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Clean Coal Technologies in China: Current Status and Future Perspectives Shiyan Chang^a, Jiankun Zhuo^b, Shuo Meng^a, Shiyue Qin^{a,b}, Qiang Yao^{a,b,*}

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ABSTRACT

Coal is the dominant primary energy source in China and the major source of greenhouse gases and air pollutants. To facilitate the use of coal in an environmentally satisfactory and economically viable way, clean coal technologies (CCTs) are necessary. This paper presents a review of recent research and development of four kinds of CCTs: coal power generation; coal conversion; pollution control; and carbon capture, utilization, and storage. It also outlines future perspectives on directions for technology research and development (R&D). This review shows that China has made remarkable progress in the R&D of CCTs, and that a number of CCTs have now entered into the commercialization stage.

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1. Introduction

Coal is the dominant primary energy source in China, accounting for about 64% of the total primary energy consumption in 2015 [1]. It is the major source and material for power generation, energy-intensive industries (steel, cement, etc.), and residential and commercial heating. In addition, it is a major source of greenhouse gases (GHGs) and air pollutants in China. In 2013, about 9.0231×10^9 t of carbon dioxide (CO₂) were emitted from fuel combustion in China, with more than 83% coming from the combustion of coal [2]. In 2012, about 79% of sulfur dioxide (SO₂), 57% of nitrogen oxides (NO_x), and 44% of particulate matter (PM) came from the direct combustion of coal, and about 93% of SO₂, 70% of NO_x, and 67% of PM emissions came from all kinds of coal utilization (including direct combustion emission and emission from coke stoves and other industrial furnaces) [3]. Although a great number of policy measures have been launched to control the consumption of coal in order to address climate change and alleviate air pollution, it is projected that coal will still play a dominant role in China's energy consumption portfolio-over 50% by 2030 [4] and around 30% by 2050-even considering the high penetration of renewable energy [5]. Therefore, it is necessary to develop more efficient and clean technology options to enable China to continue to benefit from using its abundant and affordable coal resources.

Clean coal technologies (CCTs) are technologies that facilitate the use of coal in an environmentally satisfactory and economically viable way [6]. China has made remarkable progress in recent years in CCTs development. By the end of 2014, the installation capacity of ultra-supercritical coal-fired plants exceeded 100 GW. A 250 MW integrated gasification combined cycle (IGCC) demonstration power plant was put into operation. Localized water slurry gasification and dry feed pressurized gasification technology with a capacity of more than 2000 t·d⁻¹ has been realized. The world's first coal direct liquefaction plant, with a capacity of more than 1 Mt·a⁻¹ (oil), was completed in 2008. The commercial demonstration plants of coal-to-olefin have also been built. Indirect coal liquefaction plants with capacities of 160-180 kt have been built. Ultra-low-emission coal-fired power generation technology has been successfully demonstrated. Successful operation of 100 kt CO₂ capture industrial equipment in a power plant has occurred. An enhanced oil recovery (EOR) demonstration project with a capacity of 150 kt and a CO₂ geological storage demonstration project with a capacity of 100 kt have been completed.

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Innovation and adoption of these technologies has played and will continue to play an important role in the green low-carbon transformation of China.

CCTs cover a wide range of coal production and utilizationrelated technologies, including green mining, coal purification, high-efficiency power generation, advanced coal conversion, pollution control, and carbon capture, utilization, and storage (CCUS). In the paper, current status and future perspectives of four kinds of CCTs in China are introduced sequentially as coal power generation, coal conversion, pollution control in coal-fired power plants, and CCUS.

2. Coal power generation

Coal-fired power generation technologies mainly consist of the traditional direct combustion of coal and the new coal gasification power generation technical routes. Regarding the direct combustion of coal, subcritical, supercritical, ultra-supercritical, and circulating fluidized bed (CFB) power generation technologies are widely used today. Coal gasification power generation technology mainly involves IGCC technology, an advanced power generation technology with high power generation efficiency and excellent environmental performance.

2.1. Current status

In the 11th Five-Year Plan (2006–2010) for national economic and social development, the government stipulated a targeted 20% reduction in energy consumption per unit gross domestic product (GDP) in 2010 relative to that in 2005, and a 10% reduction in SO₂ emissions. To meet this target while continuing the robust development of China's power industry, China promoted a program of "shutting down small-scale thermal power plants" in order to replace small units with large ones in 2007. Meanwhile, China also conducted research into developing supercritical and ultra-supercritical units with power generation capacities over 600 MW [7]. High-efficiency and clean power generation technologies were applied to transform existing old thermal power units. These measures greatly improved the efficiency of thermal power generation industry in China. During the period of the 12th Five-Year Plan, China conducted basic research into 700 °C ultra-supercritical power generation [8]. Researches into CFB and IGCC were also further conducted [9,10]. And the commercial demonstration of the largest 600 MW supercritical CFB boiler units in the world was put into operation [9].

This achievement greatly contributed to the optimization of the thermal power industry structure, the comprehensive enhancement of coal-fired power generation efficiency, and the reduction of pollutant emissions. The power supply coal consumption rate reduced significantly these years as shown in Fig. 1 [11,12].

2.1.1. Supercritical and ultra-supercritical coal-fired power generation technology

China has now realized the great leap forward development of ultra-supercritical coal-fired power generation technology. By the end of 2014, the total installed capacity of ultra-supercritical units exceeded 100 GW, and these units formed the majority of newly constructed units in China. One of the 1000 MW ultra-supercritical thermal power projects in China, the Shanghai Waigaoqiao No. 3 power plant, implemented a series of innovations and optimizations toward energy saving and emission reduction. A coal consumption rate of 276 gce·(kW·h)⁻¹ (gce means gram coal equivalent) was attained by the plant, reaching the forefront of the international level.

Chinese researchers developed a 600 MW large-scale air-cooling



Fig. 1. China coal-fired power supply coal consumption rate [11,12].

system, and developed and constructed the world's first 1000 MW ultra-supercritical air-cooling unit. The total installed capacity of the units equipped with the air-cooling system now reaches 66 GW.

The 1000 MW double-reheat ultra-supercritical units have been built in China with efficiency more than 47% [13]. Two sets of 1000 MW double-reheat ultra-supercritical units at the Guodian-Taizhou power plant completed their grid connection in 2015. The power supply coal consumption rate of these sets has achieved 266.53 gce-(kW·h)⁻¹. Each unit of the plant is designed and manufactured entirely in China, and currently exhibits the world's highest parameters and highest efficiency. The technology of these doublereheat ultra-supercritical units has been applied in three power plants.

