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Research on Carbon Emission Reduction Technologies for Coal-Fired Power Plants

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Abstract: As global population growth and industrialization continue to accelerate, CO_2 emissions have been rising, intensifying the greenhouse effect. The latest assessment report from the Intergovernmental Panel on Climate Change (IPCC) indicates a persistent increase in global temperatures, with continuation expected. These changes may lead to land reduction, displacement, decreased food production, and heightened flood risks in coastal and low-lying areas. Reducing CO_2 emissions has thus become a global priority. China, being the largest CO_2 emitter, is crucial in combating climate change. Its coal-fired power plants are under pressure to transition to cleaner technologies. This study explores carbon emission reduction technologies for coal-fired power plants, analyzing key sources of emissions and proposing advanced solutions such as biomass co-firing, ammonia co-firing, and Carbon Capture, Utilization, and Storage (CCUS). Emphasis is placed on their potential to enhance efficiency and sustainability in alignment with China's carbon neutrality goals.

Keywords: carbon emission reduction, coal-fired power plants, carbon emissions analysis

1. Introduction

Rapid industrial development and deforestation have significantly increased atmospheric CO_2 levels, reducing the natural capacity for carbon absorption. The Sixth Assessment Report, Climate Change 2023 by IPCC, reports that global temperatures have already risen by 1.1°C, with all regions experiencing unprecedented shifts in climate patterns. These include rising sea levels, frequent extreme weather events, and accelerated polar ice melting [1]. Rising temperatures are expected to exacerbate global changes, with the report forecasting a 1.5°C to 4.5°C increase by mid-century, especially in polar areas, leading to more ice melting and sea level rise. This could cause land loss, displacement, reduced food production, and increased flooding in coastal and low-lying areas. Addressing global warming and reducing CO_2 emissions are now critical global concerns.

As the top global CO_2 emitter, China is pivotal in combating climate change. In 2020, it set bold "Dual Carbon" targets at the UN: peak emissions by 2030 and carbon neutrality by 2060 [2]. This approach demonstrates China's dedication to climate action and offers sustainable development solutions, aiming to shift its economy to green practices and lead in environmental governance.

Under the dual carbon strategy, China's coal-fired power plants are under increasing pressure to transform and upgrade. The white paper China's Energy Transition, released by the State Council Information Office on August 29, 2024, highlights China's commitment to promoting a new model of green energy consumption and building an advanced energy system to achieve a green transformation in energy production [3]. While coal-fired power generation is anticipated to maintain

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a substantial presence in China's energy mix in the near term, it is imperative that the sector undergoes a transformation toward enhanced cleanliness and operational efficiency.

According to the International Energy Agency's (IEA) 2023 CO_2 Emissions Report, in 2023, coal combustion accounted for more than 65% of the global increase in carbon dioxide emissions [4]. Coal-fired power plants, a key part of China's traditional energy mix, are major CO_2 emitters and central to the country's carbon footprint. With China's goals to peak carbon emissions and achieve carbon neutrality, these plants need significant changes to reduce their environmental impact and meet the nation's climate targets.

Reducing emissions in coal-fired power plants involves a holistic approach, targeting operational efficiency, emissions control, fuel supply, design, and maintenance. Technological innovation, cost management, and policy support are crucial for achieving low-carbon, efficient, and sustainable operations. This article explores technological solutions and strategies for full-process carbon reduction in coal-fired plants, providing practical solutions for China and the world.

2. Overview of carbon emissions from coal-fired power plants

2.1. Analysis of carbon emission sources

Carbon emission sources in coal-fired power plants are typically divided into three main categories: direct emissions, indirect emissions, and other indirect emissions, as shown in Figure 1.

