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A Review of Coal-Biomass Co-Firing in China: Technological Pathways, Challenges, and Strategic Roles for Dual Carbon Goals

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ABSTRACT

To achieve China's "Dual Carbon" goals and promote the low-carbon transition of coal-fired power generation, biomass, as a key carbon-neutral energy source, has made research on its co-firing technology with coal of significant strategic importance. This paper systematically reviews the development status of biomass co-firing technology both domestically and internationally, noting that many European countries and China have made remarkable progress in demonstration projects and application scale, though gaps remain in the localization of key equipment and technical challenges. Using systematic literature review and case study comparison methods, the study evaluates the maturity, adaptability, and retrofitting costs of technical pathways such as direct, indirect, and parallel co-firing. The findings indicate that biomass co-firing can effectively reduce CO_2 emissions and enhance operational flexibility, but it also faces engineering challenges such as combustion instability, slagging, and corrosion, which require mitigation strategies like fuel pretreatment and combustion optimization. Furthermore, policy analysis reveals that China's "14th Five-Year Plan" for Bio-Economy Development and the "Action Plan for Low-Carbon Retrofit and Construction of Coal Power (2024–2027)" have synergistic effects in promoting technology scale-up and supply chain development. Finally, the paper proposes implementation recommendations from the perspectives of technological breakthroughs, policy incentives, and industrial collaboration, aiming to provide insights for building a clean energy system and supporting high-quality development in China.

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INTRODUCTION

To actively address global climate change governance, China formally proposed the "dual carbon" goals in 2020, namely "carbon peak" and "carbon neutrality." "Carbon peak" refers to the point at which carbon dioxide emissions reach a historical maximum during a certain period before gradually declining; "carbon neutrality" means achieving a balance between anthropogenic carbon dioxide emissions and removals through measures such as transforming the energy structure, enhancing carbon sinks, and deploying carbon capture technologies.

To achieve the "carbon peak" and "carbon neutrality" goals, a fundamental transformation in both the structure and utilization mode of China's energy system is required. The traditional method of biomass waste disposal is landfill; however, rather of utilizing this approach, why not transform biomass waste into alternative value added, such as employing it as feedstock for energy production (Chua et al., 2025). In this context, biomass energy(Chen et al., 2024), as a widely distributed renewable resource, not only enhances national energy security but also significantly reduces greenhouse gas emissions(Khan et al., 2024), providing crucial support for environmentally friendly development(Blondeau et al., 2020).

Given China's current coal-dominated power generation structure, achieving the "dual carbon" goals requires optimizing the synergistic utilization of coal and biomass, as well as accelerating the research and engineering application of coal-biomass co-fired power generation technology(Song and Zhang, 2024). According to the concept of “carbon neutrality,” the carbon emissions generated from biomass combustion as a substitute for coal can be considered offset by the CO_2 absorbed during the growth of the biomass(Wang et al., 2024). Therefore, co-firing biomass with coal can significantly reduce the carbon emissions of coal-fired power generation, while 100% biomass firing is regarded as nearly zero-carbon emission(Xie et al., 2023). This technological pathway can rely on the mature environmental protection devices and high-efficiency power generation systems of existing coal-fired units, ensuring the deep treatment of conventional pollutants and efficient system operation while fully utilizing the "carbon-neutral" characteristics of biomass energy to drastically reduce the total carbon emissions of the unit(Akash et al., 2024). Meanwhile, a risk prevention and control mechanism should be established to address the potential risks in the co-firing process, driving the transformation of coal resources toward cleaner, low-carbon, safer, and more efficient directions(Zhang, 2025).

As a renewable "carbon-neutral" energy, biomass energy is a powerful alternative to fossil fuels and has been scaled up in various energy production sectors. Compared to other biomass conversion technologies, co-firing technology has stood out due to its high level of industrial maturity, and its feasibility has been fully validated through large-scale operations in several European and American countries, as well as in China(Sher et al., 2025).

Globally, biomass co-fired power generation technology has developed in a diversified manner. Many EU member states support this technology through financial subsidies and tax incentives, and have established dedicated research and development funds to promote its progress(Bai et al., 2023). Countries such as Denmark, Germany, and the Netherlands have successfully operated multiple biomass co-fired power plants, achieving significant results(Roni et al., 2017).

The Drax power plant in the UK is one of the largest biomass co-firing plants in the world.Since 2012, it has gradually completed the full conversion of four units to biomass fuel, achieving coal-free power generation for these units(Hammond and Spargo, 2014).An overview of the power plant, together with the particle conveying system and the pulverizer, is presented in Figure 1.

At the Ferrybridge C power station in the United Kingdom, four 500 MW pulverized-coal boilers were retrofitted by installing six biomass swirl pre-combustion burners on the rear wall of the boilers, together with the construction of an independent biomass reception and pulverizing system. Operational results indicated that the retrofit was effective, enabling a biomass co-firing ratio of up to 20%. The plant's burners and biomass feeding system are shown in Figure 2.

