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# Clean Coal Technologies in China: Current Status and Future Perspectives

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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.



## 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 $9.0231 \times 10^9$ t of carbon dioxide ($CO_2$) 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 ($SO_2$), 57% of nitrogen oxides ($NO_x$), and 44% of particulate matter (PM) came from the direct combustion of coal, and about 93% of $SO_2$, 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 $t \cdot d^{-1}$ has been realized. The world's first coal direct liquefaction plant, with a capacity of more than 1 $Mt \cdot a^{-1}$ (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 $CO_2$ capture industrial equipment in a power plant has occurred. An enhanced oil recovery (EOR) demonstration project with a capacity of 150 kt and a $CO_2$ 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 utilization-related 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 $SO_2$ 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 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.

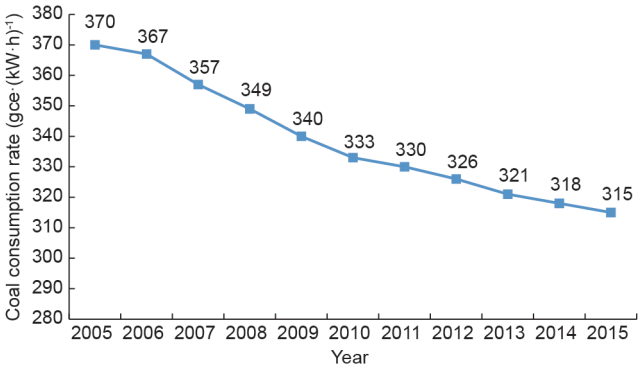


**Fig. 1.** China coal-fired power supply coal consumption rate [11,12].

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 double-reheat 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