} CNY/kJ. In comparison with the previous literature [75], the ranking of the electricity price dropped because the crude oil price declined in recent years. In addition, the coal industry slumped since 2012, inducing a slump in the price of raw coal and coke.

The economic benefit of electricity in 2015 is improved compared to that in 2008. Because the energy price tends to be more rational, the market price of oil and gas will continue to increase. The scarce and nonrenewable feature of natural gas inevitably leads to an increase in price. However, the low cost of coal mining and transportation make the coal price the most competitive. Especially for the decline of coal prices since 2012, the electricity price does not have a competitive advantage compared to coal if there is no supported subsidy for the electricity price. Specifically, electricity can be a good substitute for gasoline, diesel, LPG and gas for the long term, but the current economic benefit remains inferior to coal.

3.1.2. Zero pollution emission

EPS can reduce the emissions of CO_2, SO_2, NO_X and other harmful pollutants. To demonstrate the environmental benefit of EPS, this paper calculates the emissions (kg/kJ) of SO_2 and NO_X with the same heating value for all energies and obtains each environmental cost (CNY/kJ).

Tables 4, 5 indicate that the environmental cost of gasoline is the highest, followed by coal and then electricity. Natural gas emits less SO_2, but generates a large amount of NO_X. Therefore, electricity possesses the best environmental benefit, with no pollution emission.

3.1.3. Better power plant distribution contributed by UHV

In 2013, the power plants in China mainly distributed power in central, eastern and southern areas (Fig. 6), contributing to a heavy haze-fog in these areas. UHV is a tool that can be used to optimize the energy structure, environmental quality and clean energy allocation [22]. However, in 2020 (see Fig. 7), the number of coal-fired power plants will decrease with higher degree of concentration. This change is a result of the development of UHV. China possesses the core and mature technology of UHV, and 90% of the UHV DC equipment is domestically made. China first established the standard system of UHV and possesses independent intellectual property rights. In addition to the technology, the Chinese government has made many efforts to develop UHV construction. The *2014 Guidance on Energy Works* [66] issued by the NEA declared that "12 transmission lines are planned to optimize the energy spatial layout and increase energy allocation efficiency". Later, NDRC and NEA clarified the arrangement and completion time of the 12 transmission lines [77].

As presented in Figs. 6 and 7, UHV will extend to China's northwest and southwest regions, accelerating wind power and hydro power consumption in the west regions. By 2020, more than 1700 billion kWh of clean energy will be sent out; this amount is equal to 700 million tons of raw coal [78]. In addition, electricity power will be transmitted from Mongolia, Russia, Kazakhstan and Southeast Asia to further release the domestic stress of power plants and the environment.

3.1.4. Less coal transportation

EPS can reduce transportation pressure in addition to its cost. In 2013, 70% of coal was transported to other regions by railway and more than 58% of railways were used to transport coal [79]. In EPS mode, UHV can transport electricity instead of coal. The power transmitted by a 1000 kV UHV AC transmission line every year is equal to the transportation of 15 million tons of raw coal by 750–1000 trains carrying 10 thousand tons and 700 thousand trucks carrying 50 t. Power transmission by UHV will reduce pressure in the transportation system. In addition, UHV has a better economic benefit compared to coal transportation. Shen R.B [80] compared the cost per

Table 3
Converted unit price and ranking of different energies.

Energy	Unit	Heating value (kcal)	(kJ)[1]	Thermal efficiency [75]	Efficient heating value (kJ)	Market price (CNY/unit)	Converted unit price ($10^{-4}\times$CNY/kJ)	Ranking	Ranking by Niu [75]
gasoline	kg	10,300	43,070.48	85.00%	36,609.91	8.1200[2]	2.218	1	1
diesel	kg	10,200	42,652.32	85.00%	36,254.47	6.37 00[3]	1.757	2	2
electricity	kWh	860	3596.18	95.00%	3416.37	0.4883[4]	1.429	**3**	**4**
LPG	kg	12,000	50,179.20	85.00%	42,652.32	3.9175[5]	0.918	4	3
natural gas	m^3	8500	35,543.60	85.00%	30,212.06	2.7270[6]	0.903	5	6
raw coal	kg	5000	20,908.00	50.00%	10,454.00	0.4200[7]	0.402	6	7
coke	kg	6800	28,434.88	70.00%	19,904.42	0.6029[8]	0.303	7	5

