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Research on Decarbonization Pathway of China's Coal-Fired Power Industry From the Perspective of Conflict Mediation

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The transition to a low-carbon energy system is imminent under the constraints of carbon-peaking and carbon-neutral targets. Undoubtedly, coal-related carbon emissions over the past decades have had profound negative impacts on human life and the global climate. However, the main position of coal in the energy system determines that pure coal reduction strategy will inevitably lead to a systemic energy crisis. To this end, we explore the conflict formation mechanism among coal enterprises, downstream coal-fired power plants, and government in the process of strategic energy decarbonization transformation from the perspective of industrial chain, and analyze the feasible conflict states and their NASH, GMR, SMR, and SEQ equilibrium characteristics by constructing a ternary GMCR model. It is found that there are two feasible conflict states s_{10} and s_{12} that simultaneously satisfy the conditions of the above four types of equilibria. In this context, the evolution paths of s_{10} and s_{12} are further analyzed and conflict mediation strategies are proposed accordingly. Meanwhile, the decarbonization transition of the energy system needs to consider both the stage characteristics and regional differences of energy reform, as well as the important role of green low-carbon technological innovation as a grip for the decarbonization transition of energy.

Keywords: carbon peak, carbon neutrality, decarbonization pathway, coal-fired power industry, conflict mediation

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INTRODUCTION

Global warming headlines are always in the mass media, and counterintuitive seasonal climate change has erupted in many countries around the world (Howe, 2021). Various measures to reduce carbon emissions are being implemented, and energy decarbonization is an important topic in the field of energy management and environmental sustainability research (Sun et al., 2020; Savina et al., 2021; Vatalis et al., 2022; Ćorović et al., 2022). As the world's largest developing country and carbon emitter, China is deemed vital to both global economic recovery (Verma et al., 2021) and CO_2 emission reduction, especially given the current influence of multiple factors, such as the COVID-19 pandemic and China's carbon-peaking and carbon-neutral targets (Jiang et al., 2021; Li et al., 2021). The thorny issue is that rapid economic development requires a large amount of energy supply (Gozgor et al., 2018), and the coal-based energy structure, which is determined by resource endowment, historical background, and economic development, makes it impossible for China, as the world's second-largest economy, to fundamentally shake the main energy source of coal and electricity in the short term.

The feasibility of deep decarbonization of energy systems and their specific pathways are prerequisites for achieving the goals of carbon peaking and carbon neutrality. Numerous studies have been carried out on reducing CO_2 emissions and alleviating fossil fuel dependence for sustainable energy transitions at the national level (Broto et al., 2018; Bompard et al., 2020). Furthermore, as the national top-level design continues to improve, energy restructuring studies at the provincial level are also gaining attention (Tan et al., 2016; Luo et al., 2021). The industrial CO_2 emission efficiency of China's provinces has three categories of high, medium, and low efficiency, and shows significant spatial agglomeration characteristics. Among them, the Northwest region has the greatest potential for industrial CO_2 emission reduction (Zhang et al., 2016).

At a relatively microscopic level, based on institutional economics and transaction cost theory, Tan and Liu (2015) explored the boundary selection problem of coal and electricity trading from the perspective of time development and asset specialization. They provided effective strategies for trading coal and electricity enterprises at the theoretical level, technical level, and realistic level. Liu and Tan (2017) analyzed the trading characteristics between coal and power generation firms and their influencing factors from the perspective of stable matching and scale linkage, and found that coal firms are more scale efficient only when their production scale is larger than the maximum scale of coal demand that power generation firms provide for themselves. However, the pricing mechanism and price regulation of coal and electricity prices in the process of coal and electricity trading are not considered in their models. Kang and Yang (2012) analyzed the coal price between coal and power generation enterprises based on the infinite round bargaining game model and found that increasing the feed-in tariff can increase the profit of both power generation enterprises and coal enterprises, which is conducive to alleviating the coal price conflict between coal and power generation enterprises. The game model does not consider the impact of market coal price on coal used for thermal power generation, so its policy effect can only be short-lived.

