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Practice on Ultra-low Emission and Energy Efficient Technologies in Coal-fired Power Plants

Abstract Restructuring of China's energy mix is accelerating due to factors such as energy security, economic cost, climate change and environmental pressure. Efficient and clean utilization of coal-generated power therefore plays an increasingly important role in solving energy and environmental problems in China. Coal-fired power plants, with Shenhua Guohua Sanhe as one of the pioneers, followed trend of this era and adopted multiple ultra-low emission and energy efficient technologies, striving to be an industry leader in environmental protection, profitability and innovation. As a result, coal-fired power plants have seen ultra-low emissions of air pollutants and record-high energy efficiency, opening up a new era of more efficient and cleaner coal generation. By the end of 2015, Shenhua Group had had 45 ultra-low emission coal units, providing strong support for implementing of the national policy on ultra-low emission and energy efficient retrofit of coal-fired power plants across China.

Keywords: coal, power generation, ultra-low emission, energy efficiency

1 Introduction

Facing increasingly daunting challenges posed by energy security, climate change and the ecological environment, the revolution of energy production and consumption has become the theme of the energy sector today. Non-fossil energy and natural gas account for bigger proportion in the energy mix. However, China's per capita recoverable reserve of oil and gas is only 6% of the world average (International Energy Agency, 2014), with high dependence on import. The fundamental role of coal in China's energy structure is therefore expected to remain in the foreseeable future. For example, the total coal consumption in 2014 was 2.81 billion tons of standard coal, accounting for 66% of China's overall energy consumption (National Bureau of Statistics Energy Statistics Department, 2014). As one of the cleanest and most efficient ways to use coal, however, power generation is still fraught with NO_x, SO_x and dust emissions. In 2014, emissions of dust, SO_2 and NO_x from power generation reached 0.98 million, 6.2 million and 6.2 million tons, respectively, accounting for 5.63%, 31.40%, and 29.84% of total emissions of these three pollutants in China (China Electricity Council, 2015; Chinese Society of Electrical Engineering, 2015).

On June 13, 2014, China's president Xi Jinping gave a five-point instruction on pushing forward revolutions in energy production and consumption at the sixth meeting of the Central Leading Group on Financial and Economic Affairs. The instruction included four specific reforms and promotion of international cooperation in the energy sector. It was then followed by the *Action Plan on Energy Efficiency Improvement and Emission Reduction in Coal-fired Power Industry (2014–2020)* issued on September 12, 2014. Then State Council executive meeting on December 16, 2015 made it official that coal-fired power plants across China would have to be retrofitted with ultra-low emission and energy efficient technologies, signaling a new direction for energy development in China. Therefore, coal generation therefore is entering a new era characterized by green and intelligent technologies.

Closely following the trend of this new era and national policies, Shenhua Group (hereinafter referred to as Shenhua) works to implement the clean energy development strategy, aiming to become a world-class clean energy supplier and provider of clean energy technical solutions. Based on the latest *Air Pollutants Emission Standard for Coal-fired Power Plants*, Shenhua takes a step further to tighten up emission standards for its own coal fleet,

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targeting 5, 35 and 50 mg/Nm^3 respectively for dust, SO_2 and NO_x with benchmark oxygen concentration of 6% (Wang, Song, Chen, & Sun, 2015) in an effort to retrofit coal plants with ultra-low emission and energy efficient technologies. By the end of 2015, Shenhua had retrofitted 45 coal units represented by those in Sanhe and Zhoushan Power Plants. These efforts were expected to bolster implementation of the national policy for ultra-low emission and energy efficient retrofit of coal-fired power plants across China. Among all the retrofitted plants in Shenhua, Sanhe took the lead in technological innovation to integrate multiple ultra-low emission and energy efficient technologies for lower emissions and higher energy efficiency, making a demonstration among all retrofitted plants while ushering in the new era of highly efficient and clean coal-fired generation.