[1] 1 kcal=4.1816 kJ (20 °C).
[2] The market price of gasoline uses the national average price of 97#gasoline (6.13 CNY/L) on Nov. 25, 2015.
[3] The market price of diesel uses the national average price (5.3 CNY/L) on Nov. 25, 2015.
[4] The market price of electricity uses the basic price in Beijing.
[5] The market price of LPG uses the national average ex-factory price (3917.50 CNY/ton) on Nov. 25, 2015.
[6] The market price of natural gas uses the national average ex-factory price (3382.73 CNY/ton) on Nov. 25, 2015.
[7] The market price of raw coal uses the national average price in Beijing-Tianjin-Tangshan regions on Nov. 25, 2015.
[8] The market price of coke uses the national average ex-factory price (including taxes) on Nov. 25, 2015.

Table 4
Converted emissions and ranking of different energies.

Energy	Unit	Efficient heating (kJ/unit)	SO_2 emission coefficient (kg/unit)[75]	SO_2 converted emission (kg/kJ)	Ranking	NO_X emission coefficient (kg/unit)[75]	NO_X converted emission (kg/kJ)	Ranking
raw coal	kg	10,454.00	0.0162000	1.5496E-06	1	0.001880	1.79835E-07	2
coke	kg	19,904.42	0.0238950	1.2005E-06	2	0.002250	1.13040E-07	3
diesel	kg	36,254.47	0.0080000	2.2066E-07	3	0.003210	8.85408E-08	4
gasoline	kg	36,609.91	0.0024000	6.5556E-08	4	0.016710	4.56434E-07	1
LPG	kg	42,652.32	0.0000136	3.1886E-10	5	0.000880	2.06319E-08	6
gas	m^3	30,212.06	5.772E-06	1.9103E-10	6	0.001134	3.75446E-08	5
electricity	kWh	3416.37	0	0	7	0	0	7

Table 5
Environmental cost and ranking of different energies.

Energy	SO_2 converted environmental cost (CNY/kJ)[1]	NO_X converted environmental cost (CNY/kJ)[2]	Total cost (CNY/kJ)	Ranking
gasoline	2.30043E-06	3.65147E-06	5.95190E-06	1
raw coal	9.06371E-07	1.43868E-06	2.34505E-06	2
coke	5.69723E-07	9.04322E-07	1.47404E-06	3
diesel	4.46246E-07	7.08326E-07	1.15457E-06	4
gas	1.89225E-07	3.00357E-07	4.89582E-07	5
LPG	1.03985E-07	1.65055E-07	2.69040E-07	6
electricity	0	0	0	7

[1,2] According to pollutant charge schedule and pollutant damage compensation, the environmental costs of SO_2 and NO_X are 5.04 CNY/kg and 8 CNY/kg, respectively [76].

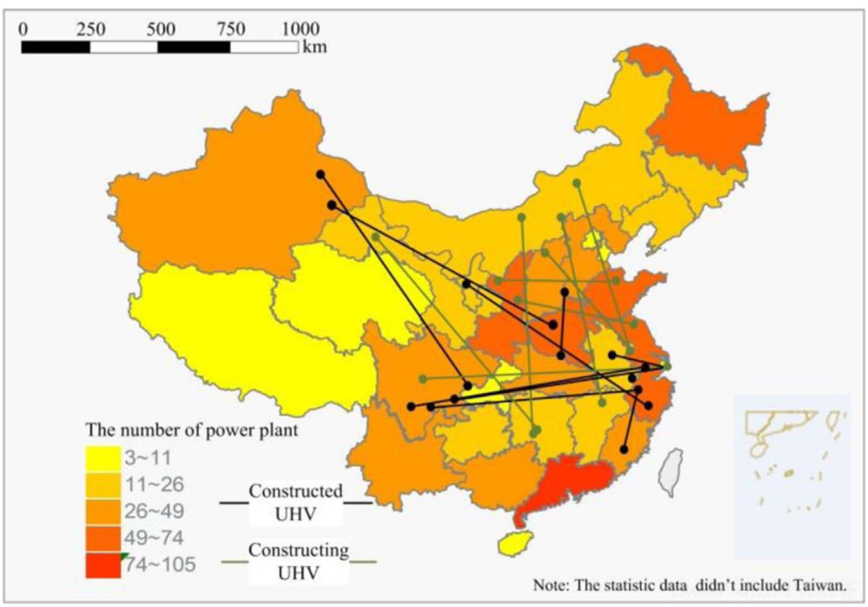

Fig. 6. Distribution of coal-fired power plants and UHV (2013).

kWh of coal transportation, ± 800 kV UHV DC transmission and 1000 kV UHV AC transmission, as shown in Fig. 8.