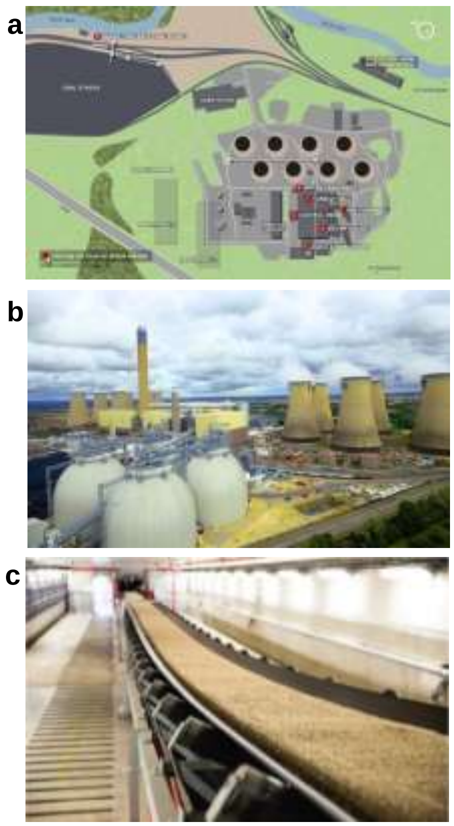

Figure 1. Overall layout of the Drax Power Plant in the UK, pellet conveyor belt and biomass pellet fuel pulverizer (A, 2017) (a) Overall Layout of the Power Plant (b) Biomass Pellet Conveyor Belt (c) Biomass Pellet Pulverizer

The Netherlands began experimenting with biomass co-firing in 1993. At present, its major biomass co-firing plants include Amer 8 & 9, Maasvlakte 1 & 2, and Eemshaven NL, among a total of eight facilities. The primary combustion modes adopted are tangential firing and opposed-wall firing in pulverized-coal boilers. In the early stage, the Dutch government supported co-firing mainly through the MEP subsidy scheme, which provided fixed feed-in premiums (FIP). Subsequently, under the Energy Agreement for Sustainable Growth signed in 2013, the subsidy mechanism was revised to a corrected feed-in tariff scheme, which strongly stimulated the development of this technology(Enescu et al., 2023).

Figure 2. Biomass swirl burners,biomass feeding device and pulverizing chamber in Ferrybridge C Power Plant,UK(A, 2017) (a) Biomass Swirl Burner (b) Biomass Feeding System (c) Pulverizing Chamber

At present, most of the biomass used for co-firing in the Netherlands is imported, with only about 30% sourced domestically, mainly comprising wood, pulp sludge waste, and palm shells. Studies have shown that the grindability of biomass is markedly lower than that of coal. As a result, in direct co-firing applications, torrefaction (a thermochemical pretreatment typically conducted under inert atmosphere to prevent combustion) or the TOP process (Torrefaction and Pelletization) is commonly employed to improve energy density and grindability (Aghamohammadi et al., 2016). Biomass pellets processed via the TOP method can achieve a bulk density of 750–850 kg/m³ and a net calorific value of 19–22 MJ/kg, allowing their direct use in thermal power plants for co-firing with coal. The process flow of the TOP technology is illustrated in Figure 3.