China now has the foundation and ability to design and manufacture 600 MW/1000 MW ultra-supercritical generator units. Chinese researchers have also gathered rich experience in the operation of 600 MW/1000 MW ultra-supercritical generator unit boilers. Units designed and manufactured in China have been exported to foreign countries. These achievements have established a solid technological foundation for the further development of supercritical power generation technology with higher parameters (exceeding 600 °C and 700 °C).

2.1.2. Supercritical CFB boiler power generation technology

A large proportion of China's coal resources has a high sulfur content. The coal-washing process produces a large amount of coal gangue that needs to be used. CFB combustion technology, with its wide fuel scope, low cost of desulfurization, and low NO_x emissions, has the advantage of largely using this kind of fuel. Thus far, China's CFB combustion boiler power generation capacity is nearly 100 GW and includes a total of more than 3000 CFB boiler units—the largest number of such units in the world.

Regarding the large-scale capacity of CFB boiler technology in China, research, manufacturing, and demonstration operations at the 300 MW level have been completed, and batch production has been achieved. The 600 MW supercritical CFB boiler demonstration project that was developed, designed, and manufactured domestically has been put into commercial operation in Baima, Sichuan (Fig. 2) [14]. It is designed for coal with high ash content and high sulfur content and for lean coal with low calorific value. The project comprises a CFB boiler design system and product system [14,15].

2.1.3. IGCC technology

Six coal-based IGCC power stations have been put into operation around the world to date, including two in the US, two in Europe, one in Japan, and one in China. The 330 MW IGCC demonstration project owned by the European Union (EU) has the largest unit capacity in the world of any IGCC power station, with its net efficiency of 45% (lower heating value, or LHV). Researches into the H-class



Fig. 2. Demonstration project of the 600 MW supercritical CFB boiler at the Baima power plant [14]. EHE: external heat exchanger; HP: high pressure; LP: low pressure; MP: medium pressure; RH: reheater; SHI: super heater; SHII: secondary super heater.

gas turbine and high-temperature syngas purification technology, integrated gasification humid air turbine (IGHAT), integrated gasification fuel cell system (IGFC-CC), and poly-generation technology have been conducted globally to further increase the efficiency of IGCC power generation.

With the support of the Ministry of Science and Technology (MOST) of China during the periods of the 10th, 11th, and 12th Five-Year Plans, Chinese researchers gathered rich experience in the design, manufacturing, and operation of large-scale coal gasification technology, synthesis gas heavy-duty turbine technology, and system optimization integration, design, operation and control technology, thus laying a firm foundation for the further development of IGCC and poly-generation technologies with larger capacity. The Huaneng Tianjin 1 × 250 MW IGCC demonstration project began in 2009. In 2012, the gasifier was successful ignited. To date, the project has been under operation with 41% (LHV) efficiency, and its operation reliability will be improved further [10,16,17].

2.2. Future perspectives

(1) High efficiency and ultra-high parameter are the development trend of coal-fired power generation technology. It is predicted that China's total thermal power capacity will reach 1.079 × 10⁹ kW by 2020 [18]. For the next stage of thermal power generation, the singleand double-reheat supercritical power generation technology at 1 GW-level should be further developed. It will exceed 600 °C, have a parameter of 28 MPa, and provide an efficiency increase of 2%-3%. Based on this development, key technological research on hightemperature heat resistant alloy material and demonstration of the 600 MW supercritical generator unit, which exceeds 700 °C, will be conducted, providing a 6%-8% increase in efficiency, with a system efficiency reaching 50%-52%. In the meantime, a batch of lowparameter and small-capacity units will be transformed to enhance their efficiency; in particular, 300 MW and 600 MW subcritical units will be transformed into supercritical units, with an efficiency improvement of 3%.

(2) High flexibility of coal-fired power plants is needed to balance power grids by compensating for variable electricity supply from renewable energy sources. The increasing proportion of renewable energy power generation in China is having an increasingly prominent impact on the stability of the grid. Because the system lacks large-scale energy storage sections, coal power has become the primary means of balancing the power grid. Coal subsystems that are used to provide a rapid response to frequent changes in load experience decreased system performance and component life. Thus, a major problem is how to strengthen the overall system load rapid response capability, and how to retain an efficient response with clean operation. The system control strategy can be optimized for high flexibility of coal-fired power plants in the large-scale renewable energy power grid. Achieving flexible operation is the main direction for the future development of coal utilization technologies. The researches on new design methods for system flexibility and control strategies for running operation are carried on in China.

(3) Fuel flexibility is another important issue in coal-fired power generation technology. Even though the general CFB boiler technology in China has reached a world-leading level, it still holds potential for its application scale to be enlarged, its efficiency to be increased, and its low-grade fuel flexibility to be improved. In order to increase the reliability of low-grade fuel CFB boiler technology, it is necessary to continuously conduct research and manufacturing for the 600 MW ultra-supercritical CFB boiler. The serial research and engineering demonstration of the energy-saving 50–300 MW supercritical CFB boiler should also be carried out further.

3. Coal conversion

Coal conversion technologies include all kinds of chemical conversion pathways for coal aside from that of combustion [19]. In this section, five coal conversion technologies will be introduced: coal gasification, coal liquefaction, coal-to-synthetic natural gas (coal-to-SNG) conversion, coal-to-chemicals conversion, and low-rank coal pyrolysis.

3.1. Current status

3.1.1. Coal gasification

Gasification is a very efficient method for converting solid fuels into gas fuels, starting from many different types of organic material [20]. It is one of the most important upstream technologies of the entire conversion process, which further produces liquid fuels, SNG, chemicals, hydrogen, and so forth. Pressurized gasification technologies—that is, General Electric's pressurized gasification technology with water coal slurry and Shell's dry feed pressurized gasification technology—have already been widely used in the chemical industry in China [21]. In the last decade, many new gasification technologies have been developed and rapidly progressed.

Entrained-flow gasification technology has reached the commercial stage (Table 1):

(1) Multi-opposed-burner coal water slurry gasification has been developed by the East China University of Science and Technology (ECUST). During the period of the 10th Five-Year Plan (2001–2005), two demonstration plants were built with the capacities of 750 t·d⁻¹ and 1150 t·d⁻¹ [23]. During the period of the 11th Five-Year Plan (2006–2010), several larger-scale units with a capacity of 2000 t·d⁻¹ were constructed. In 2014, a larger unit with a capacity of 3000 t·d⁻¹ was put into operation in the Inner Mongolia Autonomous Region.

(2) (Non)-molten slag-grading gasification technology, also called the Tsinghua gasifier, has been continually upgraded from the first generation in 2002 to the third generation plus in 2015. Two gasifiers with a capacity of 500 t-d^{-1} were successfully run in 2006; since then, more than 30 gasifiers using Tsinghua technology have been put into operation.