2 Ultra-low emission and energy efficient retrofit in Sanhe power plant

As an important power supplier for east Beijing, Sanhe operates with four units of 1.3 GW total installed capacities. Units 1 and 2 are 350 MW subcritical coal-fired units manufactured by Mitsubishi (completed desulfurization and heating supply renovation in 2007 and 2009, respectively) from the first construction phase. Units 3 and 4 are two 300 MW subcritical coal-fired co-generation units constructed in the second phase.

In July of 2014, Unit 1 passed ultra-low emission test, with dust, SO_2 and NO_x emissions of 5, 9 and 35 mg/Nm^3 respectively (Hebei Provincial Environmental Monitoring Center, 2014), first of its kind in the region of Beijing, Tianjin and Hebei. With the success of Unit 1, ultra-low emission and energy efficient upgrading have been subsequently carried out on the other three units, and the dust, SO_2 and NO_x emissions of which have outperformed those of natural gas turbines. Thus, the entire plant has achieved ultra-low emission operation. In particular, dust emission of Unit 4 was only 0.23 mg/Nm^3 (National Environmental Monitoring Center, 2015), creating a new record for retrofitted coal plants in China. The adjusted heat consumption of Unit 3 under turbine heat-rate acceptance (THA) conditions was 7,878.77 kJ/(kW·h) after retrofit of flow passage in the steam turbine, also one of the best among similar units in China.

In addition to electricity, Sanhe also supplies heat to people in Beijing and Hebei Province. The four units, with designed maximum heating capacity of 1,220 MW, can provide reliable heating for 24.4×10^6 m^2. In winter, heating supplied by Sanhe could replace 160 small coal-fired boilers, saving 325,000 t of standard coal every year.

2.1 Exploration and application of ultra-low emission technologies

As a pioneer in technological innovation, Sanhe uses industry-university-research institution collaboration to carry out research on key technologies and system integration, building up ultra-low emission technologies with Shenhua. The overall technical route is shown in *Figure 1*, i.e., highly-efficient low NO_x combustor + selective catalytic reduction (SCR) + low-temperature electrostatic precipitator (ESP) retrofitted with high frequency power + integrated desulphurization and de-dust process (additional spraying layer/revolving turbulator for wet flue gas desulfurization/highly efficient ridged demister and tubular demister in desulfurizer) + wet electrostatic precipitator + integrated chimney-cooling tower.

Based on different conditions of these four units, Sanhe came up with individualized retrofit goals for every unit. By integrating multiple technologies and formulating different technical routes, each retrofit process was engineered to be representative and demonstrative. Retrofit goals for every unit are shown in Table 1 below.

Dust control technology: Installation of low-temperature economizer before ESP for full recovery of waste heat and enhancing ESP efficiency. Retrofitting ESP with high-frequency power; installation of high-efficiency demister in desulfurization system and adding WESP at the end of desulfurization process in Units 1, 2 and 4 to ensure ultra-low emissions of dust (with gypsum).

SO_2 control technology: GGH systems are dismantled from Units 1 and 2 to eliminate the effects on emissions caused by air leakage in GGH. An additional spraying layer is applied in the absorption towers of Units 1 and 2, while revolving turbulator wet desulfurization technology is applied in Units 3 and 4. High-efficiency demister and precipitator are also installed. Optimal layout for outmost

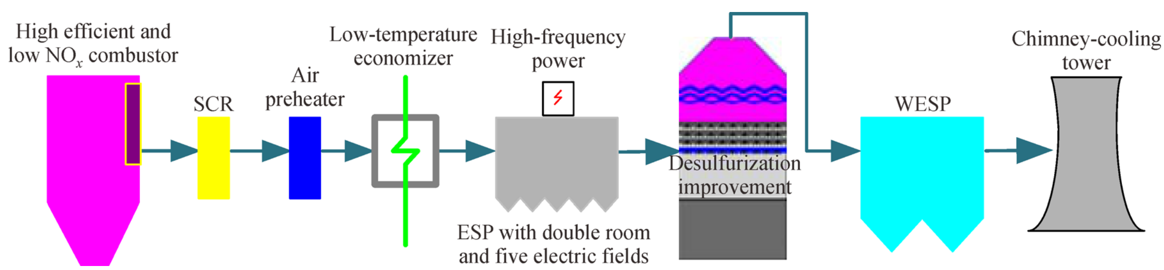

Figure 1. Ultra-low emission technical route for coal-fired power generation in Sanhe power plant. WESP: Wet ElectroStatic Precipitator.