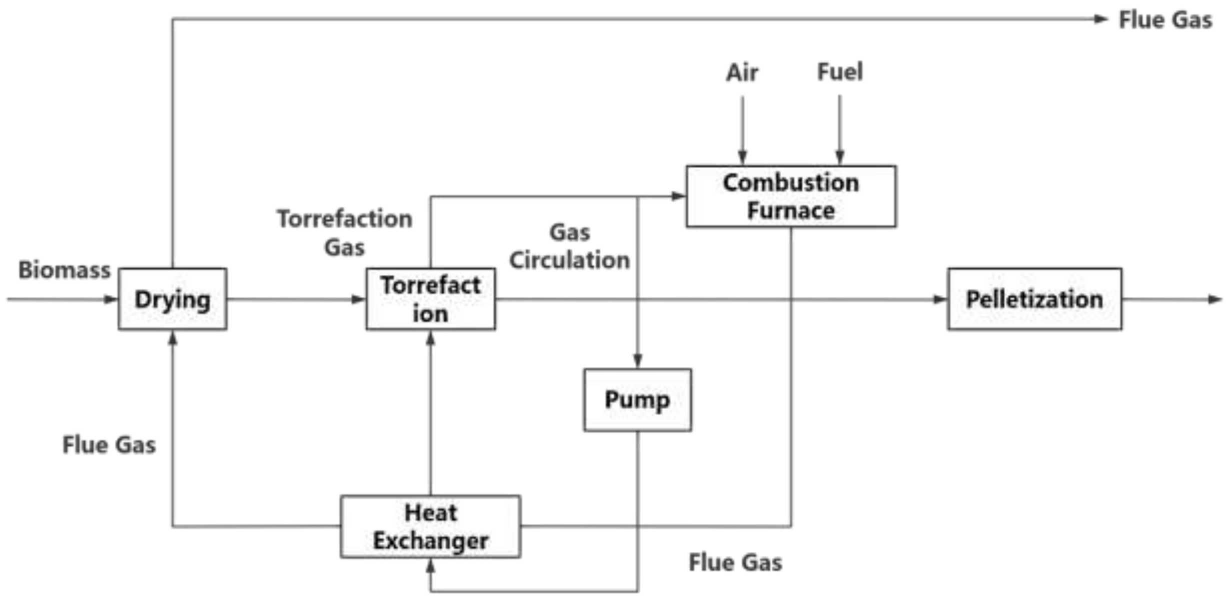

Figure 3. TOP process in Netherland

As a major agricultural and forestry nation, Brazil possesses abundant biomass resources, particularly bagasse and sorghum, which are primarily utilized for sugar production and ethanol manufacturing. The share of biofuel consumption in Brazil has exceeded 15% of total petroleum use, whereas in most other countries this proportion remains at only 2%–5%(Lucena and Silva, 2022). Brazil initiated biomass co-firing for power generation in 2009; however, to date, there have been no specific policies or large-scale projects dedicated to integrating biomass into coal-fired power plants. Recent studies have focused on the co-firing of sugarcane bagasse and sorghum with coal under oxy-fuel combustion conditions(Zihao et al., 2025).

Denmark relies primarily on wind power and biomass for electricity generation and has accumulated extensive experience and operational cases in biomass co-firing(Meibom et al., 2013), with a predominant focus on combined heat and power (CHP). The country has set a target to achieve full substitution of fossil fuels with biomass in thermal power generation by 2030, aiming for a reduction of CO_2 emissions by 80–95% compared to 1990 levels. Since initiating straw-fired power generation in 1999, Denmark has developed the sector over more than two decades, with biomass-based electricity now accounting for over 25% of total generation(Lund et al., 2022). This share is projected to increase to 57% by 2026. Denmark's DONG Energy plant achieved 100% biomass fuel replacement in 2023 and plans to reach carbon neutrality by 2025.

Germany, as the world’s leading producer of biogas, primarily utilizes biomass resources for biogas generation in combined heat and power (CHP) applications(Bagherian et al., 2021). At present, most of the operational biomass co-firing plants in Germany are dedicated biomass-fired facilities, with sewage sludge serving as the predominant fuel, followed by straw and waste wood. The boilers employed are mainly pulverized-coal units, with a smaller proportion being fluidized-bed systems.

In Japan, coal-fired power plants are predominantly based on supercritical (SC) and ultra-supercritical (USC) technologies. Japan has pledged to reduce CO2emissions by 26% from the 2013 level by 2030, with biomass co-firing in coal-fired power plants regarded as a key short- to medium-term solution for achieving this target. Consequently, biomass co-firing has developed rapidly in recent years. By 2017, approximately 29 large-scale coal-fired units were operating with biomass co-firing, and about 50% of newly constructed coal-fired units were designed to incorporate biomass co-firing(Liu et al., 2023).

In Japan, recent projects such as the Takehara Power Plant have implemented co-firing ratios of up to 20% using wood pellets. Similarly, Korea's Tangjin Power Plant began co-firing biomass in 2022 as part of its decarbonization roadmap.

Circulating Fluidized Bed (CFB) Boilers have shown excellent performance in biomass co-fired coal power generation due to their good fuel mixing capability and longer residence time. The Lagisza power plant in Poland built the world's first supercritical circulating fluidized bed power plant. Additionally, Korea's Southern Power Company launched the world's first ultra-supercritical CFB boiler power plant in 2016(Ren and Zhao, 2015).

The successful experiences of these countries demonstrate that, with the support of policies and technological innovations, biomass co-fired coal power generation can not only effectively reduce greenhouse gas emissions but also promote the rational use of biomass resources.

DOMESTIC RESEARCH STATUS

In China, the Shiliquan Power Plant represents the first demonstration project exploring the co-firing of coal with straw, officially commissioned in 2005.The project successfully achieved a co-firing ratio of up to 20%, with wheat straw as the primary fuel. Another milestone was the Guodian Jingmen Power Plant, which entered commercial operation in October 2013 (Zhang, 2025). Supported by the National Renewable Energy Development Fund, the plant realized stable economic performance through the mixed combustion of biomass-derived gas and pulverized coal.

Table 1. Status of Pulverized Coal–Biomass Co-Firing Power Plants in Operation Worldwide (Namakka et al., 2026)

Country	Power Plant	Unit Capacity/MW	Co-Firing Ratio	Biomass Type
UK	Drax	6×660	100%	Wood pellets, straw pellets
	Fiddler's Ferry	4×500	20%	Wood pellets
Netherlands	Amer	600	80%	Wood pellets
	Maasvlakte #3	2×1100	20%	Meat and bone meal
	Eemshaven	2×800	25%	Wood pellets
Denmark	Avedore	575	100%	Straw pellets
	Avedore	2×430	100%	Straw, wood pellets
Poland	Lagisza	460	10%	Coal washing sludge
Finland	AlholmensKraft	265	50%	Wood pellets
Austria	Zeltweg	137	30%	Biomass syngas
Japan	Takehara	2x250	20%	Wood pellets
Korea	Tangjin	2x500	15%	Wood pellets
China	Jingmen	660	15%	Biomass syngas
	Shiliquan	140	20%	Wheat straw
	Qinhuangdao	2×300	10%	Municipal sludge