(3) In 2004, the Xi'an Thermal Power Research Institute Co., Ltd. conducted a pilot-scale test of a $36-40 \text{ t-d}^{-1}$ (10 MW) two-stage dry pulverized coal pressurized gasifier [24]. The same technology was also applied in the Tianjin IGCC project of the China Huaneng Group in 2012; this gasifier had a capacity of 2000 t-d⁻¹.

(4) Other entrained-flow pressurized gasification technologies, such as multi-component slurry gasification technology, the dry powder gasification process with a single burner, and crushed coal pressurized gasification, have also been developed and built in commercial demonstration plants with capacities of 1000– $3000 \text{ t} \cdot \text{d}^{-1}$.

Research into new gasification technologies has also been

conducted. An underground coal gasification demonstration base was built by the ENN Group and started to produce gas in 2009, with a daily gas production of up to 3×10^5 m³ and an accumulative generated electricity of over 4.7 GW-h. This technology has realized continuous and stable gasification to date [25]. However, the problems of underground pollution and sustainable operation are still two major challenges to be addressed in the future. Other advanced gasification technologies, such as catalytic gasification, hydro-gasification, and supercritical gasification, have also been widely explored, and several small-scale pilot plants have been built.

3.1.2. Coal liquefaction

In the field of coal liquefaction, the Shenhua Group built the world's first and largest 1 Mt·a⁻¹ direct liquefaction facility in 2004. This facility has been successfully put into operation at the end of 2008. The final products of the facility include diesel fuel, naphtha, and liquefied gas. Spaceflight kerosene and aviation jet fuel from the coal liquefaction process have also been tested recently at this facility. A rocket engine powered by liquid oxygen coal-based spaceflight kerosene was jointly developed by the Shenhua Group and the China Aerospace Science and Technology Corporation. Trial operation of this engine was completed in 2015 [26]. A coal and oil co-processing technology demonstration plant with a capacity of 450 kt·a⁻¹ has also been built by the Shaanxi Yanchang Petroleum (Group) Co., Ltd.

In the field of indirect liquefaction, Institute of Coal Chemistry and Lu'an Group are conducting researches into low-temperature slurry bed technology, high-temperature slurry bed technology, and high-temperature fixed fluidized bed technology [27,28]. During the period of the 10th Five-Year Plan, three indirect liquefaction pilot plants were built with capacities of 160 kt·a⁻¹, 160 kt·a⁻¹, and 180 kt·a⁻¹, respectively [28]. A demonstration project of a low-temperature slurry bed with 1 Mt·a⁻¹ capacity is

Table 1

Technology development status of coal conversion technologies in China.

| Coal conversion | technologies | Status by 2015 | Descriptions |
|-------------------------------------|---|--------------------------|---|
| Coal gasification | Entrained-flow gasification | Commercial/mature | More than 100 gasifiers have been built or are planned to be built |
| | Fluidized gasification | Demonstration | Pilot test has been completed; commercial demonstration is now in progress |
| | Fixed-bed gasification | Mature | Applied widely in China with most of the technologies being introduced from abroad |
| | Underground coal gasification | Demonstration | A demonstration project has been operated successfully |
| | Catalytic gasification | Pilot | Pilot tests are in progress |
| | Hydro-gasification | Pilot | Pilot tests are in progress |
| | Supercritical gasification | Pilot | The largest pilot plant test platform (6 $t \cdot d^{-1}$) in China was established in 2011 |
| Coal liquefaction | Direct | Commercial | The world's first and largest commercial plant has been operated successfully |
| | Indirect | Commercial | Several large-scale demonstration plants have been built |
| Coal-to-SNG | | Pilot | Domestic researches are still at the stage of pilot research, with some going through the industrial sidetrack test successfully |
| Coal-to-olefin | Coal-to-methanol-to-olefin (coal-to-MTO) | Demonstration/commercial | Commercial demonstration plants have been built based on various pathways, such as dimethylether/methanol-to-olefin (DMTO), DMTO-II, and Sinopec methanol-to-olefin (S-MTO) |
| | Coal-to-methanol-to-propylene (coal-to-MTP) | Pilot | A pilot test has been completed; demonstration plants are under construction |
| | Syngas selective conversion to light olefin | Laboratory | A new catalyst has reportedly been developed |
| Coal-to-methanol-to-aromatics | | Demonstration | A pilot test has been completed; demonstration plants are under construction |
| Coal-to-methanol-to-ethylene glycol | | Demonstration | Demonstration plants have been constructed |
| Low-rank coal pyrolysis | | Pilot & demonstration | Pilot and demonstration projects have been built based on various pyrolyzers, such as revolver, moving bed, fluidized bed, and downer |

The status-rating method is in line with that of the Electric Power Research Institute (EPRI) [22]. "Mature" indicates significant commercial experience (several operating commercial units); "commercial" indicates nascent commercial experience; "demonstration" indicates a concept verified by an integrated demonstration unit; "pilot" indicates a concept verified by small pilot facility; "laboratory" indicates a concept verified by laboratory studies and initial hardware development. in the equipment-testing stage, and a 4 Mt·a⁻¹ large-scale hightemperature slurry bed industrial equipment is under construction.

3.1.3. Coal-to-SNG conversion

Several large-scale coal-to-methane plants are in service or under construction in China. Most of these projects apply existing gasification and methanation technologies. For example, crushed coal pressurized gasification technology was applied in the Datang Hexigten Banner project $(4 \times 10^9 \text{ m}^3 \cdot \text{a}^{-1})$, the Datang Fuxin project $(4 \times 10^9 \text{ m}^3 \cdot \text{a}^{-1})$, and the China Kingho Ili Kazak Autonomous Prefecture project $(5.5 \times 10^9 \text{ m}^3 \cdot \text{a}^{-1})$. In addition, an adiabatic fixed-bed reactor has been widely used for the methanation process in current approved projects.

Domestic research and development (R&D) in coal-to-SNG conversion has been carried out recently. The Datang International Chemical Technology Research Institute Co., Ltd. has built a methanation plant with a capacity of 3000 m³·h⁻¹ (SNG), and has realized stable operation for more than 5000 h. The average methane content of the products is 96.41% [29]. The methanation catalyst that was developed has successfully gone through the industrial sidetrack test. The Southwest Research and Design Institute of Chemical Industry and the China National Offshore Oil Corporation (CNOOC) Gas & Power Group Ltd. also jointly developed a methanation process. Their constructed 2000 m³·h⁻¹ plant has been operated successfully. The Dalian Institute of Chemical Physics (DICP) and the Northwest Research Institute of Chemical Industry have also carried out research on methanation.