From the perspective of energy consumption, the dominant factor influencing GHG emissions can be traced back to energy use (Crippa et al., 2019). At the same time, the consumption proportion of household consumption sector and transportation industry is also high (Ma et al., 2019). In general, thermal power plants are the major contributors to energy-related CO_2 emissions (Muhammad, 2019). In some countries, continuous emissions monitoring systems (CEMS) are applied to measure emissions in thermal power plants, but they are costly and require continuous calibration (Cusworth et al., 2021a). As monitoring technologies continue to evolve, remote sensing and next-generation airborne visible/infrared imaging spectrometers (AVIRIS-NG) are being applied to quantify large amounts of fossil CO_2 emissions (Nassar et al., 2017; Duren et al., 2019; Cusworth et al., 2021b). In reality, carbon capture and storage (CCS) is considered to be an advanced carbon emission reduction technology. Wang S. et al. (2016), Zhang X. et al. (2019), and Guo and Huang (2020) analyzed the carbon reduction investment strategies of power producers, but they did not focus on the impact of fuel price fluctuations on emission reduction investment strategies. In addition, in the analysis of government incentive policies, the issue of government incentives under the influence of fuel price risk has not been paid special attention (Zhou et al., 2014).

The existing literature is rich in exploring the trading strategies between coal companies and coal-fired power producers, as well as the investment decisions on green technologies for coal-fired power plants. However, the government's penetration in the energy decarbonization process has been increasing since China's carbon-peaking and carbon-neutral targets were set. In the past, the modular energy efficiency and emission reduction paths of coal, power, and polluters were not sufficient to support the achievement of the dual carbon targets, and the government's need for a systematic solution for energy decarbonization transition has become more urgent. The factors influencing the implementation of carbon emission reduction in different types of enterprises have been diverse (Chen et al., 2018), but the prerequisite for the solution of this type of problem is to correctly deal with the conflict of interests between the various subjects involved in the process of decarbonization of the energy system. In fact, conflict occurs virtually everywhere in society and economics, and a powerful methodology called the graph model for conflict resolution (GMCR) (Kilgour et al., 1987; Fang et al., 1993) was put forward and then further associated extensions (Hipel et al., 2011; Xu et al., 2018) were designed to handle real-world conflict. The most obvious advantage of this approach is that it can fully consider the preference characteristics of different decision-makers in the conflict problem and can well reflect the conflict state evolution. In addition, unlike the classical game model, this approach also provides different definitions of stability allowing a more detailed analysis of the stable state of conflict.

Therefore, this study firstly analyzes the elements of conflict formation among government, coal enterprises, and coal-fired power plants in the process of low-carbon transition of energy system, and constructs a ternary conflict resolution graph model based on the theory of GMCR. Secondly, the conflict feasible states of government, coal enterprises, and coal-fired power plants are ranked with the help of preference statement method in GMCR theory. In addition, the stability characteristics of NASH, GMR, SMR, and SEQ for different feasible states and the evolution paths of key stable states are further analyzed. Finally, the results of the GMCR stability analysis are used to suggest targeted countermeasures for decarbonization of China's energy system.

FORMATION OF TERNARY CONFLICT IN COAL-FIRED POWER INDUSTRY CHAIN

The Marketization Reform Process of Coal Industry and Thermal Power Industry

China's coal industry has, successively, gone through the stages of planned pricing, combination of regulation and release, and market-oriented reform. In general, from the liberalization of coal prices in 1993 to the cessation of coal price regulation by the

TABLE 1 | Evolution of coal price policy for power generation.

Year	Policy connotation
Before 1984	The coal pricing power and the distribution power of the usage amount are controlled by the central government, and the model of single pricing and unified rationing is implemented.
1985-1994	The power industry still adopts a low-cost unified purchase model, and only the coal required for unplanned power generation needs to be purchased outside the system.
1994-1996	Most of the coal guide prices were canceled, and the two prices were merged, but the disputes over coal power interests were intensified.
1996-2001	The coal guide price model was restored, and large companies in the industry negotiated the next year's coal contract by means of an order meeting according to the price increase set by the government.
2002	The government announced the implementation of the dual-track system of coal and electricity prices and canceled the policy of guiding coal prices. However, the feed-in tariff is still dominated by government administrative control and guidance.
2004	The "Notice of the Opinions on Establishing a Coal-Power Price Linkage Mechanism" stipulates that a coal-power price linkage cycle shall be no less than 6 months. If the average coal price in the cycle changes by 5% or more than the previous cycle, it will be adjusted accordingly electricity price.
2012	The "Guiding Opinions on Deepening the Reform of Thermal Coal Marketization" adjusted the price linkage policy in 2004 in two aspects: (1) The implementation period was adjusted from at least 6 months to 1 year; (2) The original 30% was adjusted to 10%.
2015	The "Notice on Matters Relating to the Improvement of the Coal-Power Price Linkage Mechanism" stipulates the organizer, the point of implementation, the interval linkage mechanism, the proportion of coal price changes to be absorbed by power companies, and the formula for calculating the linkage.
2020	The government decided to abolish the coal price linkage mechanism. The existing benchmark feed-in tariff mechanism to "benchmark price + up and down floating" market-based mechanism.
2022	The central government requires first to determine a reasonable range of coal to achieve the "upper limit of electricity and lower limit of coal". Secondly, the price of coal and electricity within a reasonable range should be effectively transmitted.