At the end of 2017, the National Energy Administration launched a national pilot program for biomass co-firing power generation. The program encompassed 58 agroforestry biomass projects, 29 sludge co-firing projects, and 2 municipal solid waste co-firing projects. Collectively, these initiatives were projected to generate approximately 8,300 GWh of additional electricity per year, replacing 2.62 million tonnes of coal and reducing carbon dioxide emissions by about 7.33 million tonnes. In 2021, further subsidy support for agroforestry biomass power generation was introduced, providing an additional impetus to the development of the domestic biomass power sector(Xie and Zhang, 2013).

Wang et al., (2025) studied the carbon mitigation potential and economic implications of biomass co-firing in coal-fired power plants in the Yangtze River Delta region. Their findings indicate that co-firing biomass at 5–20% can reduce CO2 emissions by 31–151 kg/MWh, and when combined with monoethanolamine-based carbon capture, 20% biomass co-firing can achieve net negative emissions of 38–69 kg CO2/MWh. However, the integration of these technologies increases generation costs by 5.4–97.3%, highlighting the economic challenges associated with large-scale implementation.

In parallel, the 14th Five-Year Plan for Bio-Economy Development has promoted the transition of biomass utilization toward combined heat and power (CHP) applications. For example, a biomass gasification project in Ningbo achieved dual outputs of syngas and coke through optimized temperature control. While significant progress has been made in the field of coal–biomass co-firing technology(Antolini et al., 2022), substantial gaps remain in the localization of key technologies and equipment compared with developed countries. Consequently, intensified efforts in research, development, and large-scale application are essential for China to bridge this technological gap and approach the international frontier.

In summary, the biomass used for co-firing is primarily derived from agricultural residues such as crop straw, as well as forestry waste including wood chips and similar materials. Owing to the flexibility of adjusting the biomass blending ratio as required, the overall power generation output is not significantly affected by seasonal fluctuations in biomass feedstock supply. Furthermore, considering both the cost of equipment retrofitting and operational simplicity, direct co-combustion of pulverized coal with biomass remains the most widely adopted approach worldwide(Xu et al., 2020).

TYPES AND CHARACTERISTICS OF BIOMASS RESOURCES IN CHINA

Characteristics of Biomass Fuels

If left to naturally decompose, crops and their residues release substantial amounts of methane and other potent greenhouse gases. Agroforestry biomass fuels differ fundamentally from coal in their physicochemical properties: they generally contain higher volatile matter and fixed carbon, lower ash content, and significantly higher concentrations of alkali metals(Ibitoye et al., 2023). In addition, relatively high moisture and chlorine contents (0.1%-1.5%) are typical features. These differences profoundly affect combustion behavior:

(a) Low-temperature reactivity: The lower pyrolysis and ignition temperatures of biomass enable rapid reactions at lower temperatures, enhancing the combustion efficiency of volatiles and bringing the flame closer to the burner;

(b) Ash-related corrosion risks: Although biomass fuels contain less ash overall, their elevated alkali metal content tends to induce furnace corrosion, fouling, and slagging;

(c) Combustion characteristics: The lower heating value and higher oxygen content of biomass result in lower flame temperatures;

(d) Particle size effects: Larger biomass particle sizes increase the risk of incomplete combustion and the formation of high-emission by-products, thus necessitating targeted optimization of the combustion process.

Advantages of Coal–Biomass Co-Fired Power Generation

1. Low capital investment: Coal–biomass co-firing can make full use of the existing infrastructure and systems of coal-fired power plants, such as boilers, steam turbines, and auxiliary facilities. Only a biomass fuel handling system needs to be added, along with minor modifications to the boiler burners, thereby keeping the initial investment relatively low.

2. No additional land acquisition: Co-firing projects typically do not require extra land for power plant construction, whereas dedicated biomass power plants do. For instance, a 2 × 15 MW biomass power plant requires approximately 68,000 m^2 of land. By extrapolation, if 180 GW of capacity were to be installed entirely as dedicated biomass power plants, the land requirement would reach 400 million m^2.

3. Market accessibility: Coal–biomass co-firing projects can directly leverage the existing electricity market infrastructure of coal-fired power plants.

4. Fuel supply flexibility: Dedicated biomass power plants rely entirely on biomass fuel supply, whereas co-firing projects are not solely dependent on biomass. This provides greater bargaining power in the biomass fuel market and reduces risks associated with supply fluctuations. As a result, co-firing projects generally entail lower investment and operational costs compared with dedicated biomass plants.

5. Higher efficiency: Co-firing projects can benefit from the large unit capacity and high steam parameters of coal-fired power plants, enabling high efficiency. This allows biomass power generation to reach efficiency levels comparable to the best-performing coal-fired power plants, even at large capacity scales. In this sense, co-firing is not constrained by boiler size or steam parameters.