Water pollution is a serious challenge of the coal-to-SNG industry. Wastewater emitted during coal gasification has a complex composition, with high concentrations of recalcitrant compounds and high toxicity [30]. Until now, wastewater treatment technologies have mainly been developed by the municipal wastewater treatment industry; however, specific technologies for coal-to-SNG wastewater treatment are necessary. A project titled "Coal Gasification Wastewater Treatment and Reuse Technology" has been supported by the National High-tech R&D Program. The activated coke adsorption and biological treatment technologies developed in this project have been applied in the Datang Hexigten Banner demonstration project [29]. Other pathways to reduce and reuse wastewater have been explored. For example, the combination of crushed-coal pressurized gasification and water-coal slurry gasification was proposed in the scheme of the 4×10^9 Nm³·a⁻¹ coal-based SNG project in East Junggar, the Xinjiang Uygur Autonomous Region. According to their scheme, wastewater from the crushed-coal pressurized gasifier will be treated and reused in the subsequent water-coal slurry gasifier [31].

3.1.4. Coal-to-chemicals conversion

Research into coal-to-olefin technology has been systematically conducted in China. DICP has developed a dimethylether/ methanol-to-olefin (DMTO) process. The first commercial unit applying the DMTO process was successfully started in 2011, with a capacity of 600 kt·a⁻¹. The DMTO-II demonstration unit was built in 2014, and contained a 1.8 Mt·a⁻¹ methanol unit and a 700 kt·a⁻¹ coal-based olefins unit. The Sinopec methanol-to-olefin (S-MTO) process was developed by the Sinopec Shanghai Research Institute of Petrochemical Technology, and was applied by the 600 kt·a⁻¹ plant of Sinopec Zhongyuan Petrochemical Co., Ltd. in Henan, which started up successfully and produced qualified polymer-grade ethylene and propylene products in 2011. Tsinghua University developed a coal-to-methanol-to-propylene (coal-to-MTP) process called fluidized-bed methanol-to-propylene (FMTP). Its industrial pilot test has been verified, based on a unit with a capacity of 30 kt·a⁻¹. Considerable progress has been made recently in direct-synthesis gas conversion to light olefins via the Fischer-Tropsch synthesis (FTS). In addition, a new process that enables selective conversion of syngas by a bifunctional catalyst has been developed by DICP [32].

With regard to coal-to-aromatics technology, methanol aromatization is being widely applied and researched. A fluidized-bed methanol-to-aromatics (FMTA) process has been developed by Tsinghua University. The first FMTA pilot plant, with a capacity of 30 kt·a⁻¹ (methanol), was constructed and operated successfully, and a 1 Mt·a⁻¹ FMTA industrial demonstration plant has been planned. The Institute of Coal Chemistry of Chinese Academy of Sciences and Sedin Engineering Co., Ltd. jointly developed the fixed-bed methanol-to-aromatics (MTA) process. A demonstration project with a capacity of 100 kt·a⁻¹ has been successfully built and operated. The Beijing University of Chemical Technology and the Shanghai Research Institute of Petrochemical Technology have also developed MTA technology.

With regard to coal-to-ethylene glycol technology, the Fujian Institute of Research on the Structure of Matter developed a core catalyst and successfully operated a demonstration plant with a capacity of 20 kt·a⁻¹ in 2009. Since then, several commercial demonstration plants have been built. ECUST also conducted research in this field. After completing an assessment of the continuous and stable operation of a 1000 t·a⁻¹ pilot plant in 2011, several demonstration plants (with capacities greater than 100 kt·a⁻¹) have been constructed. By the end of 2015, the total production capacity of coal-to-ethylene glycol had reached 2.11 Mt·a⁻¹ [33].

3.1.5. Low-rank coal pyrolysis

Low-rank coals (lignite and subbituminous coal) are those that have been subjected to the least metamorphic change during the coal-forming process, thus retaining greater fractions of moisture and volatile matter and containing less fixed carbon than the high-rank bituminous and anthracite coals [34]. It has been estimated that more than 55% of China's proved coal reserves are made up of subbituminous coal and lignite [35]. There are some difficulties in low-rank coal utilization, such as increased difficulties in transportation and storage. Therefore, upgrading and highly developed technology such as liquefaction, gasification, and pyrolysis of coal are needed to convert low-rank coals into highly valuable products [36]. Several pilot and demonstration projects with coal pyrolysis have been launched in China. The Dalian University of Technology developed a kind of lignite solid heat carrier pyrolysis process. Engineering testing of different kinds of coal has been carried out. A so-called coal-topping process was proposed by the Institute of Process Engineering. This integrated multiproduct process for obtaining a high yield of light liquid fractions and gaseous products by flash pyrolysis was realized in a CFB system [37]. A 10 t \cdot d⁻¹ pilot test was completed in 2014, and a 200 kt·a⁻¹ industrial demonstration is under design.

Thus far, problems still exist for low-rank coal pyrolysis technology, including poor economic efficiency, the difficulty in controlling the quality of tar, the previously mentioned difficulties with wastewater treatment, and so on [38]. Further research into the optimization of the pyrolysis process, reactor improvements, oil processing, the comprehensive utilization of pyrolysis gas, and oil-electric-heat poly-generation is still needed.

3.2. Future perspectives

Coal conversion technologies play an important role in the developing of alternative fuels or chemicals which will be needed to act as substitutes for China's rare oil resources. However, due to falling oil prices in recent years, overall losses in the coal chemical industry have increased, the operating load has dropped, and construction progress on planned projects has slowed down [39]. It is projected that there are clear signs that the oil market is adjusting and will gradually rebalance in an outlook report of BP P.L.C. [40]. Petroleum and other liquid fuels will remain the largest source of energy in the world, at least until the year of 2040 [41]. Therefore, no matter what, most coal conversion technologies will likely continue to be regarded as a strategic reserve technology to be studied. Nevertheless, coal conversion should be further developed in order to make it more competitive. It is necessary to find better options to maximize conversion efficiency via low energy consumption, low water consumption, and a low pollution emission mode. Overall planning, technical studies, new technique development, and systematic optimization are needed [42].

One possible approach is to achieve technology upgrades via incremental innovation. As to most conversion technologies, the construction of larger equipment is considered to be a primary means to upgrade technology. Such upgrade will be helpful toward accumulating valuable experience and reliable data, and identifying new problems in science and engineering. Plans are in place for water-coal slurry gasifier with a capacity of 4 kt·d⁻¹, and pulverized coal pressurized gasifier with a capacity of 3 kt·d⁻¹. A direct liquefaction plant with a capacity of 2 Mt·a⁻¹ and a coal and oil co-processing plant with a capacity of 0.5–1 kt·a⁻¹ are also on the drawing board. In addition to the upgrading measures, the optimal integration of coal conversion with thermal power generation, oil refining, hydrogen production, biomass conversion, fuel cells, and other related energy technologies should be strengthened in order to achieve energy cascade utilization and material recycling.