Table 1

Design Target for Ultra-low Emission Retrofit in Sanhe Power Plant

Units	Dust (mg/Nm^3)	SO_2 (mg/Nm^3)	NO_x (mg/Nm^3)
Unit 1	5	35	50
Unit 2	3	35	50
Unit 3	3	15	25
Unit 4	1	15	25

nozzles is designed to eliminate SO_2 escape along the side walls, which ultimately reduces ultra-low SO_2 emission.

NO_x control technology: Low NO_x combustor is modified to ensure NO_x emission concentration of less than 200 mg/Nm^3 at the outlet of boiler under all operating conditions and less than 170 mg/Nm^3 at boiler maximum continuous rating (BMCR). SCR device is installed behind the economizer for ultra-low NO_x emission.

Flue gas from Units 1 and 2 is channeled through long distance fiberglass flue to towers of Units 4 and 3 respectively. Thus, cooling towers and chimneys of all units in Sanhe are integrated.

Figures 2–4 compare emission concentration levels of Unit 1 at full load before and after retrofit. Significant improvement of pollutant concentration can be noticed where average dust, SO_2 and NO_x emissions were 4.03, 20.95, and 39.11 mg/Nm^3 respectively with stable ultra-low emission performance.

Based on the successful retrofit and equipment selection of Unit 1, efforts were made to improve dust removal performance of Wet ElectroStatic Precipitator (WESP) in Unit 2, which reduced of dust, SO_2 and NO_x concentrations to 1.77, 15.88 and 31.62 mg/Nm^3 respectively at full operation capacity. In addition, further optimization was devised for emission reduction in Units 3 and 4 with concentration of dust, SO_2 and NO_x from Unit 4 decreased to an average of 0.51, 8.16, and 26.32 mg/Nm^3 respectively, significantly outperforming those of Units 1

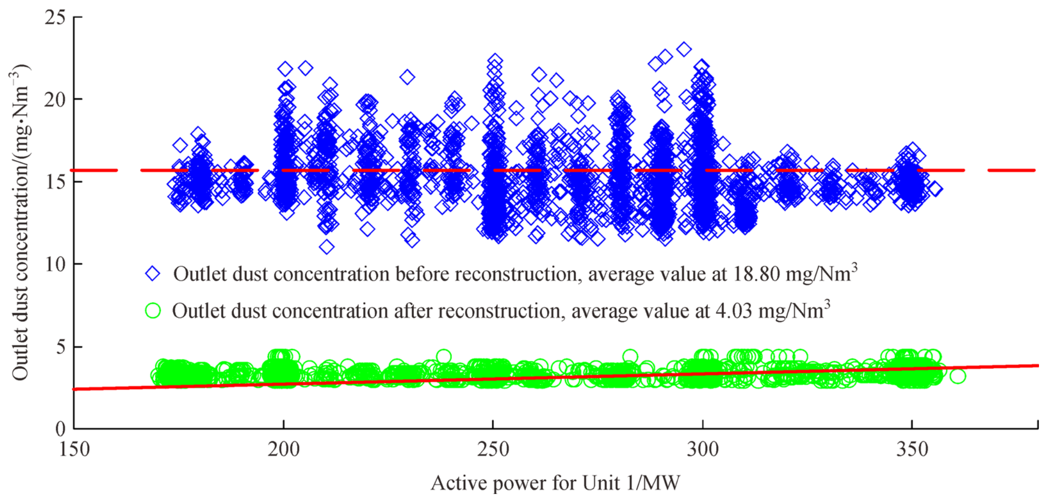

Figure 2. Dust emission concentration of Unit 1 at full operation capacity before and after retrofit.