Source: Collated from the official website of China's National Energy Administration (http://www.nea.gov.cn/) and Baijixing Power Grid (https://tech.bjx.com.cn/).

state in 2005, coal prices have basically achieved market-oriented reforms (Zheng, 2017). A price formation mechanism dominated by the market and supplemented by the government's macro-control is realized gradually (Wang et al., 2016; Wang, 2018; Zhang et al., 2019). However, coal prices fluctuate wildly due to numerous uncertain events. **Table 1** lists China's key policies to stabilize thermal coal prices over the years, among which the most critical and longest-running policy is coal-electricity price linkage (Bai, 2014; Li et al., 2015; Tan and Liu, 2015; Fan et al., 2018). However, Ye et al. (2018) pointed out that it has problems such as a long lag period, a high proportion of power generation companies digesting coal price fluctuations, and inadequate policy implementation. On the contrary, Zhang and Shi (2022) found that the abolition of coal-power linkage to implement electricity price marketization, although it can solve the structural contradiction of coal and electricity, will make the coal price increase bring a greater degree of industrial sector production costs and increased cost of living for residents. Objectively, the coal-power linkage policy is a transitional measure to deal with

TABLE 2 | Evolution of China's thermal power industry policy.

Year	Policy connotation
1982	In the sixth five-year plan, the policy of "investing and building by the state, enterprises, collectives, and individuals, and developing large, medium and small thermal power plants in a comprehensive manner" was implemented in terms of finance, taxation, and plan management.
1985	The central government has put forward the policy that the development of the energy industry should be "lefted on electricity, with active development of thermal power, the vigorous development of hydropower, and focused, step-by-step construction of nuclear power".
1986	The "Temporary Regulations on the Development of Small Thermal Power" formulated the basic principles of coal-power linkage, hot spot co-generation, and restricted development.
1987	The policy of "separation of government and enterprises, the province as an entity, joint power grid, unified dispatch, and pooling of funds to run electricity" was proposed and implemented, and the provinces supported the small thermal power industry as a major economic growth point.
1991	The Ministry of Energy has launched the policy of "replacing small units with large ones", i.e. "replacing old units with high energy-consuming and high-polluting low and medium voltage units with high-parameter and large-capacity units".
1995-1999	The series of documents emphasize the strict requirements that "grid enterprises shall not acquire power from power plants that should be shut down, and that project approval and implementation shall be carried out in accordance with the system of mutual linkage between the renovation of old units and the shutdown of small thermal power plants".
2002-2003	China separated the power generation assets from the grid and established five major power generation companies and the State Grid Corporation, forming a market pattern of "separation of plant and grid, bidding for grid access, breaking monopoly and introducing competition".
2007	The central government emphasizes the comprehensive use of economic, legal, and administrative means to create a fair competitive environment for all units, reward closed enterprises and localities, and promote the elimination of backward small thermal power plants.
2014	The "Action Plan for Upgrading and Renovation of Coal Power Energy Saving and Emission Reduction (2014–2020)" puts forward ultra-low emission requirements for coal-fired power plants at the national level for the first time.
2015	The "Work Plan for the Comprehensive Implementation of Ultra-Low Emission and Energy-Saving Transformation of Coal-fired Power Plants" provides specific implementation rules for the electricity price subsidy, the hours of power generation utilization, the policy of halving the collection of pollutant discharge fees, and financial credit support for ultra-low emission coal-fired power generating units.
2017	The "Opinions on Promoting Supply-side Structural Reform and Preventing and Resolving the Risk of Overcapacity of Coal Power" guides local power generation enterprises to further standardize the planning and construction of coal-fired self-provided power plants while resolving excess capacity of coal power.