Another possible approach could be to realize a fundamental change of technology via radical innovation. New principles, catalytic bases, chemical reaction pathways, reaction-oriented control methods, and mechanisms of the direct synthesis of olefins, aromatics, and special oxygen compounds from syngas need to be properly investigated. Fundamental research is needed on the reaction of free radicals in the process of coal pyrolysis and liquefaction, and on the relationship between liquid and gas products with the composition and molecular structure of primary coal resources. Some progress has recently been made. For example, as mentioned in Section 3.1.4, the newly developed bifunctional catalyst by DICP may permit the use of coal- and biomass-derived syngas with a low H_2/CO ratio to avoid high water consumption during the water-gas shift [32]. The advent of this new technology is worth looking forward to.

At the same time, water conservation and environmental protection must be seriously considered in the coal conversion process. Additional efforts to handle high-organic and high-salt wastewater should be taken to achieve zero-emission wastewater recycling [43]. New technologies and new materials are highly encouraged.

4. Pollution control in coal-fired power plants

Coal consumption has caused serious environmental problems

in China, especially from the largest consumer—the coal-fired power plant, which contributed more than 17%, 38%, and 37% of national emissions of PM, SO_2 , and NO_x , respectively, in 2013 [44]. Therefore, emission control at coal-fired power plants has played an important role in clean coal technologies in China, as with efficiency promotion.

4.1. Current status

4.1.1. Policies and regulations

Regulations and pollution control policies are definitely causing reductions in polluting emissions from thermal power plants. Since 2004, emission limits have become stricter (Table 2), accelerating the use of air pollution control devices (APCDs) and the installation and application of similar new technologies in most coal-fired power plants. For example, in accordance with the new emission standard that took effect in 2012, electrostatic precipitators (ESPs) and flue gas desulfurization (FGD) units were installed in most coal-fired power plants, and selective catalytic reduction (SCR) units were installed in 80% of coal-fired power plants by 2014 [45]. At the same time, a series of national and local policies were issued and implemented. In 2012, the central government supplied ¥1.09 billion CNY to support the 15 key cities included in the Air Pollution Control in Key Areas during 12th Five-Year Plan for the implementation of comprehensive improvements in coal-fired boilers. Another such policy is the on-grid tariff premium policy, which compensates coal-fired power plants with 15 $\text{CNY} \cdot (\text{MW} \cdot \text{h})^{-1}$, 10 $\text{CNY} \cdot (\text{MW} \cdot \text{h})^{-1}$, and 2 $\text{CNY} \cdot (\text{MW} \cdot \text{h})^{-1}$ for the costs of desulfurization, denitration, and PM removal, respectively.

Due to stricter emission limits for coal-fired power plants, the total emissions of SO₂, NO_x, and PM have continually decreased since 2006 (Fig. 3) [46], even though the electric output from coal-fired power plants increased from 2.4×10^{12} kW·h to 4.2×10^{12} kW·h in 2006–2014. In particular, due to a new emission standard issued in 2011, SO₂, NO_x, and PM unit emissions declined rapidly from 2.3 gce·(kW·h)⁻¹, 2.8 gce·(kW·h)⁻¹, and 0.4 gce·(kW·h)⁻¹, respectively, in 2011 to 1.5 gce·(kW·h)⁻¹, 1.5 gce·(kW·h)⁻¹, and 0.2 gce·(kW·h)⁻¹, respectively, in 2014.

4.1.2. Desulfurization technologies

Flue gas desulfurization systems in coal-fired power plants can be categorized into four types: wet scrubbers, spray dry scrubbers, sorbent injection, and regenerable processes, according to the specific chemical reactions and flow conditions [47]. Among these, wet flue gas desulfurization (WFGD) technology has become the most-used technology around the world because of its cheap and abundant solid sulfur agent, easy-to-use byproduct, adaptability to a wide range of coal, and possibility of greatly reducing engineering costs [48].

Due to increased use of FGD, the thermal power share of total SO_2 emissions decreased from 62.7% in 2005 to 38.4% in 2014 [49]. The greater reduction in SO_2 emissions per electric output found in the later years (Fig. 3) is mainly due to the following factors:

(1) FGD operation and removal efficiency improved in response to the relevant emission standard (GB 13223-2011) and

Table 2

Related policies and regulations for pollution control.

| Pagulation (malio) | | Emission limits (mg·(Nm ⁻³)) | | | |
|---|-------------------------|--|-----------------|----|------|
| regulation/policy | | | NO _x | PM | Hg |
| Emission standard of air pollutants for thermal power plants (GB 13223-2003) | | 400 | 450 | 50 | |
| Emission standard of air pollutants for thermal power plants (GB 13223–2011) | Normal area | 100 | 100 | 30 | |
| | Key emission limit area | 50 | 100 | 20 | 0.03 |
| Upgrade and transformation plan for energy saving and emission reduction in coal-fired power plants (2014–2020) | | | 50 | 10 | |



Fig. 3. Total and unit emissions of SO₂, NO_x, and PM in coal-fired power plants [46].

to the Upgrade and transformation plan for energy saving and emission reduction in coal-fired power plants (2014-2020) that was published later (Table 2). Related technologies for improving the efficiency of WFGD can be divided into three categories. The first category aims to enlarge the resident time for the SO₂ reaction; examples include using a dual spraying cycle in one absorber tower, or having two absorber towers in one WFGD system. The second category aims to improve the gas-liquid mixing process; examples include installing tray or cyclone technologies in the inlet of the spraying level in the absorber tower. The third category aims to improve the liquid drop removal efficiency of the humidity eliminators installed in the spraying layer, which simultaneously remove the fine particles entrained to the absorber. The efficiency of humidity eliminators also affects the removal of fine particles in the absorber, where the fine particle capture efficiency of liquid droplets is controlled by inertial impaction and thermophoresis, based on the temperature gradient and on the droplet Stokes number and diameter in the wet scrubbing absorber [50].

(2) The energy efficiency of the coal-fired power industry was increased in order to reduce fuel consumption and pollutant emissions, based on policies that shut off low-efficiency power plants with capacities less than 200 MW in 2007 [45] and that installed new ultra-supercritical units. In 2005, units sized at less than 300 MW accounted for more than 50% of the total coal-fired power plant capacity. This proportion was reduced to 25% by the end of 2012, while the proportion of units sized 600 MW and over rose to 40.15% [51].