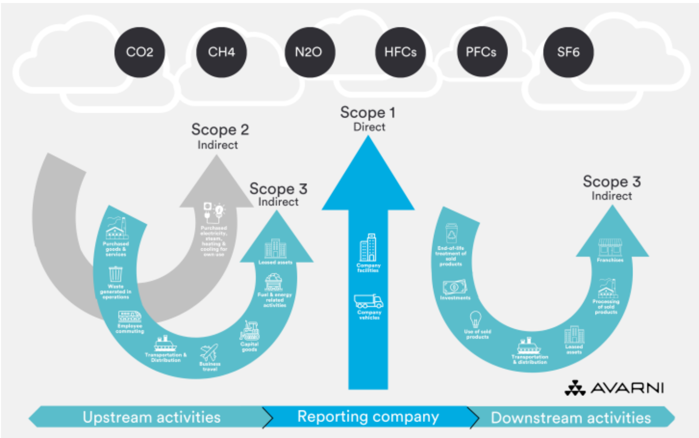

Figure 1: Analysis of carbon emission sources [5]

2.2. Direct emissions

Coal-fired power plants emit direct CO_2 during coal combustion, which is the main source of carbon emissions. This occurs as coal reacts with oxygen, releasing CO_2 and thermal energy for electricity generation. The CO_2 is then released into the atmosphere. Coal also contains sulfur and nitrogen, which can produce harmful gases like SO_2 and NO_x during combustion, affecting the environment and health.

Coal-fired power plants reduce direct CO_2 emissions by improving combustion efficiency, using advanced coal-cleaning tech, and installing CCS systems. Optimizing combustion and boiler efficiency cuts coal usage and CO_2 output per unit of electricity. CCS captures CO_2 from combustion, preventing atmospheric release and allowing for storage or industrial use.

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2.3. Indirect emissions

Indirect CO_2 emissions from coal-fired power plants stem from purchased energy for operations like pumping and lighting, as well as the entire supply chain from coal mining to electricity distribution. These emissions include those from mining equipment, transport vehicles, construction materials, and power transmission infrastructure. CCS technology also adds to indirect emissions due to energy use. Factors like market prices and renewable energy policies affect these emissions. Technological improvements, such as efficient boilers and cogeneration, can help reduce them.

2.4. Other indirect emissions

This category encompasses the broadest range of emissions, covering all indirect emissions beyond those detailed in Section 2.1.2. It includes emissions throughout the entire value chain, such as the extraction and processing of raw materials, product manufacturing and delivery, employee commuting, emissions resulting from customer use of products, and product disposal. Quantifying and reducing these emissions are particularly challenging due to the numerous stages involved in the supply chain and product life cycle. Managing and mitigating these emissions typically requires cross-departmental and cross-industry collaboration, along with thorough analysis and management of the supply chain.

3. Existing emission standards and regulations

With the establishment of dual-carbon goals, China is continuously improving its carbon emission standards and regulatory framework to address climate change and promote green, low-carbon development.

3.1. Emission standards per Ten Thousand Yuan GDP

The Chinese government has been dedicated to cutting energy intensity and carbon emissions. Data from the National Bureau of Statistics shows that from 2012 to 2021, China reduced its energy consumption per GDP unit by 26.4%, averaging a 3.3% annual decrease, which saved about 1.4 billion tons of standard coal. This reduction indicates progress in energy efficiency and industrial restructuring in China.

3.2. Dual-control of carbon emissions

The Work Plan for Accelerating the Construction of a Carbon Emission Dual-Control System [6] proposes that by 2025, the carbon emission accounting system will be further refined, with plans to implement a dual-control system focused primarily on intensity control, supplemented by total emissions control, during the 15th Five-Year Plan period. This initiative includes integrating carbon emission targets into national planning, developing action plans for achieving carbon peak and carbon neutrality, and enhancing relevant regulatory systems.

3.3. Carbon emission trading management

The Interim Regulations on the Management of Carbon Emission Trading [7] took effect on May 1, 2024, striving to regulate carbon trading and associated operations, enhance the management of greenhouse gas emissions, and foster the growth of a sustainable, low-carbon economy and society. The regulations clarify the scope of carbon emission trading, the identification of key emitting entities, the allocation and settlement of quotas, and market supervision.

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3.4. Energy Saving and Carbon Reduction Action Plan

The Energy Saving and Carbon Reduction Action Plan for 2024-2025 [8] sets specific energy-saving and carbon reduction targets and actions. These include reducing and substituting fossil fuel consumption, promoting non-fossil energy usage, and implementing energy-saving and carbon reduction transformations in key industries to ensure achievement of the binding energy-saving and carbon reduction targets outlined in the 14th Five-Year Plan.

3.5. Standard and measurement system construction

The notice on the Action Plan for Further Strengthening the Construction of Carbon Peak and Carbon Neutrality Standard and Measurement System (2024-2025) [9] highlights the importance of accelerating the development of corporate carbon emission accounting standards, product carbon footprint standards, and carbon labeling standards to support the establishment of dual-control carbon emission and carbon pricing policy systems.