From Fig. 8, we find that:

1) With a distance between 610 km (A point) and 2400 km (B point), the cost per kWh of 1000 kV UHV AC is less than that of coal transportation.
2) With a distance exceeding 870 km (C point), the cost per kWh of ± 800 kV UHV DC is always less than that of coal transportation;

Therefore, for short distances, coal transportation has a lower cost, but with increasing distance, the economic benefit of UHV outperforms that of coal transportation. Other studies [81–83] have obtained similar results.

3.2. Weakness

3.2.1. Low social acceptance

End-users pay more attention to the economic benefit rather than the environmental benefit. Lian L. et al. [84] investigated the intentions of replacing coal-fired boilers with electric boilers of 72 boiler users. Their survey showed that only one user had a strong willingness to replace the boiler, and 68 users did not want to change their current status primarily because the electricity price was higher than the coal price. This can also be demonstrated according to Table 3 in the present paper. In addition, electricity outages occur at unsuitable times, while coal can be supplied continuously. For households, many users, especially elders who are used to coal, are reluctant to try a new energy source that has a higher cost. The higher price, untimely power outages and habits are reasons leading to low social acceptance; these reasons may hinder the development of EPS to a certain degree.

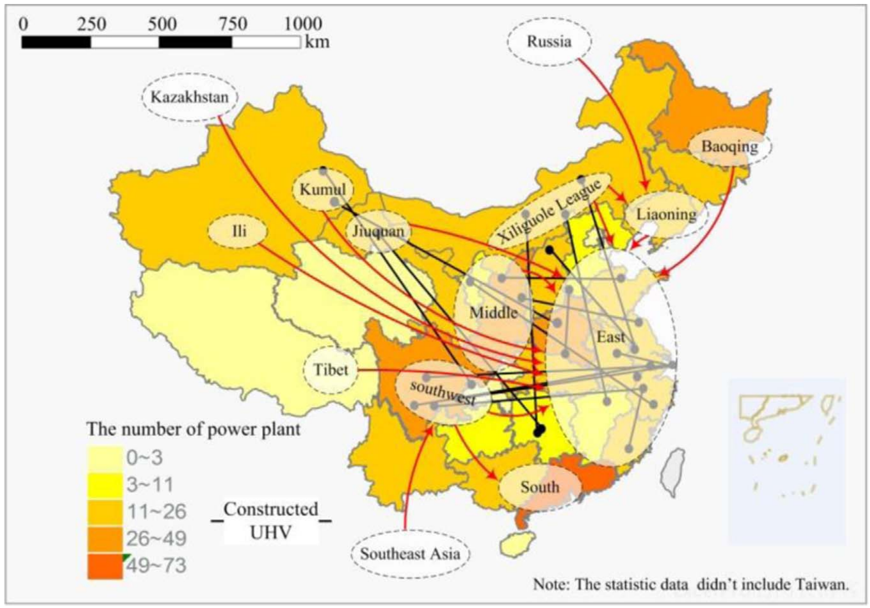

Fig. 7. Distribution of coal-fired power plants and UHV (2020).

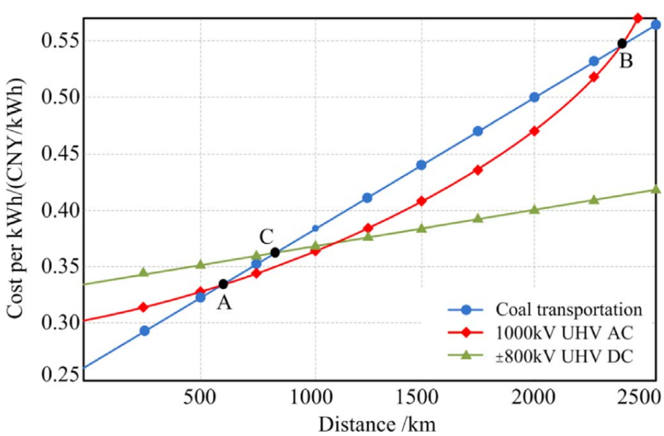

Fig. 8. Curves of the cost per kWh.