The production of flue gas desulfurization gypsum (FGDG), the byproduct of wet and semi-dry desulfurization processes, has been increasing rapidly in China. The estimated production in 2010 was around 0.85 Gt, with less than 30% being reused. FGDG has a variety of beneficial applications; for example, it can be used as a cement retarder agent instead of natural gypsum; as feedstock in cement production; as a raw material in concrete products, gypsum powder, and grout; as an ingredient in waste stabilization; as a fill material for structural applications and embankments; and as raw material for wallboard manufacturing [52]. Another important use of FGDG is as an alkali soil amendment; its use in this context was first tested in 1996–2001 in Shenyang in Northeastern China [53]. By the end of 2009, 7000 ha of alkali soil had been reclaimed with FGDG by Tsinghua University research groups in the north of China, and 13 400 ha of soil will be reclaimed in 2016.

4.1.3. Denitration technologies

The formation of NO_x from coal-fired power plants varies significantly by coal type, boiler size, combustion technology, boiler load, and operation conditions. Therefore, the emission control of NO_x from coal-fired boilers is more complex than that of other pollutants. The major denitration technologies in coal-fired power plants can be categorized into low-NO_x combustion, selective non-catalytic reduction (SNCR), SCR, and a combination of these three denitration technologies.

In response to an emission standard for air pollutants from thermal power plants that was published in 2012 (GB 13223–2011), denitration devices were widely applied in thermal power plants, causing NO_x emissions from coal-fired power plants to continuously decrease from a peak value of 1.1×10^7 t in 2011 to 6.2×10^6 t in 2014. By 2014, SCR units were installed in 80% of coal-fired power plants [45] and made up almost 95% of installed denitration capacity [54].

With the publication of the Upgrade and transformation Plan for energy saving and emission reduction in coal-fired power plants (2014–2020), a stricter limit has been set on NO_x emissions, restricting them to below 50 mg·Nm⁻³. As a result, higher removal efficiency is required for denitration. One method of improving efficiency is to increase the catalyst in the SCR reactor from two layers to three layers, thereby increasing the removal efficiency from 75%–85% to 90%. Another method is to keep the catalyst operating in a wide load range, especially under lower loads at 320 °C, the lowest temperature required by a vanadium-tungstentitanium (V-W-Ti) catalyst. Flue gas reheating systems have been designed to meet this demand; examples include using a higher temperature flue gas bypass or extracting steam from the turbine to reheat the flue gas inlet of the SCR reactor.

Although it is difficult to meet strict emissions laws using only a low NO_x burner (LNB), an LNB can reduce NO_x emissions from a furnace for bituminous coal to less than 200 mg·Nm⁻³, and emissions from a furnace for lean coal to less than 450 mg·Nm⁻³ [55]. Thus, LNB-SCR technology is the dominant method of denitration used in thermal power plants to meet limits of less than 50 mg·Nm⁻³. This combination can simultaneously achieve good technical and economic benefits.

When flue gas flows through a V-W-Ti catalyst, the vanadium (V) component is active in the oxidation of SO₂ to SO₃ [56]. The subsequent reaction with water (H₂O), and ammonia (NH₃) to form ammonium sulfate ((NH₄)₂SO₄) or bisulfate (NH₄HSO₄) causes blockage of the air-preheater inlet and acid corrosion of the downstream equipment, and also increases PM_{2.5} emissions to a concentration of 2.5 mg·Nm⁻³ in flue gas [57].

4.1.4. PM control technologies

Due to health and environmental concerns, the formation and control of fine PM pollution, especially PM_{2.5}, have been widely studied in China. Mechanisms of PM formation corresponding with coal combustion stages were investigated in detail by Yao et al. at Tsinghua University [58-60]. Fig. 4 [59] outlines these formation mechanisms and some control methods. Ultrafine PM formation can be reduced at an early stage of the pulverized coal combustion of high-sodium lignite and anthracite coal in a down-fired Hencken flat-flame, with the help of some advanced technologies developed by Tsinghua University [61,62]. These technologies include novel in situ low-intensity phaseselective laser-induced breakdown spectroscopy (PS-LIBS), an inflame two-stage diluted sampling system, and a thermophoretic sampling system. Using a time-scale analysis approach, three characteristic times of the minimum mean diameter of primary particles (7 ms, 10 ms, and 21 ms), the initial increment point of particle-phase sodium, and the maximum devolatilization have been found to be highly correlated [63].

During the char combustion stage, temperature-driven condensation, inherent minerals shedding, and collision-aggregation on the surface of char dominate the formation of intermediate mode particles, such that the char properties significantly affect fine particle formation [59]. Controlled by the vaporizationnucleation-condensation and solid-gas-solid processes, the yield of $PM_{0.1}$ from lignite combustion is 1.6 times than char combustion, and is 5–8 times from the co-combustion of lignite and char in a 25 kW sustained down-fired combustor (Fig. 5) [64]. Li et al. [65] used the semi-coke briquettes that are commonly used for direct household use (cooking and heating). The average emission factors of primary $PM_{2.5}$, elemental carbon, organic carbon, and carbon monoxide for the tested semi-coke briquettes were reduced by about 92%, 98%, 91%, and 34%, respectively, compared with those of the 20 raw coals tested [65]. Progress with the injection of high-temperature sorbents, such as kaolinite, lime, silica, and alumina, into the flame zone was made by Si et al. from the Huazhong University of Science and Technology (HUST) [66]. The results show that sodium aluminosilicate plays an important role in PM_{2.5} reduction by kaolin, due to the interaction between the metals and particles at the submicron size; the sorbents transform the particles from submicron size to supermicron size. In post-combustion control, sulfation, phosphonation, and nitration will also affect the distribution of fine particles. Due to abundant phosphate content in municipal sewage sludge (MSS), the phosphonation of inorganic matter during the cooling of flue gas from the co-combustion of MSS with coal obviously reduces the mass concentration of fine particles [67].

Besides formation control during coal combustion, an effective method of reducing fine PM is ash removal from the flue gas from the furnace. However, the removal efficiency is lower than 90% for fine particles, which are between 0.1 µm and 1.0 µm in size when using traditional ESP and a bag filter [68]. To meet the new emission standards, a series of technologies have been researched and developed. Fig. 6 shows the general control strategies for fine particles from coal-fired power plants in low-temperature flue gas (< 140 °C). These are defined as multi-field coupled control technologies, and involve two kinds: hybrid conventional approaches (e.g., bag filter, ESP, wet ESP); and novel agglomeration approaches involving acoustic force [69–71], electrostatic force, chemical bonds, and thermophoretic force [58]. Wet ESP, low-temperature ESP, and hybrid ESP/bag systems have been widely applied in Chinese coal-fired power plants. When the flue gas temperature inlet of the ESP decreases from 130 °C to 90 °C, the PM_{2.5} removal efficiency increases from 95.9% to 97.5%, due to the lower specific resistance of fly ash, and to reduced flow. Wet ESP is normally installed after the FGD system; it greatly reduces PM_{2.5}, and can also reduce the emission of SO₃ mist, mercury (Hg), and other heavy metals [72].