Source: Collated from the official website of China's National Energy Administration (http://www.nea.gov.cn/) and Baijixing Power Grid (https://tech.bjx.com.cn/).

the violent fluctuations in the coal market, and its role as a coal price regulation policy itself means that coal prices are greatly influenced by the market.

Compared with the market-oriented reform process of coal, the marketization of China's power structure is relatively low. As **Table 2** shows, although market-based reforms in both the power generation and coal industries began in the 1980s, the government still holds dominant control over the power generation industry. Coal fuel accounts for 60%–70% of the cost of power generation, and the efficiency of coal consumption is determined as a priority by the level of technology and capacity scale of the generating units (Bai, 2014), so changes in coal prices affect the long-term trend of technological optimization, budget, production, and operation performance of downstream thermal power industry. In general, the degree of marketization of electricity prices lags far behind. The coal price market is the essential reason for the structural contradiction between coal and electricity (Zhang and Shi, 2022).

The Shifting Role of Government in Coal-Power Industry Conflict

Global power systems are facing certain crises under the effects of decarbonization—all these negative phenomena have resulted in increased risk of violation of the power balance and insufficient supply. Geographically, thermal coal price growth remained positive in 2021, with growth rates of 4.9% and 3% in Europe and Asia, respectively (Savina et al., 2021). Power system is gradually developing into a hybrid energy system with multiple inputs and outputs (Arent et al., 2021), in which the coal-fired power generation chain has obvious deficiencies in energy supply, safe operation, and clean consumption. As presented in **Figure 1A**, China's total CO_2 emissions have broadly gone through three phases in the past 30 years, namely the slow growth phase (1990–1999), the rapid growth phase (2000–2013), and the oscillating and fluctuating phase (after 2014). At the same time, the share of CO_2 emissions from coal to total emissions (SEC_TE) has remained above 30% for a long time. Therefore, the coal de-capacity strategy was adopted in the decarbonization transition of the energy system, as shown in **Figure 1B**, after years of growth, total raw coal production (TRCP) experienced a small decline in 2014, followed by a larger decline in 2015.

Furthermore, **Figure 1B** also presents that the share of power in end-use energy consumption (SP_EEC) continues to grow, especially in 2019 for the first time above a quarter. A stable supply of electricity is vital to the security of the energy system, yet coal-fired power plants cannot operate without a stable supply of coal. From the perspective of industrial symbiosis, coal industry and electric power industry should maintain coordinated development. However, it is not the case, and in **Figure 1B**, the up-and-down oscillation of SRCCP_CP (share of raw coal consumed for coal-fired power generation in coal production) under the overall upward movement of SP_EEC in the last 15 years reflects, to some extent, the increased supply volatility of the coal-fired power generation chain.

In general, considering that carbon-peaking and carbon-neutral targets make the government face huge pressure to reduce carbon emissions, the government's position in the coal power industry conflict is different from its previous role as a regulator of the price of electricity and coal. The Chinese government has to deal with the decarbonization of thermal power plants, however investment in carbon reduction technologies for power plants is affected by fluctuations in upstream coal prices. Therefore, the establishment of the government's dual carbon goal makes it necessary to strengthen its penetration in the coal power industry conflict, and transform it into the third type of interest appealers and decision-makers, instead of only a price mediator, in the coal power industry conflict.

Ternary Conflict in Coal-Fired Power Industry Chain

A ternary conflict has formed between the government, coal enterprises, and coal-fired power generation enterprises under the combined effect of the differences in the degree of marketization of the coal market and the electricity market, as well as carbon-peaking and carbon-neutral goals. As shown in **Figure 2**, the most straightforward option to achieve the goal of a low-carbon transformation of the energy system in the context of high-quality macroeconomic development in China is to curb the size of the coal-fired power generation industry and promote the development of green energy. However, the scale of green energy production cannot yet guarantee the safe and stable supply of the energy system after the contraction of the coal-fired power generation industry in the short term, and there are still many shortcomings in green energy itself. Even in the long run, Chai and Li (2022)use the evolutionary game model to analyze the evolutionary law between the governmental power subsidy policy and the energy structure state of power generation enterprises. It is found that the future energy structure is a combination of clean utilization of traditional energy and renewable energy in a certain proportion, rather than a hybrid transition mode of traditional energy and renewable energy. Therefore, the first element of the ternary conflict is the incongruity between the government's energy system decarbonization reform and the secure and stable supply of the energy system.