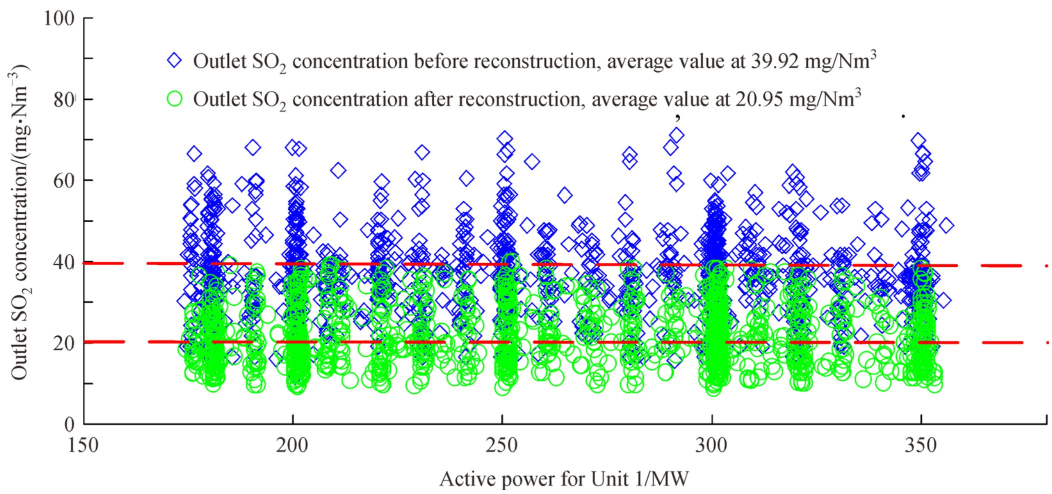

Figure 3. SO_2 emission concentration of Unit 1 at full operation capacity before and after retrofit.

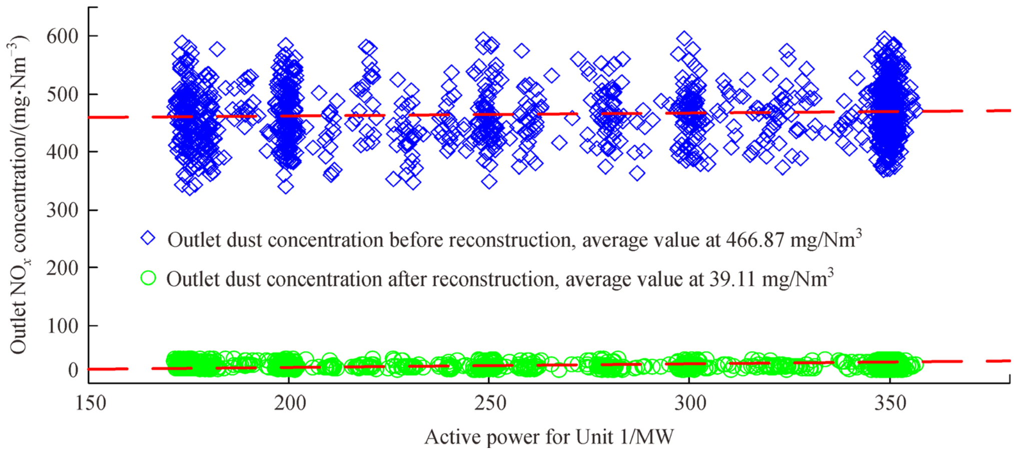

Figure 4. NO_x emission concentration of Unit 1 at full operation capacity before and after retrofit.

and 2. While ensuring desulfurization and denitrification efficiency, Unit 3, with no WESP due to lack of space, managed to achieve an average dust emission of 1.73 mg/Nm^3 by enhancing systemic de-dusting capability. As a national demonstration power plant, Sanhe has been regarded as an industry leader and model in innovation.