4.1.5. Demercuration technologies

Coal contains a variety of trace heavy metal elements including Hg, plumbum (Pb), arsenic (As), cadmiun (Cd), cobalt (Co), nickel (Ni), and so forth. In Chinese coal, the concentration of Hg is 0.15–0.22 mg·kg⁻¹. More than 99% of the Hg in coal is released from the combustion furnace into flue gas, in the form of gaseous Hg⁰ [73]. As a result, the effective control of Hg⁰ emission from coal-fired power plants has become the main technologies and researches for recent years. Two approaches can be used to effectively remove Hg⁰. One is injecting strong Hg oxidizer, such as halogens and ozone, into the system to transform Hg⁰ to Hg²⁺,



Fig. 4. Formation mechanism and control methods of fine particles during coal combustion [59].

which can then be removed by wet FGD which exhibits efficiencies ranging from 40% to 90%. If SCR units are installed, the capture of Hg²⁺ in WFGD systems is increased up to 89% [74]. Another method is injecting effective sorbents to capture Hg⁰ [75].

APCDs in coal-fired power plants, such as SCR, ESP, WFGD, and wet ESP, have been found to be effective in removing most of the Hg^0 (> 80%), due to the oxidation reaction catalyzed by SCR followed by capture in the WFGD or wet ESP. A series of field tests showed that the capture efficiencies of Hg^{2+} in ESP, bag filter, and WFGD were 29%, 67%, and 80%, respectively [73].

4.2. Future perspectives

The future development of pollution control technologies for coal-fired power plants may focus on the following topics.

(1) High-efficiency and low-cost control technologies are needed, such as joint control of pollutants and the industrial application of novel multi-field fine particle control technologies based on fundamental research.

(2) Control technologies for heavy metals and volatile organic compounds (VOCs) require more study and commercial application for the absorption and catalytic oxidation of VOCs and heavy metals such as Hg, As, selenium (Se), Pb, and so forth.

(3) Reuse of the byproducts of APCDs is an important issue. Examples include the utilization process for the byproducts of multi-pollutant removal and semi-dry desulfurization, and the regeneration of V-W-Ti catalysts.

5. Carbon capture, utilization, and storage

China accounts for more than 25% of global CO₂ emissions, and CCUS technologies will play an important role in CO₂ reduction



Fig. 5. The effects of co-combustion of lignite and lignite char on the formation of fine particles [64].

in the future. Therefore, most of the research and demonstration projects for carbon capture and storage (CCS) have been implemented in recent years, and great progress has been made in the development of CCS technologies.

5.1. Current status

5.1.1. CO₂ capture technologies

 CO_2 capture technologies can be categorized into three methods: pre-combustion capture, post-combustion capture, and oxy-fuel combustion, as shown in Fig. 7 [73]. Regarding pre-combustion technologies, the GreenGen IGCC project aims at capturing 2 Mt-a⁻¹ of CO_2 from a 400 MW_e IGCC power plant whose generating efficiency is expected to be 48.4%. Implementation of the project is intended to occur in three phases; after the completion of Phase 3, the CO_2 that has been captured will be used in EOR. The commissioning of a 250 MW IGCC demonstration power station (Phase 1) was finished in 2011 [76].

Regarding post-combustion, three demonstration projects are in operation with scales of 3000, 100 000, and 10 000 t·a⁻¹ (CO₂), respectively, as listed in Table 3. These demonstration projects show that post-combustion capture technologies are commercially available, mature technologies.

Fig. 8 shows the roadmap for oxy-fuel combustion technology R&D [77]. A 3 MW_t pilot-scale oxy combustion boiler was put into commission at the end of 2011. It can capture 7000 t of CO_2 per year, reducing the CO_2 concentration from the boiler by 80%. A 35 MW_t new-built oxy-fuel boiler was finished at the end of 2014. This system includes all the units in the oxy-fuel combustion boiler, such as the air separation unit (ASU), the boiler, and the CO_2 compression and purification unit; thus, its operation will provide additional design and operating data and experience in oxy-fuel combustion. In addition, a long-term target has been set and a program will be launched to build new oxy-fuel boilers with capacities of 200–600 MW_e after 2020.

5.1.2. CO₂ transportation technologies

Transportation is the most technically mature step in CCS, and the pipeline is the most mature form of CO_2 transport. The project team of EU-China Near Zero Emissions Coal found that the average cost of transportation was 12 yuan per 100 km·(t CO_2)⁻¹, or 26 yuan per 200 km·(t CO_2)⁻¹ [78]. China plans to complete 80 km of the supercritical pipeline project in 2015, 200 km in 2020, and not less than 1000 km in 2030 [79].

5.1.3. CO₂ storage and utilization technologies

One of the major challenges in CCS is the issue of storage, which limits large-scale CCS operations at a global level, both in the short term and in the longer term. Table 4 shows the potential for the storage and utilization of CO_2 in China [80]. There are 1.19×10^{11} t of CO_2 storage in China's saline aquifers. Regarding utilization, China is projected to utilize almost 51 Mt·a⁻¹ in 2020



Fig. 6. Multi-field coupled control technologies for fine particles from coal-fired power plants.



Table 3

Typical demonstration projects for post-combustion capture in coal-fired thermal power.

| No. | Project name | Project description | Site | Scale ((t CO_2)·a ⁻¹) | Operating time |
|-----|--|---|--------------------|--------------------------------------|----------------|
| 1 | Huaneng Gaobeidian CO ₂ Capture Project | Utilization: reuse in the beverage industry Specifications: rate > 85%; CO ₂ purity > 99.9% | Chaoyang, Beijing | 3 000 | 2008 |
| 2 | Huaneng Shidongkou CO2 Capture Project | Utilization: reuse in the beverage and other industries Specifications: CO_2 purity > 99.5% | Baoshan, Shanghai | 100 000 | 2010 |
| 3 | China Power Investment Co. Shuang- huai CO ₂ Capture Project | Utilization: industrial usage Specifications: rate > 95%; CO2 purity > 99.5% | Hechuan, Chongqing | 10 000 | 2010 |



Fig. 8. The roadmap for oxy-fuel combustion technology in China [77]. CPU: CO₂ processing unit; FGC: flue gas cleaning.

and 249 $Mt \cdot a^{-1}$ in 2030 for CO_2 storage. However, this considerable potential would cover only a small portion of the CO_2 resulting from large-scale CO_2 capture from coal-fired power plants.

Shenhua's 100 kt·a⁻¹ (CO_2) CCS demonstration project, which is currently in operation, is located in Ejin Horo Banner of Ordos City, the Inner Mongolia Autonomous Region. It is currently China's first pilot project for deep salt/saline aquifer storage, as well as China's first entirely coal-based CCS demonstration project. The CO₂ is captured from Shenhua's direct coal liquefaction plant, which is located about 11 km west of the storage site.