For coal enterprises, they face the risks of capacity compression, environmental protection, and price volatility in the process of decarbonization of the energy system, and these risks are the second element in the creation of the triadic conflict.

—Production capacity pressure comes from coal mining activities, which have profound negative impacts on environment and human life (Hendryx, 2015; Grigoriou and Rothaermel, 2017), namely air pollution, climate change, resource depletion, etc. Mining of coal, not just its burning, causes occupational diseases and public health problems as well (Graber et al., 2014; Hall et al., 2019). Most of these health problems are related to inhalation of mining-related dust and chemicals (Munawer, 2018; Hendryx et al., 2020). Avoiding the above issues is possible through a package of restrictions on coal capacity in China. For example, disposal of "zombie coal enterprises" by overall withdrawal, closure and clearance, restructuring and integration, and other strategies to reduce capacity and the compression of new production capacity. Moreover, the rapid expansion of hydropower, nuclear power, solar energy, and other green energy sources at the macro level, will squeeze coal power production capacity under double carbon constraints (He et al., 2020).

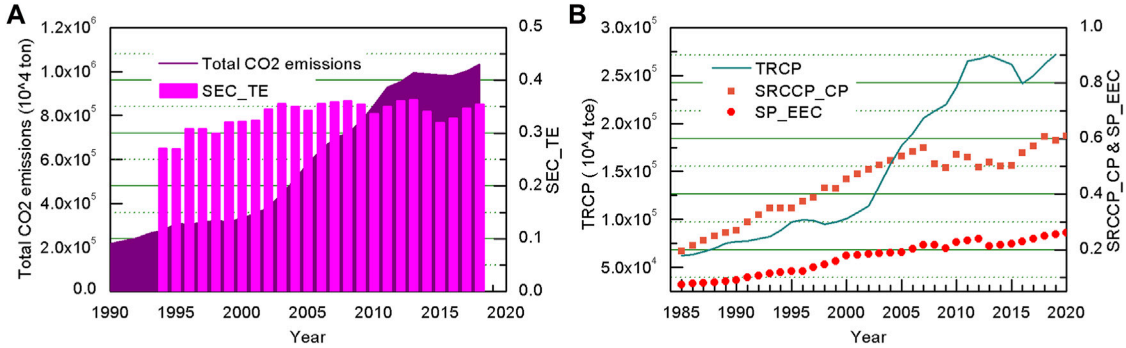

FIGURE 1 | Time evolutionary characteristics of carbon emissions, power production and consumption, and coal production capacity in China. Source: 1) The data of total CO_2 emissions and SEC_TE were obtained from CSMAR Carbon Neutrality Research Database; 2) The data of TRCP came from CHINA ENERGY STATISTICAL YEARBOOK 2020; 3) The vast majority of the data for SRCCP_CP and SP_EEC were obtained from CHINA ELECTRICITY STATISTICAL YEARBOOK 2021, except for the data from 2001 to 2004 obtained by linear interpolation.