4. Low-carbon technologies in the fuel supply and design phase

4.1. Biomass co-firing technology and its impact on CO_2 emissions

Biomass co-firing in coal plants reduces fossil fuel use and CO_2 emissions by using biomass as a supplementary fuel. Biomass, such as waste and residues, absorbs CO_2 as it grows, making it carbon-neutral when burned compared to fossil fuels. Research led by Cai Wenjia's group at Tsinghua University, published in Environmental Science & Technology, suggests that Chinese coal-fired units could achieve negative carbon emissions through biomass co-firing in combination with carbon capture and storage technology [10].

However, biomass co-firing technology presents certain challenges [11]. First, biomass fuel may have a lower combustion efficiency compared to coal, as its calorific value and energy density are generally lower. Second, the costs associated with biomass fuel—including collection, transportation, storage, and pretreatment-are relatively high. Additionally, biomass fuel supply may be seasonal and unstable, potentially affecting the continuous operation of power plants. Biomass co-firing may also increase emissions of NO_x and sulfur oxides (SO_x), which could have adverse environmental and health impacts. Technical challenges include biomass fuel pretreatment, modifications for boiler adaptability, and the potential for boiler material corrosion.

Despite these challenges, biomass co-firing technology offers substantial environmental benefits. It can reduce CO_2 emissions from coal-fired power plants, enhance biomass resource utilization, and contribute to lowering coal power carbon emissions and supporting green, low-carbon development. The Chinese government is also promoting related technologies; for instance, the Coal Power Low-Carbon Transformation Construction Action Plan (2024-2027) [12] stipulates that, after upgrades, coal-fired power units should be capable of co-firing at least 10% biomass fuel, significantly reducing coal consumption and carbon emissions. With technological advancements and cost reductions, biomass co-firing technology is expected to be widely adopted globally, advancing the international carbon reduction agenda. Its impact on CO_2 emissions can be summarized in the following aspects.

4.1.1. Carbon-neutral characteristics

The CO_2 absorbed by biomass during its growth is equivalent to the CO_2 released when it is burned, making biomass combustion a “zero-carbon” emission process. This carbon cycle characteristic enables biomass co-firing to reduce the carbon footprint of coal-fired power plants.

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4.1.2. Substitute for fossil fuels

Biomass, as a substitute for coal, can lower coal consumption and the associated CO_2 emissions. The ratio of biomass to coal in co-firing can be adjusted based on the specific conditions of the power plant and the availability of biomass resources.

4.1.3. Technology maturity

Biomass co-firing technology has reached relative maturity in some countries, including the UK and Sweden, where effective policy incentives have spurred its rapid development [13]. In China, biomass co-firing is also being gradually adopted, with plants like Huadian International Shiliquan Power Plant and Huaneng Rizhao Power Plant beginning to implement biomass co-firing.

4.1.4. Environmental impact

In addition to reducing CO_2 emissions, biomass co-firing can influence other environmental factors, such as NO_x and SO_x emissions. Some studies suggest that biomass co-firing may reduce these pollutants, though this effect depends on the specific combustion technology and co-firing ratio used.

4.1.5. Economic viability

The economic viability of biomass co-firing depends on factors like biomass fuel prices, collection difficulty, and market benefits. In regions with abundant biomass resources, such as Shaanxi Province, large-scale coal-fired power plants co-firing biomass-based fuel have been proposed. This approach offers near-zero investment advantages and maintains stable plant operation.

4.2. Ammonia Co-firing technology and its environmental benefits

Ammonia co-firing is a method that blends ammonia with coal to reduce CO_2 emissions in coal-fired power plants. As a clean energy source, ammonia can substitute for coal, cutting fossil fuel reliance and CO_2 emissions. The combustion of ammonia primarily produces water and nitrogen, not CO_2, making it a strong candidate for greenhouse gas reduction. The heat from ammonia combustion is similar to coal, making it a viable alternative fuel [14].

In ammonia co-firing, ammonia is introduced into the boiler through specially designed nozzles to burn alongside coal. Its rapid combustion rate and flame propagation improve combustion efficiency and reduce pollutants resulting from incomplete combustion. While ammonia co-firing technology offers significant environmental benefits, it also faces technical challenges, such as the generation of nitrogen oxides, the safe storage and transportation of ammonia, ammonia escape during combustion, and potential corrosion of boiler materials.