Table 2 shows cost increase per kilowatt hour due to ultra-low emission retrofit. The calculation takes into account lifecycles of the main equipment and additional retrofit equipment (including WESP, desulfurization reconstruction, low temperature economizer, etc.), assuming 15-year operation running 5,000 h every year.

2.2 Application of energy efficient technologies

Technologies for energy efficiency improvement in coal-fired power plants mainly include: Retrofit on steam turbine flow, comprehensive utilization of waste heat in boilers (such as low-temperature economizer), optimization of steam turbine cold-end, combination of induced draft fan and booster fan, and heat (steam) supply retrofit on pure condensing units. In addition, efforts were also made to retrofit on frequency conversion, air pre-heater sealing, ESP high-efficiency power supply, air heater, steam turbine vacuum system optimization, heat and drainage system optimization, and energy efficiency of utility system. These specific retrofits have all remarkably reduced energy consumption in equipment and systems. The overall technical route for energy efficiency improvement is shown in *Figure 5*.

Sanhe Power Plant has prioritized retrofitting of steam turbine flow for better energy efficiency. With fixed coal consumption in boilers and fixed capacity of main electric equipment, cutting-edge technologies and structure design were applied to improve flow passage efficiency and blade security. Advanced sealing technologies were also employed to reduce air leakage, remarkably improving the economic performance of the units. After flow retrofit, the coal consumption of the units has been reduced by more than 16 g/(kW·h).

Before retrofit, thermodynamic tests on Units 3 and 4 showed thermal efficiency of steam turbine was 3%–6% lower than that of the designed figure, indicating serious efficiency inadequacy and waste of energy. Also, the annual coal consumption before retrofit was 28,050 t more than that after retrofit, amounting to an economic loss of about 18 million RMB every year. In this context, the flow capacity increase of steam turbine and the retrofit of steam sealing were carried out on the two 300 MW subcritical units. Steam turbine heat consumption (adjusted under THA operation condition) before and after the retrofit is shown in *Figure 6*, which indicates a substantial reduction of heat consumption in steam turbine after flow passage retrofit. With better energy efficiency and economic

Table 2

Economic Analysis of Ultra-low Emission Retrofit

Generation Units	Investments on Fixed Assets (10,000 CNY)	Capacity (MW)	Influence on tariff (tax inclusive) (0.01 CNY/(kW·h))
Unit 1	5856	350	0.67
Unit 2	6198	350	0.77
Unit 3	4955	300	0.61
Unit 4	7036	300	0.90

Note: Fixed asset investment is total retrofit investment deducting retrofit investment to meet the regulated emission standards for coal-fired power plants.

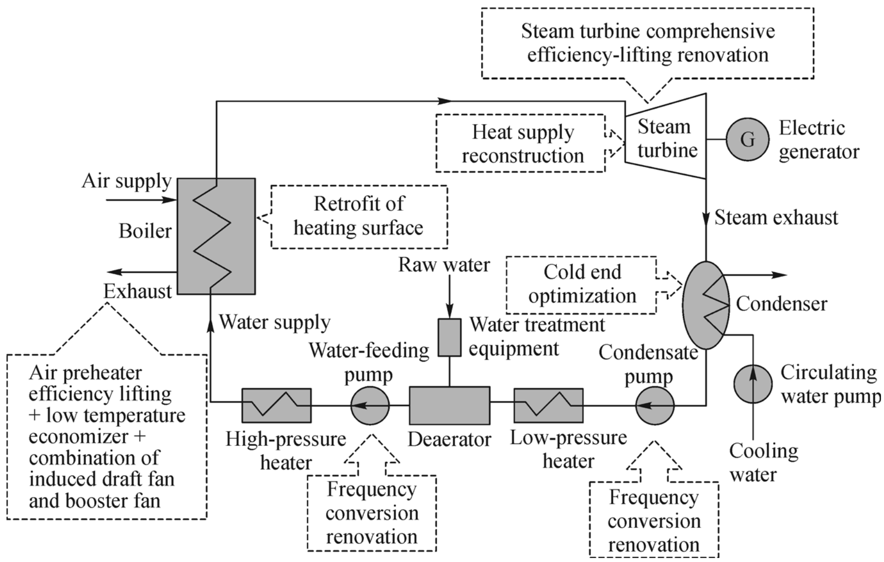

Figure 5. The overall technical route for energy efficiency retrofit.