In summary, implementing coal–biomass co-firing in large, high-efficiency coal-fired power plants represents the most cost-effective technological pathway for achieving substantial CO2 reductions while maintaining high capacity and efficiency.

TECHNICAL CHALLENGES AND MITIGATION STRATEGIES IN COAL-BIOMASS CO-FIRING

The distinct physicochemical properties of biomass, compared to coal, introduce several technical challenges that must be managed for stable and efficient co-firing operation.

Combustion Instability and Flame Stability

Root Cause: High volatile matter content and lower ignition temperature of biomass lead to rapid devolatilization near the burner, potentially causing unstable combustion, pulsations, and a shift in the flame front.

Mitigation: Optimizing burner design (e.g., dedicated biomass burners), adjusting secondary air distribution, and implementing advanced combustion control systems with real-time monitoring of fuel blends.

Slagging, Fouling, and Corrosion

Root Cause: High alkali (K, Na) and chlorine content in biomass ash lowers ash fusion temperatures and promotes the formation of sticky deposits (slagging on furnace walls, fouling on convective heat surfaces) and corrosive alkali chlorides.

Mitigation: Fuel pre-treatment (e.g.,leaching, torrefaction), blending with high-Si/Al coals or additives (e.g.,kaolin), maintaining lower superheater temperatures, and employing sootblowers more frequently.

Fuel Preparation and Handling

Root Cause: Low bulk density, fibrous nature, and poor grindability of biomass can cause feeding system blockages, excessive wear in coal mills, and pulverization difficulties.

Mitigation: Dedicated biomass crushing and drying systems, use of pelletized or torrefied biomass to improve density and grindability, and separate fuel feeding lines.

Fuel Quality and Characterization

Ensuring consistent fuel quality is critical. Characterization of coal-biomass blends should adhere to relevant ASTM standards to assess suitability for combustion.

Key tests include: ASTM D5865 for Gross Calorific Value (Higher Heating Value, HHV); ASTM D3172 for Proximate Analysis (moisture, ash, volatile matter, and fixed carbon); ASTM D4239 for Sulfur Content; ASTM D1857 for Ash Fusibility; ASTM E871 for Moisture Analysis in biomass.

Regular monitoring of these parameters helps maintain the minimum required HHV and predict ash behavior.

TECHNICAL CHARACTERISTICS AND PROJECT EXPERIENCE OF COAL–BIOMASS CO-FIRED POWER GENERATION

Policies on Biomass Co-Firing

With the accelerating pace of the global energy transition, the development of a clean, efficient, and renewable energy system has become an international consensus. Biomass, as a "zero-carbon" renewable energy source, is one of the potential substitutes for fossil fuels and has already been widely applied in various energy production activities, including large-scale power generation, combined heat and power (CHP)(Su' ait et al., 2025), as well as industrial and residential heating at multiple scales. Among the various biomass utilization technologies, co-firing with coal is regarded as the most promising pathway for large-scale industrial deployment, with numerous successful demonstration cases both in Europe and North America and in China(Mustapha et al., 2025).

To fully implement the spirit of the 20th National Congress of the Communist Party of China, actively respond to the strategic decisions of the CPC Central Committee and the State Council, coordinate the low-carbon retrofitting of existing coal-fired units and the low-carbon construction of new units, enhance the clean and efficient utilization of coal, and accelerate the establishment of a clean, low-carbon, safe, and efficient modern energy system to support the achievement of carbon peaking and carbon neutrality goals, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the Action Plan for Low-Carbon Retrofit and Construction of Coal Power (2024–2027) in July 2024.

According to the Action Plan, by 2025, the first batch of low-carbon retrofitting projects for coal-fired power generation units will have commenced, accompanied by the deployment and application of a number of low-carbon power generation technologies.The unit carbon emissions of these projects are expected to decrease by approximately 20% compared with the average level of similar coal-fired power units in 2023, and will be significantly lower than those of the most advanced operating coal-fired units, thereby accumulating valuable experience for the clean and low-carbon transformation of coal-fired power.

By 2027, the application pathways of low-carbon technologies in coal-fired power generation will be further expanded, and both construction and operating costs will be markedly reduced. At that time, the unit carbon emissions of relevant projects are projected to decrease by around 50% compared with the average level of similar coal-fired units in 2023, approaching the carbon emission level of natural gas-fired power plants. This will enable coal-fired power to play a leading role in advancing the clean and low-carbon energy transition.

The Action Plan stipulates that biomass resources such as agricultural and forestry residues, desert plants, and energy crops should be utilized. Comprehensive consideration should be given to factors including the availability of biomass resources, the safe operation requirements of coal-fired units, the need for flexible load regulation, efficiency assurance, and economic feasibility, so as to promote the development of coal-fired power generation coupled with biomass. As a clean and efficient pathway for energy utilization, biomass-coal co-firing technology holds significant importance for alleviating the energy supply-demand contradiction in China and for reducing carbon emissions.