Despite these challenges, ammonia co-firing technology remains a promising carbon reduction approach. Working towards streamlining carbon market operations, bolstering the oversight of greenhouse gas emissions, and advancing a green, low-carbon development trajectory for the economy and society. First, it significantly reduces CO_2 emissions since the main by-products are water and nitrogen gas, thereby helping to mitigate greenhouse gas emissions. Second, the rapid combustion and flame propagation of ammonia increase combustion efficiency, decreasing pollutants from incomplete combustion. Additionally, ammonia can counteract NO_x formation by reacting with these compounds to produce harmless nitrogen gas, further reducing emissions of harmful pollutants. Moreover, this technology offers flexibility in coal-fired power plants, allowing for adjustments in the ammonia-to-coal mixing ratio based on operational conditions, thus adding technical adaptability to the power generation process [15].

5. Low-carbon technologies in the operation and maintenance phase

During the operation phase of coal-fired power plants, energy is generated by burning coal, a process that releases a substantial amount of CO_2. Most CO_2 emissions from power plants occur during this operational phase. Factors such as power plant efficiency, the type and quality of coal, and combustion technology all influence CO_2 emissions. To reduce these emissions, a combination of technologies can be implemented.

5.1. Carbon Capture, Utilization, and Storage (CCUS) technology

5.1.1. Overview of CCUS technology

CCUS technology is a comprehensive approach designed to lower atmospheric CO_2 concentrations to combat global climate change. It involves three main stages: carbon capture, transportation, and utilization and storage. According to the IEA report [4], by 2030, CCUS technology in China's power sector is expected to capture approximately 190 million tons of CO_2 per year, increasing to around 770 million tons by 2050 and surpassing 1.2 billion tons by 2070.

The process of capturing carbon dioxide from industrial sources can be accomplished through various techniques including pre-combustion, post-combustion, and oxy-fuel combustion. Pre-combustion capture is typically more applicable to gasification processes, whereas post-combustion capture is often employed in conventional coal-fired power plants.

The next step, transportation, involves moving the captured CO_2 to its destination for use or storage via pipelines, tanker trucks, or maritime vessels, with the choice of mode being influenced by distance, economic factors, and market demands.

Finally, the utilization and storage of CO_2 encompass its application in areas such as enhanced oil recovery, chemical manufacturing, construction materials, and agriculture. For storage purposes, CO_2 is generally injected into deep geological reservoirs like saline aquifers or exhausted oil and gas reservoirs.

5.1.2. Carbon capture technology

Carbon capture during the operation phase of coal-fired power plants can be achieved through pre-combustion capture, post-combustion capture, or oxy-fuel combustion technology. The most commonly used absorption methods are chemical absorption, physical absorption, and membrane separation technology.

5.1.2.1. Chemical absorption

Chemical absorption is the most widely used CO_2 absorption method. This method primarily relies on aqueous solutions of ethanolamines, such as Monoethanolamine (MEA), Diethanolamine (DEA), and Methyldiethanolamine (MDEA) [16]. These methods involve a chemical reaction between CO_2 and the solvent to form unstable salts, which are then decomposed to release CO_2 under heating or depressurization conditions, thus capturing CO_2. The advantages of chemical absorption include good selectivity and high absorption efficiency. However, the drawbacks are high energy consumption during the regeneration process and potential equipment corrosion. Many researchers are currently exploring non-amine-based absorbents [17].

5.1.2.2. Physical absorption

Physical absorption has been widely applied in industrial processes, particularly in emission sources with high CO_2 concentrations, and is considered a relatively mature and reliable technology. Physical

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absorption is based on the difference in solubility, utilizing the characteristic that the solubility of CO_2 in certain physical solvents changes with pressure or temperature to achieve capture. This method does not involve chemical reactions but promotes the dissolution and release of CO_2 by changing operational conditions such as pressure and temperature. The advantages of physical absorption include a regeneration process that does not require additional chemical reactions, lower energy consumption, and reduced equipment corrosion issues. Common physical absorption solvents include methanol, N-methylpyrrolidone (NMP), polyethylene glycol dimethyl ether, and propylene carbonate, among others. However, the downside of this method is that the solvent may be sensitive to impurities in flue gas (such as SO_2, NO_x), which can affect its performance and stability. Therefore, in practical applications, pretreating the flue gas to remove these impurities may be necessary.