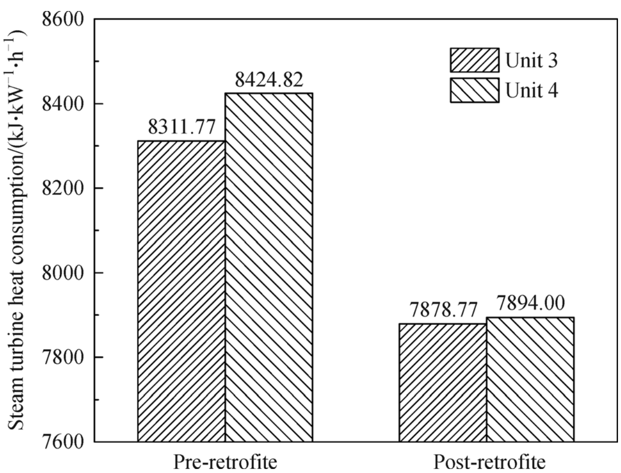

Figure 6. Comparison of steam turbine heat consumption before and after the flow passage retrofit.

performance, the units have seen safe and stable operation of both generation units and auxiliary equipment with vibration, expansion, expansion differential, axial displacement and bearing temperature of steam turbine in each experimental condition all within the safety range.

In addition, recovery and comprehensive utilization of waste heat from flue gas were made possible with the installation of low-temperature economizers before electric precipitation. Energy efficiency improvement is shown in Table 3.

Table 3

Energy Efficiency Improvement through Flue Gas Waste Heat Recovery by Low-temperature Economizer

Generation Units	Reduction in coal consumption (g/(kW·h))		
	100% load	75% load	50% load
Unit 1	2.14	1.52	0.70
Unit 2	1.69	0.84	0.47
Unit 3	–	–	–
Unit 4	1.55	1.03	0.44

2.3 Summary on Sanhe ultra-low emission retrofit

The successful demonstration of Sanhe adequately proved the technical feasibility of ultra-low emission retrofit, which is also reliable in monitoring and acceptable in cost. Striving to be an industry leader in environmental protection, profitability and innovation, with over 30 years of rapid growth, China is now embracing the new norms in its economic development while paying more attention to ecological improvement. It is therefore of great relevancy and significance for coal-fired power plants to retrofit the equipment for ultra-low emission and better energy efficiency, with technological innovations as the fundamental guarantee. It is also important to shift from learning, introducing and absorbing advanced experience, concepts and technologies from developed countries in the past to indigenous innovation now. Ultra-low emission retrofit and its long-term operation can be attributed to technological innovation, thanks to continuous efforts to develop and apply new techniques, equipment and on-line monitoring for pollutant removal and constant optimization of the way environmental protection facilities operate. It is in this way that coal-fired plants could better meet the increasingly stringent requirements on emissions (such as heavy mental, NH_3 and PM 2.5) while reducing energy and material consumption at the same time. The successful practice of ultra-low emission retrofit in Sanhe could serve as the reference for other coal-fired power plants.

Technological innovation in Sanhe continues after the ultra-low emission retrofit, with priority now given to improving stability and economic viability of the environmental protection system. While exploring new technologies to reduce conventional pollutant emissions, Sanhe also cooperates with research institutions to conduct research and demonstration of other frontier technologies. Technologies for heavy metal-mercury measurement and removal were developed, and a mercury removal demonstration device for 300 MW unit has also been built. With the existing environmental protection facilities, mercury concentration in flue gas from Units 2 and 3 are 3.33 and 2.45 $\mu g/Nm^3$, respectively, less than the national standard of 0.03 mg/Nm^3 (30 $\mu g/Nm^3$) stipulated in the *Air Pollutants Emission Standard for Coal-fired Power Plants* in 2011. The ultimate target of subsequent research in mercury removal is 1/10 of national standard (3 $\mu g/Nm^3$), with efforts made to bring concentration of mercury and its compounds in flue gas to less than 1 $\mu g/Nm^3$.