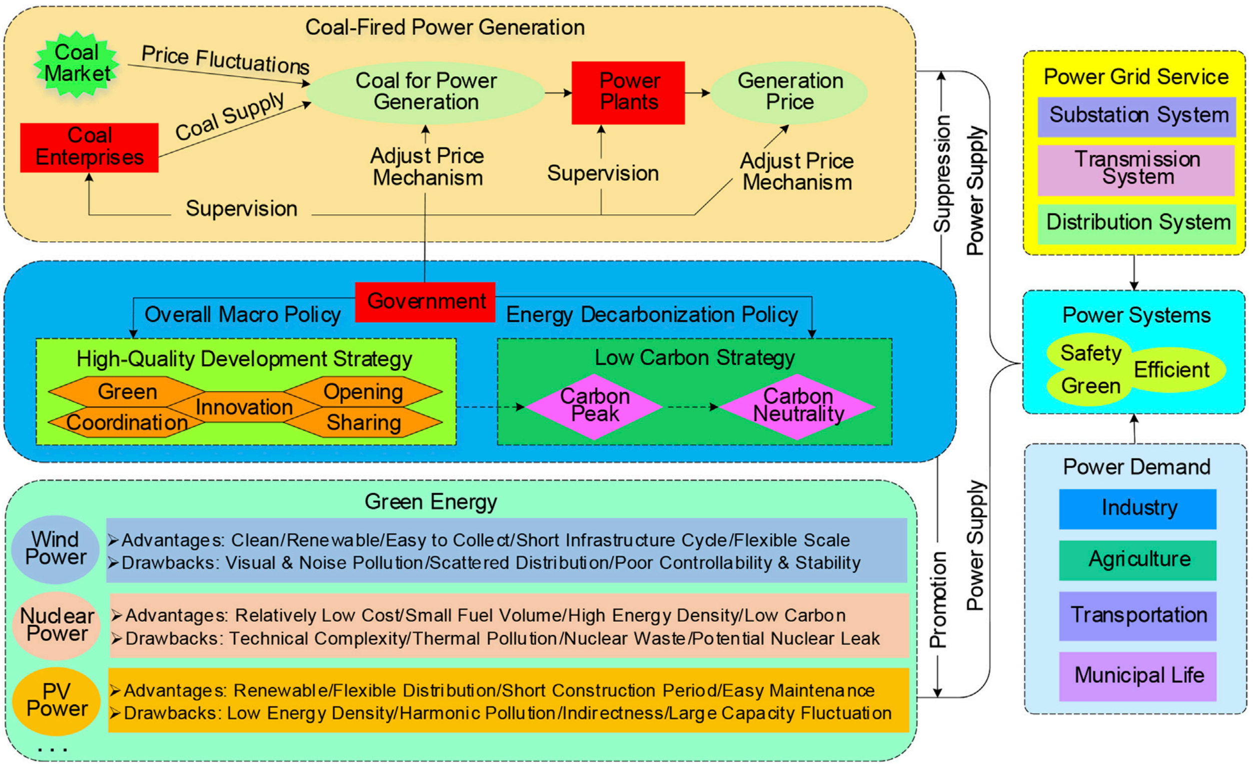

FIGURE 2 | Ternary conflict in coal-fired power industry chain.

—Environmental protection pressure is mainly reflected in strict environmental protection, energy consumption, and water consumption standards. In detail, coal-related environmental challenges consist of the handling of the escape of coalbed methane (CBM), soil erosion, coal gangue, mine drainage, and land subsidence (Wang et al., 2020). For coal enterprises, improving their environmental governance capabilities is a prerequisite for obtaining long-term development opportunities (Husted and de Sousa-Filho, 2017; Lemly, 2019). In detail, the environmental pressure of coal enterprises includes costs of coal consumption, exploration costs of coal resources, environmental prevention costs, environmental governance costs, environmental impact costs, costs of ecological environment damage, and environmental management and education costs (Guo et al., 2019).

—In the context of the current complex situation of international energy supply and demand, coal prices under the guidance of a market-oriented pricing mechanism often fluctuate irrationally and violently. For a long time, the Chinese government has continuously improved the coal price formation mechanism. In the period 2016– 2021, the price of coal for power generation in China has successively implemented the coal-power price linkage mechanism and the "basic price + floating up and down" dual-track system (Li, 2019). Since May 2022, based on adhering to the coal price formed by the market, clarify the reasonable range of price, strengthen the regulation of range, and guide the coal price to operate in a reasonable range (NDRC, 2022). In essence, the trade-offs and adjustments between the market and planned price formation mechanisms are the basic means of stabilizing coal prices, yet the price regulation is usually not as effective as it should be.

The third element of the ternary conflict is the operational dilemma faced by coal-fired power producers. Specifically, these include declining profits, fluctuating fuel prices, and higher energy consumption and emission standards.