The 14th Five-Year Plan for Bio-Economy Development establishes a strategic framework for the holistic utilization of biomass resources, fostering innovation across the supply chain. Concurrently, the Action Plan for Low-Carbon Retrofit and Construction of Coal Power (2024–2027) provides a direct policy conduit and market incentive for biomass co-firing as a tangible decarbonization pathway. The synergy between these policies drives technology promotion by simultaneously stimulating supply-side resource development and demand-side technology adoption in power plants, which is aligned with global efforts towards affordable and clean energy and climate action.

To ensure the sustainable promotion of co-firing technology, establishing a stable, scalable, and cost-effective biomass supply chain is paramount. Policy support should extend beyond the power plant to encompass the entire logistics network, encouraging the development of professional biomass collection, processing, and distribution enterprises. Business models such as farmer cooperatives and long-term feedstock supply agreements can improve efficiency and reduce costs.

From a national strategic perspective, implementing dedicated programs on biomass-coal co-firing technology constitutes a key measure in support of the innovation-driven development strategy, the new energy security strategy, the high-quality development strategy, and the “carbon peaking and carbon neutrality” goals. Such programs will focus on addressing critical technical challenges in biomass-coal co-firing, advancing systematic research and technological breakthroughs, and establishing a technology system with independent intellectual property rights, thereby fostering the high-quality development of China’s biomass energy industry.

Technical Pathways for Biomass Co-Firing in Large-Capacity Pulverized Coal-Fired Power Plants

In large-capacity coal-fired power plants, several technical pathways have been developed to enable the co-firing of coal with biomass, as illustrated in the Figure 4. These pathways include the following approaches.

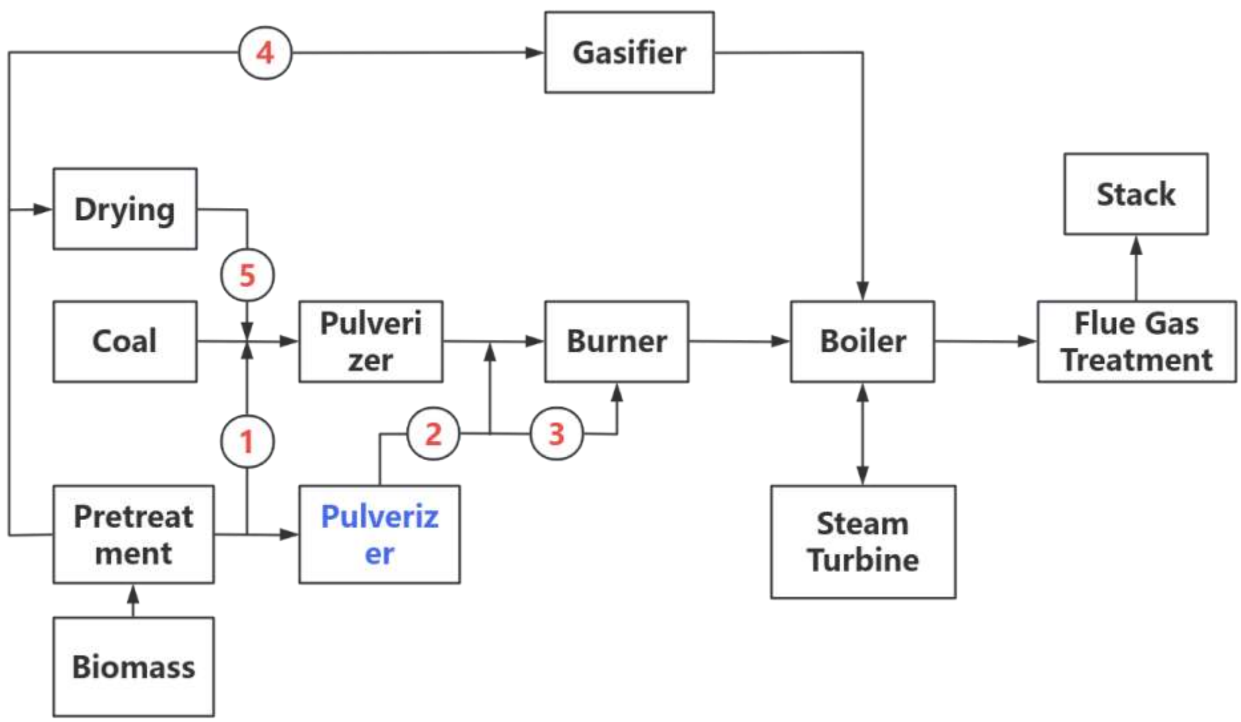

Figure 4. Technical Pathways for Biomass Co-Firing in Large-Capacity Pulverized Coal-Fired Power Plants

Direct Co-Firing

Direct co-firing technology achieves energy conversion by synchronously combusting coal and biomass within a single combustion chamber. It features a high degree of system integration and requires minimal additional equipment. Based on the point at which biomass is introduced into the fuel processing chain, direct co-firing can be divided into five technical branches:

(1) Coal mill co-firing: Biomass is fed into existing coal milling equipment for simultaneous pulverization, with the mixed fuel subsequently injected into the furnace through the original burners.