3.2.2. High investment cost of UHV

The high investment cost of UHV is one reason that restricts EPS development. For example, the investment for the Xiluodu-Jinhua ± 800 kV UHV DC Transmission Project (1680 km) is 23.855 billion CNY [85]. The investment per kilometers is 14.199 million CNY/km, while the investment of a general transmission project is 2–4 million CNY/km. A high investment cost induces difficulty in management and communication.

3.2.3. Immature clean coal technology

CCTs, such as desulfurization, denitrification, and high efficiency pulverized coal boilers, have better effects on pollution control. However, these technologies have not been industrialized because of their high application cost and poor economy [86]. A large technical gap between China and other developed countries exists in the design, manufacture and high parameter system optimization of large capacity coal-fired generating units. The coal gasification technology in China is far behind the foreign advanced level. A 600 MW supercritical pressure circulating fluidized bed and IGCC are still in experimental stages [87]. Coal-based polygeneration and CO_2 capture and storage, lignite quality improvements and processing, underground coal preparation and other clean coal technologies [88] have met obstacles. It is clear that CCT still does not satisfy the demand for industrial production.

3.3. Opportunity

3.3.1. Potential competitiveness of electricity price

Table 3 indicates that the converted unit price of electricity is higher than the converted unit price of coal and natural gas. However, over the long run and with merging with the international market, the price of natural gas will be gradually consistent to the real price [75]. The *2015 China Oil and Gas Industry Development Analysis and Outlook Report Blue Book* [89] declares that a "lower price of natural gas cannot reflect its scarcity, as well as the real value and real cost" and "natural gas price marketization reform should be accelerated". Thus, the scarce and non-renewable features of gas also determine the inevitable increase in price. Therefore, electricity price competitiveness will eventually surpass those of other fuels in the long term.

3.3.2. Largest clean coal market

It is verified that CCT has enormous potential in protecting the environment and improving the electricity generation efficiency. At present, China has become the largest clean coal market in the world [90] and CCT has been listed in the *China 21stCentury Agenda* [91], providing opportunities for the development and innovation of CCT.

3.3.3. More attention must be paid to wind and solar energy curtailment

China suffers from higher wind and solar energy curtailment. In the first half of 2015, the average ratio of wind curtailment was 15.2% [92], while the values in 2013 and 2014 were 11% [93] and 8%, respectively [94]. Additionally, the average ratio of solar curtailment in the first three quarters was 10% [95]. Fortunately, on December 28th, 2015, NEA issued *Management Approach on Full Acquisitions of Renewable Energy Generation*[96], giving priority to electricity generated by renewable energy resources and guaranteeing full acquisition of this power. The situation above shows that China has focused more attention on solving wind and solar curtailment, and UHV can realize the transmission of the electricity generated by renewable energy sources. Therefore, the increased attention that has been paid by the Chinese government to wind and solar energy curtailment provides a good opportunity to develop EPS.

3.4. Threat

3.4.1. Lack of complete policies

The policies for CCT, energy price, and electricity price subsidies are incomplete at the present stage.

1) CCT policy: There are a few special policies on CCT development. Current policies related to CCT development, such as R & D policies, industrial policies, environmental policies, and energy-saving policies, are not compatible [97]. A portion of the special funds is designated for the purchase of equipment, but does not involve the purchase of clean coal and demolition of backward coal equipment. Some emission standards are not practical, failing to consider the influences of scale differences and existing technologies. Additionally, an industry standard and certification mechanism for CCT have not been formed.
2) Energy price policy: The current energy price mechanism cannot reflect the real value of energy sources. In addition to the coal price, the prices of oil, natural gas and electricity are regulated by the government rather than the market, inducing problems such as inefficient resource allocation, overproduction, and so on. On October 15th, 2015, *Several Opinions to Push Forward the Reform of the Price Mechanism* [98] was issued by SC. This publication indicates that mechanisms for oil, gas and electricity pricing by the market will be established. It is clear that China needs to develop more special policies to support the reformation of the energy price; it is a long and hard process for electricity to gain a competitive advantage in price.
3) Electricity price subsidy policy: There are no strict rules for an electricity price subsidy. The enthusiasm of EPS end users is not sufficient. The objective of an electricity price subsidy is to encourage end users to use electricity power by reducing the use cost. However, the electricity price subsidy policy is still incomplete and needs to be improved. In Table 3, we calculate that only with less than 0.1034 CNY/kWh can the electricity price be more competitive than that of other energies, but the present price is 0.4883 CNY/kWh. Price reformation is a long-term and slow process; the electricity price has no advantage over the price of coal and natural gas in the short term. Therefore, a price subsidy and tax support are the preferred measures to promote EPS.