The Phase 3 expansion of Sanhe will adopt highly efficient supercritical units made by domestic manufacturer for higher generation and energy efficiency with SSS clutch and NCB pattern employed for maximum heat supply in winter. Taking full advantage of previous ultra-low emission practice, dust, SO_2 and NO_x emissions of the new units are less than 2.4, 12, and 25 mg/Nm^3, respectively. The maximum design load for heat supply in Phase 3 is 950 MW, with 2×350 MW ultra-supercritical heat supply units. Once in operation, the new units are expected to replace 52 small boilers, contributing to reduction of dust, SO_2 and NO_x emissions by 765.33, 522.52 and 119.99 t, respectively every year.

3 Prospect of clean coal generation

Reduction of fossil fuels in the primary energy mix is the trend of China's energy development. However, with an energy structure characterized by the abundance of coal and the scarcity of oil and gas, it is important that China sticks to a diversified energy strategy, where coal serves as the fundamental energy with coordinated development of nuclear and renewable energy. The practice of Sanhe proves that highly efficient and ultra-low emission operation of coal-fired power plants is safe, affordable and reliable. According to statistics released by China Electricity Council in 2014, coal consumed by generation units with capacity of 6,000 kW and above accounted for 41.88% of total coal consumption, which was lower than the average level of developed countries. In the new era, efforts should be made in the following areas in order to promote R&D and collaborative innovation and take the lead in developing technologies for clean and efficient utilization of coal:

(1) In utilization, use more coal for clean and efficient power generation while reduce fragmented consumption by households and small boilers. In mining, reduce production of low-grade coal with high sulfur and ash content whilst increase beneficiation and pre-processing so as to improve coal quality for power generation and reduce emissions.

(2) Step up research and development of technologies for efficient and thorough pollutants removal and energy efficiency improvement. Emphasis should be placed on tapping the potential of pollutants removal in coal combustion by exploring high-efficiency and low NO_x combustion technologies, reducing the use of ammonia, extending the life cycle of catalyst and accelerating the research and application of low temperature catalyst. In the meantime, efforts should also be made to achieve coordinated control and deep cleaning of multiple pollutants, optimize the operation of environmental protection equipment and seek balance between energy efficiency and environmental protection. These would all be of great practical importance to the clean and efficient utilization of coal.

(3) Further improve the thermal efficiency of coal-fired units, pushing forward the development and application of 610/620 °C ultra-supercritical unit, secondary reheat unit and even 700 °C ultra-supercritical generation technologies.

(4) Promote the development of cogeneration and polygeneration systems. The cogeneration unit, which could effectively reduce the cold source loss, can achieve a theoretical energy utilization efficiency of above 80%. It is therefore considered an important substitute for small coal-fired boilers, reducing fragmented household coal combustion and saving energy.

(5) Promote the application of circulating fluidized bed (CFB) technology, which is characterized by strong adaptability to various coal types, stable combustion, wide range for load regulation and low cost in main pollutants control. CFB technology would be of great significance for the utilization of low-grade coal with high efficiency and low pollution.

(6) Accelerate research on carbon capture, utilization and storage (CCUS) technologies. Significant progress has been made so far on chemical absorption, oxy-fuel combustion and ICCC for CO_2 capture. The key to CCUS application however lies on reducing investment cost and system stability and system optimization.

(7) Promote demonstration of concentrating solar power (CSP)/coal-fired hybrid power generation. Compared with photovoltaic power generation, CSP system operates with better output stability and higher adjustability. Combining CSP and coal-fired generation could achieve widespread energy utilization with optimized resource allocation. It is also one of the options to integrate desalination device with the coupled system for clean and efficient coal-fired generation as well as cost reduction of CSP generation.

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