5.1.2.3. Membrane separation technology

This technology utilizes the difference in permeation rates of membrane materials for different gases (such as CO_2 and N_2) to achieve separation. It includes the use of inorganic membranes, organic polymer membranes, and mixed-matrix membranes. Membrane separation has the advantages of a simple process, low energy consumption, and low investment. However, it currently faces challenges such as lower purity of separated CO_2 and the need to improve the durability of membrane materials [18].

5.2. Energy storage technology

Energy storage technology is a vital component of the power system, especially during the operation and maintenance phase, where it enhances the grid's peak-shaving capability and reliability, promotes efficient renewable energy usage, and effectively reduces CO_2 emissions.

5.2.1. Physical energy storage

Three primary forms of physical energy storage technologies include pumped storage, compressed air energy storage (CAES), and flywheel energy storage. Pumped storage uses off-peak electricity to pump water to a high-elevation reservoir, which is then released during peak hours to generate electricity, thus storing and releasing electrical energy. Flywheel energy storage, meanwhile, stores kinetic energy in a high-speed rotating flywheel, which can be converted into electrical energy when needed. These technologies are crucial for enhancing the grid's ability to effectively manage energy supply and demand.

5.2.2. Chemical energy storage

Lithium-ion batteries, celebrated for their energy efficiency, durability, and quick charging capabilities, are extensively utilized in both grid energy storage and electric mobility solutions. Fuel cells, which produce electricity by combining hydrogen and oxygen through electrochemical reactions, are noted for their high performance and minimal environmental impact. The vanadium redox flow battery, featuring vanadium in a liquid electrolyte, stands out for its extended operational life, tolerance to deep discharge cycles, and stringent safety measures. These cutting-edge energy storage technologies are crucial for bolstering the dependability and eco-friendliness of energy infrastructure.

5.3. Deep peak shaving technology

Deep peak shaving technology involves adjusting the operating load of coal-fired power generation units to enable stable operation at loads below the rated capacity, meeting the power grid's variable

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demand. This technology significantly enhances the grid's peak-shaving capability, supports renewable energy integration, and reduces carbon emissions [19].

5.4. Flexible Direct Current power supply technology

Flexible Direct Current (FDC) power supply technology is an advanced power transmission technology that uses Voltage Source Converters (VSC) and switchable devices, such as Insulated Gate Bipolar Transistors (IGBT), to achieve flexible control of the AC power grid through high-frequency modulation. This technology transmits active power between different power grids while providing reactive power support, enhancing grid stability and reliability.

6. Future outlook

Carbon reduction technologies in coal-fired power plants are encountering unprecedented development opportunities. With the global focus on climate change and the establishment of carbon neutrality targets, nine departmentshave issued the "Implementation Plan for Technology to Support Carbon Peaking and Carbon Neutrality (2022–2030)," highlighting increased emphasis on scientific innovation and policy support for carbon reduction in China [20]. It is anticipated that, in the future, coal-fired power plants will adopt advanced CCS technologies, enhance energy conversion efficiency, increase the utilization of clean energy, and promote the commercialization and large-scale application of low-carbon technologies through policy guidance and market mechanisms.

Additionally, research on the low-carbon transformation of China's coal power industry suggests that it must transition from a coal-dominated structure to a new power system characterized by a high proportion of renewable energy and the complementary integration of various energy forms. This transformation will drive significant changes in coal-fired power plants in terms of technology, policy, and market adaptation to align with the evolving energy structure and environmental requirements.

7. Conclusion

This article provides a analysis on the status of carbon emissions from coal-fired power plants and explores various technological pathways for achieving carbon reduction. Biomass and ammonia co-firing technologies, both effective methods for reducing direct CO_2 emissions, offer substantial environmental benefits. In addition, the development of CCS technology provides new possibilities for carbon reduction. The application of energy storage and deep peak shaving technologies will improve the grid's peak-shaving capability and promote the efficient use of renewable energy. With the maturation of these technologies and supportive policies, coal-fired power plants are expected to transition from traditional energy sources to cleaner alternatives, contributing significantly to the achievement of global carbon reduction targets.

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