3.4.2. High risk in UHV management and finance

Slower approval procedures and more difficult project management are the main obstacles for UHV. A tremendous project investment, wide construction range and multiple investors are the basic features of UHV, which likely lead to interlinking problems between various levels of management, unequal rights and responsibilities, delayed cost accounting, and so on. In short, more risk is hidden in the construction and operation processes of UHV than in a general transmission project.

4. Discussion and conclusions

4.1. Discussion

Although renewable energy sources have made significant progress in recent years in China, renewable energy faces a variety of bottlenecks and questions in connecting to the power grid because of the intermittences of wind power and solar energy. The relief that renewable energy can provide to the tense situation of China's energy supply and the role of renewable energy in adjusting the energy structure are limited [99,100]. Therefore, in the short term, coal will be still the main fuel used in China. EPS in the present paper is defined as a substitute for coal with three main aspects: clean electricity generation, UHV development and decentralized coal reduction. EPS can promote the construction of UHV, impelling the accommodation of wind and solar power in remote areas of China. EPS can optimize the energy structure, simultaneously promoting the utilization of renewable energies and extending the market of renewable energies. EPS can optimize the consumption structure of coal and be an effective tool to reduce air pollution and impel the development of renewable energy.

According to the SWOT analysis above, although few weaknesses and threats of EPS exist in the present stage, the strengths and opportunities impel the development of EPS. Therefore, the present paper insists that EPS is a good substitute for coal. However, the advent of EPS in China needs the support of policy, technology, market, humanity, finance and many other internal and external factors. This paper gives some support measures that are listed below:

4.1.1. Rationalize energy price

At the present stage, the converted unit price of electricity is higher than those of LNP and natural gas, resulting in an inferior economic benefit. Energy price marketization reformation can make electricity price competitiveness stand out from those of other energies, and it is a long-term endeavor that needs to be met.

4.1.2. Complete electricity price subsidy

Compared with energy price reformation, an electricity price subsidy is a short-term and immediate measure to increase the economic benefit and social acceptance of EPS. Based on a current multi-step electricity price mechanism, the Chinese government can provide a gradient subsidy, meaning that the more electricity that is used, the more subsidies are offered. The government can also provide a subsidy for the purchase of electricity, electric appliances, clean coal, and coal-fired equipment dismantlement.

4.1.3. Impel optimization of UHV

China possesses UHV core and mature technologies and has established the standard system for UHV. However, in terms of the risks regarding the high cost, management and finance, China cannot stop the pace of advancement for optimizing the design, technology, construction material and management mode of UHV.

4.1.4. Innovate clean coal technology

CCT, such as coal-based polygeneration and CO_2 capture and storage, lignite quality improvement and processing, and underground coal preparation, has not been mastered. China should learn foreign advanced clean coal technology and promote CCT international compatibility.

4.1.5. Improve consumption ratio of thermal coal

In China, thermal coal consumption accounted for 55% of total coal consumption in 2013, while the ratio in America reached 91% in 2011 [101]. NDRC set a target that by 2020 the consumption ratio of thermal coal will be increased to 60% [102]. Therefore, increasing the concentrated utilization of coal in thermal plants and shrinking the decentralized coal market can contribute to the reduction in air pollution and growth in electrification level.

4.2. Conclusions

In China, the economic benefit of EPS is not currently obvious, but the environmental benefit is significant. As one of the main aspect of EPS, UHV can promote the consumption of renewable energies in remote regions. UHV management and technology optimization are solutions to lower the risk in UHV trans-provincial project management, finance, high construction cost, and so on. In terms of clean coal technology, a large gap exists between China and other developed countries. Fortunately, China has become the biggest clean coal market, providing a chance to innovate CCT. Reducing decentralized coal consumption by the end user is another important aspect of EPS. Enormous substitution potential and firm determination from the government will impel the realization of this aim. Policy support is also inevitable in the process of EPS development. Currently, an energy price policy, electricity price subsidy and other support policies have been positively planned and prepared. Therefore, EPS in China has a good development prospect, and electricity is a very good substitute for coal.

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