China National Petroleum Corporation (CNPC) and Sinopec have successively launched CO₂-EOR campaigns in the oil fields of Jilin, Zhongyuan, Shengli, Jiangsu, Daqing, Changqing, and more, and have gained notable results. In addition, Yanchang Petroleum Group has scheduled and is implementing a long-term CO_2 -EOR project (from 2010 to 2020). The project is supported by the US-China Clean Energy Research Center on Advanced Coal Technology Consortium (CERC-ACTC). In this program, 60 injection wells will be finished and 200–300 km of pipeline will be constructed before 2017; by the end of 2020, the CO_2 capture system will be finished for the full flow of CCS-EOR.

5.2. Future perspectives

CCUS technological development in China will focus on the following items:

| The potential for CO_2 storage and utilization in China. | | | | | | |
|--|-----------------|--|---------------------------------------|----------------------------------|--|--|
| Itom | | Dreducet | Potential for CO ₂ storage | | | |
| Item | | Product | 2020 | 2030 | | |
| Storage | Saline aquifers | _ | 119.194 Gt | | | |
| Utilization | Geological | Oil, coal-bed methane, water, carbonates, etc. | 9.6–10.2 Mt·a ⁻¹ | 132.15-136.40 Mt·a ⁻¹ | | |
| | Chemical | Biodegradable polymer materials, alcohol, hydrocarbons | 40.34-40.46 Mt·a ⁻¹ | 111.05 Mt·a ⁻¹ | | |
| | Biological | Micro algae biofuel/bio-fertilizer | 1292 kt·a ⁻¹ | 1.87 Mt·a ⁻¹ | | |

Table 4The potential for CO2 storage and utilization in China

(1) R&D of key issues for CO_2 capture. These issues include fundamental research on flame speed and other combustion characteristics; ash formation and deposition; and the formation and control of pollutants under different conditions, such as oxygen pressure, coal types, and high-pressure CFB reactors.

The oxygen-carrier is the key factor in a CO₂ capture chemical reaction loop. The structure and characteristics of the oxygen-carrier, the reaction mechanisms for different types of fuels, the regeneration mechanism, and recycling technologies are significant for further studies.

Types of new absorbers will be further studied and developed for high-efficiency and low-cost CO_2 separation. Examples include raw materials and the manufacturing process for the industrial application of the sorbents.

(2) Technical and economic optimization of long-distance CO_2 transport, based on the flow characteristics, erosion, and security of supercritical CO_2 .

(3) Further development of geological modeling, related devices, and monitoring systems for EOR and the coal-bed methane process. The demonstration operation of open-pond and tubular technologies for algae culture will be accomplished to develop key processes and to optimize the reactor and system.

Relevant mechanisms and the development of technologies for new and long-term CO_2 utilization will be studied; these include CO_2 mineralizers and chemical utilization for biodegradable polymer materials, alcohols, and hydrocarbons.

(4) Implementation of a demonstration of the whole CCUS process. This demonstration should implement CO_2 capture, transport, and utilization or storage; it will help to further develop key devices, system optimization, and operation regulation, and to accelerate the commercial application.

6. Conclusions

Coal is the most abundant energy resource in China, and will continue to be the dominant energy source in China for decades. In order to better use coal, it should be developed in a sustainable manner. CCTs have achieved remarkable development during the past 10–15 years.

(1) In the field of coal-fired power generation technology, China has reached a new level in the past 10 years. The world's largest ultra-supercritical generating units have been developed and manufactured in China, and the world's most advanced ultrasupercritical power generation units have been established here. Independent R&D of 600 MW air-cooling units has achieved great progress. A 250 MW IGCC demonstration power plant was completed and put into operation. A breakthrough was made with the 600 MW ultra-supercritical CFB boiler technology, which has been put into commercial operation.

(2) Quite a lot of coal conversion technologies have progressed rapidly in recent years from pilot scale to demonstration and commercial scales. To convert coal in a more efficient, economical, and environmental manner, radical innovations in new catalytic bases, chemical reaction pathways, reaction-oriented control methods, and mechanisms are needed.

(3) Due to progress in combustion and pollutant-control technologies, and to the driver of stricter emission standards and policies, the total emissions and unit emissions of SO₂, NO_x, and PM are continuously decreasing even though electricity output is rapidly increasing. Pollutant-control technologies play an important role in clean coal technologies.

(4) Demonstrations of CO_2 capture, such as pre-combustion capture, post-combustion capture, and oxy-fuel combustion, and CO_2 storage and utilization, such as saline aquifer storage, CO_2 -EOR, micro algae cultivation, and so forth, have been accomplished. The whole CCUS process will be demonstrated in the next few years, which will accelerate its commercial application in China.

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Compliance with ethics guidelines

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Nomenclature

- APCD air pollution control device
- ASU air separation unit
- CCS carbon capture and storage
- CCT clean coal technology
- CCUS carbon capture, utilization, and storage
- CERC-ACTC US-China Clean Energy Research Center on Advanced Coal Technology Consortium
- CFB circulating fluidized bed
- CNOOC China National Offshore Oil Corporation
- CNPC China National Petroleum Corporation
- CPU CO₂ processing unit
- DICP Dalian Institute of Chemical Physics
- DMTO dimethylether/methanol-to-olefin
- ECUST East China University of Science and Technology
- EHE external heat exchanger
- EOR enhanced oil recovery
- EPRI Electric Power Research Institute
- ESP electrostatic precipitator
- EU European Union
- FGC flue gas cleaning
- FGD flue gas desulfurization
- FGDG flue gas desulfurization gypsum
- FMTA fluidized-bed methanol-to-aromatics

FMTP fluidized-bed methanol-to-propylene

- FTS Fischer-Tropsch synthesis
- GDP gross domestic product
- GHG greenhouse gas
- HP high pressure
- HUST Huazhong University of Science and Technology
- IGCC integrated gasification combined cycle
- IGFC-CC integrated gasification fuel cell system
- IGHAT integrated gasification humid air turbine
- LHV lower heating value
- LNB low NO_x burner
- LP low pressure
- MOST Ministry of Science and Technology
- MP medium pressure
- MSS municipal sewage sludge
- MTA methanol-to-aromatics
- MTO methanol-to-olefin
- MTP methanol-to-propylene
- PM particulate matter
- PS-LIBS phase-selective laser-induced breakdown spectroscopy RH reheater
- R&D research and development
- SCR selective catalytic reduction
- SH super heater
- SHII secondary super heater
- S-MTO Sinopec methanol-to-olefin
- SNCR selective non-catalytic reduction
- SNG synthetic natural gas
- VOC volatile organic compound
- WFGD wet flue gas desulfurization

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