(2) Premixed co-firing: Biomass and raw coal are premixed prior to entering the milling system, undergoing joint conveying and grinding processes before combustion via the original burners. Common characteristics of pathways (1) and (2): Minimal modification of existing coal-fired infrastructure and outstanding economic feasibility. Risks: Conflicting physical properties of coal and biomass (e.g., fiber toughness, composition) can accelerate coal mill hammer wear, cause primary air duct blockages, induce combustion pulsations, and destabilize the flame.

(3) Fuel delivery pipe co-firing: Biomass undergoes dedicated crushing and drying pretreatment. Qualified feedstock is then precisely injected into coal powder pipelines, forming a mixed stream that enters the original burners.

(4) Pulverized coal burner co-firing: Pretreated biomass is supplied via an independent pipeline directly into the burner nozzle region, achieving fuel mixing within the burner. Characteristics of pathways (3) and (4): Both require dedicated pretreatment systems for biomass. Transportation stages are prone to pipeline clogging due to the physicochemical properties of biomass.

(5) Dedicated biomass burner co-firing: A fully independent biomass processing chain—including crushers, dedicated burners, and feeding systems—is constructed, enabling physical decoupling from the pulverized coal system. Pathway (5) characteristics: Minimal interference with the coal combustion process and better fuel adaptability, but at the expense of the highest system retrofit cost.

Indirect Co-Firing

In the indirect co-firing route, biomass is first gasified in a gasifier and then the resulting syngas is introduced into the boiler for combustion through dedicated burners(Kamble et al., 2019).

1. Technical Features and Advantages

a. High Compatibility with Existing Systems: The separate injection of syngas minimally interferes with the aerodynamics, flame stability, and ash-slag characteristics of the original coal combustion system, making it particularly suitable for supercritical and ultra-supercritical units sensitive to combustion disturbances.

b. Effective Isolation of Harmful Substances: Alkali metals (e.g., potassium, sodium) and chlorine present in biomass are largely retained in the gasification residue or removed during syngas cleaning, thereby significantly reducing the risks of high-temperature corrosion, fouling, and slagging on boiler heating surfaces.

c. Flexibility and Measurability: Syngas derived from biomass allows for independent metering and adjustment, facilitating accurate accounting of biomass power generation. This supports compliance with renewable energy quota systems and green power certification, and provides a convenient interface for potential future integration with carbon capture and storage (CCS).

2. Limitations and Challenges

a. High Initial Investment: Requires the addition of a complete system including gasifiers, syngas cleaning units, dedicated pipelines, and burners, resulting in significantly higher retrofit costs compared to direct co-firing.

b. System Footprint and Integration Complexity: Gasification and purification facilities require additional space, posing challenges to the layout of existing power plants. Simultaneously, system operation and control become more complex, demanding higher levels of automation and operational expertise.

c. Operational Costs and Economics: Energy consumption for gasification, catalyst replacement, syngas cleaning, and equipment maintenance contribute to additional operational expenses. The economic viability heavily depends on biomass feedstock costs and relevant electricity price subsidy policies.

3. Application Status and Development

Prospects

This technology is particularly suitable for processing biomass fuels with high alkali and chlorine content (e.g., straw, certain agricultural and forestry residues). It has seen mature application in European combined heat and power (CHP) projects, such as in Denmark and Finland, achieving biomass energy substitution rates exceeding 30%. In recent years, China has also explored indirect co-firing technology in related demonstration projects, considering it a feasible technical option for the low-carbon transformation of large coal-fired units. It has been included in the technological reserve system of the *Action Plan for Low-Carbon Retrofit and Construction of Coal Power (2024–2027)*.

Parallel Co-Firing

Parallel co-firing involves constructing an independent biomass-fired boiler, with its steam merged with that from the coal boiler before entering the steam turbine, jointly driving the generator. Advantages: Enables 100% substitution of biomass fuel and completely eliminates interference with the coal boiler operation.

1. Technical Principle and System Configuration

In this system, biomass fuel is completely combusted and converted to steam within an independent combustion system. The newly built biomass boiler is usually equipped with a complete set of auxiliary systems including fuel handling, feeding, combustion, flue gas cleaning, and ash disposal. The generated steam parameters can be designed to be similar to or slightly lower than those of the original coal-fired boiler. The steam streams are then merged in a common header before the turbine inlet. A centralized coordinated control system is responsible for balancing the load between the two boilers to ensure the safe and stable operation of the turbine(Sun et al., 2021).

2. Core Advantages

a. Thorough Fuel Substitution: Enables 100% substitution of coal with biomass, making it one of the most thorough technological pathways for the complete biomass conversion of a coal-fired power plant.

b. Absolute Operational Independence: The biomass combustion system is completely physically isolated from the original coal system at the combustion stage, fundamentally eliminating any interference from biomass characteristics on the combustion stability, efficiency, slagging, and corrosion of the pulverized coal boiler.

c. High System Flexibility and Reliability: The two boilers can be started, stopped, and adjusted independently, providing significant operational flexibility. When biomass supply fluctuates, the coal-fired boiler can quickly compensate for the load, ensuring power supply security and stability.

d. Facilitates Policy Accounting and Certification: The biomass-generated electricity portion is easy to meter and monitor separately, providing a clear boundary for obtaining renewable energy feed-in tariffs, participating in green power trading, and offsetting carbon emissions.

3. Main Challenges and Limitations

a. High Initial Investment Cost: Requires the construction of a complete new biomass boiler island and its auxiliary systems, including the boiler proper, flue gas cleaning devices, a chimney, and expanded water treatment and biomass fuel handling facilities. The capital intensity is significantly higher than that of direct or indirect co-firing retrofit schemes.

b. Thermodynamic Parameter and Efficiency Limitations: Constrained by biomass fuel properties and techno-economic factors, standalone biomass boilers typically operate at lower main steam temperatures and pressures. This results in their inherent cycle thermal efficiency being lower than that of modern high-parameter ultra-supercritical coal-fired units. Even after steam merging, the overall power generation efficiency of the system is often lower than that of high-efficiency coal-fired units and generally lower than that of well-designed indirect gasification co-firing routes.

c. Large Footprint and System Integration Complexity: Constructing a new boiler requires additional land, posing challenges to plant site planning. Furthermore, the coupling of steam systems, coordinated load control, and the operation management of two independent flue gas treatment systems all increase system complexity and operational maintenance difficulty.

d. Economics Highly Policy-Dependent: The project's economic viability is extremely reliant on long-term, stable, and low-cost biomass fuel supply, as well as sustained and strong policy support such as renewable energy electricity price mechanisms. Without subsidies, its levelized cost of electricity (LCOE) is usually not competitive.

4. Applicable Scenarios and Current Development Status

Parallel co-firing technology is particularly suitable for regions with abundant and stable biomass resources, and for retrofit projects of existing coal-fired power plants with extremely stringent emission reduction requirements or pursuing complete coal-phase-out transformation. In Europe, some coal-fired plants have adopted this path during their transition to biomass plants. In China, this technology is regarded as a potential option for deep low-carbon retrofitting of coal-fired power plants. It is especially suitable for adding a biomass boiler alongside an existing coal-fired combined heat and power (CHP) plant to substitute part of the coal for heating. However, for large-scale pure power generation applications, cost and efficiency hurdles still need to be overcome. With advancements in biomass pretreatment technologies and the development of corrosion-resistant boiler materials, there is potential to improve the parameters and efficiency of standalone biomass boilers and enhance their economics in the future.

CONCLUSION

Against the backdrop of the global energy transition and climate change mitigation, as one of the world's largest energy consumers and carbon emitters, China has identified the promotion of an energy revolution and the pursuit of green and low-carbon development as a key component of its national strategy. Within this context, advancing research on biomass co-firing in coal-fired power generation is not only a response to the national energy security strategy, but also a necessary pathway for optimizing the energy structure and promoting sustainable economic and social development.

First, from the perspective of technological self-reliance and capability enhancement, the primary objective of dedicated research on biomass co-firing with coal is to break foreign monopolies in this field and achieve localization of core technologies and critical equipment. This would not only allow China to independently master and further develop this advanced technology, reducing dependence on imported solutions, but also secure a favorable position in the global competition for energy technologies and strengthen the pursuit of technological leadership. Through breakthroughs and indigenous innovation, China can effectively reduce costs, improve equipment performance, and enhance the international competitiveness of domestic enterprises, thereby laying a solid foundation for the high-quality development of its energy sector.

Second, from the perspective of environmental protection and emission reduction, the application of biomass co-firing technology can significantly reduce carbon emissions from coal-fired power plants. By blending biomass with coal in the combustion process, not only can the energy efficiency of coal-fired power generation be improved, but coal consumption and greenhouse gas emissions can also be reduced. This is of vital importance for alleviating China's environmental pressures and achieving its carbon peaking and carbon neutrality goals. Moreover, this technology contributes to lowering the operational costs of coal-fired power plants and improving their economic performance, thereby easing the financial burden on enterprises and fostering sustainable industrial development.

Finally, the promotion and application of biomass co-firing will strongly stimulate the development of the associated industrial chain. From the collection, processing, and transportation of biomass feedstock, to the manufacturing, installation, and maintenance of power generation equipment, and ultimately to the transmission, distribution, and consumption of electricity, the entire value chain will be revitalized and upgraded. To accelerate the large-scale adoption of biomass co-firing technology in China, a coordinated multi-stakeholder approach is recommended: (1) intensify R&D to overcome technical bottlenecks and accelerate standard formulation; (2) refine subsidy mechanisms and integrate co-firing into the carbon emissions trading market; (3) foster the growth of a professionalized biomass logistics industry; and (4) promote diversified demonstration projects to accumulate localized operational data and expertise. This will not only creates substantial employment opportunities and promotes regional economic development, but also fosters new growth drivers, injecting fresh momentum into the transformation and upgrading of China's economic structure.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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