— Upstream fuel price fluctuation risk: with the increase in the level of per capita electricity consumption, the amount of coal consumed in power generation is also increasing as presented in **Figure 1**. Coal-fired power generation does not have a substitution relationship between labor and capital in the short term, and the complementarity between coal and combustion-supporting materials is not strong (Zhang et al., 2011). Therefore, in the short term, if the price of coal rises, enterprises cannot reduce the input demand for coal by increasing labor and auxiliary materials but only by adjusting production to reduce losses, which will lead to conflict with the government's goal of securing a stable supply of electricity.

— Supply guarantee pressure of downstream power demand: as depicted in **Figure 1**, in terms of electricity demand and supply, the share of electricity in China's end-use energy consumption has tripled in the last 30 years. Among them, the proportion of coal-fired power generation in the total installed capacity has remained above 50% for a long time (Wang et al., 2018). Therefore, coal-fired power plants bear the important responsibility of a stable power supply.

— Environmental regulatory pressure: under the goals of carbon peak and carbon neutrality, the environmental protection pressure of coal-fired power plants has increased sharply, and the continuous improvement of energy consumption and emission standards has led to an increase in the operating costs of coal power companies' generator sets.

GMCR MODEL OF TERNARY CONFLICT IN COAL-FIRED POWER INDUSTRY CHAIN

Graph model for conflict resolution (GMCR) is a conflict modeling and analysis tool with weaker data requirements compared with classical game theory (Xu et al., 2018; Kong et al., 2019). It can analyze the strategy and preference characteristics of decision-makers based on conflict information and then explore the equilibrium characteristics of conflict feasible states with the help of different stability definitions, which provides strong support for solving the ternary conflict problem of coal-fired power generation industry chain. In detail, GMCR of the ternary conflict can be expressed as $G = N, \{O_i\}_{i\in N}, S, P$. Here, $N = \{DM_C, DM_P, DM_G\}$ is composed of coal enterprises (DM_C), coal-fired power plants (DM_P), and government (DM_G). $O_i = \{A_1, A_2, \cdots, A_{h_i}\}$ is the strategy set of DM_i (i, $i \in N$), $A_1, A_2, \cdots, A_{h_i}$ is the specific policy of DM_i ($h_i = |O_i|$). $S = \{s_1, s_2, \cdots, s_m\}$ represents the set of all feasible states of conflict. $P = \{\succ_i, \sim_i\}$ represents the preference characteristics of DM_i. $s_k \succ_i s_t$ indicates that preference of DM_i for state s_k is better than that of state s_t, and $s_k \sim_i s_t$ indicates that there is no difference in preference between s_k and s_t.

Strategy Behaviors of Ternary Conflict in Coal-Fired Power Industry Chain

In the market-oriented coal industry, production goals of coal enterprises are to pursue the maximization of their own interests, and their strategies can be abstracted into $O_C = \{A_1, A_2, A_3\}$. Among them, the main way is to establish a regional coal joint sales organization to increase the price negotiation advantage in coal sales, or to expand the scale of coal enterprises through continuous acquisitions, mergers and integrations to implement the large group strategy. Therefore, A_1 is used here to represent the price increase strategy. The profits of coal enterprises are mainly determined by coal price and yields. Driven by interests, coal companies will have a greater possibility to choose to default with downstream coal-fired power plants when the difference between the immediate market price of coal and the contract price of thermal coal is sufficient to compensate for the economic losses caused by breaching the long-term contract. In order to depict the above scenario, A_2 is used to indicate the reduction in the supply of coal for coal-fired power generation. Moreover, another illegal and unethical tactic of coal enterprise is A_3, which is to reduce the quality of coal with the main purpose of transferring to downstream thermal power producers the risk of lost profits due to differences between key contracts and market prices.

Coal-fired power generation bears a high peak load demand and is strategically important for national energy security. The business goal of coal power enterprises is to ensure the supply of electricity and maximize their own benefits under the conditions of meeting their normal operation. Faced with the tight supply and soaring prices of upstream coal, coal-fired power grid prices are in a long-term loss situation. When the losses accumulate to a certain level, coal-fired power plants will take the following measures under pressure to survive: gradually stop the operation of generating units, cut the power supply, and reduce the loss. Therefore, the strategy of coal-fired power companies can be abstracted as $O_P = \{A_4\}$, where A_4 is to reduce the amount of coal-fired power supply.

In the context of the double carbon constraint, government departments need to consider both the carbon emission reduction target, safe and stable supply of electricity and the set of their

TABLE 3 | Feasible states of ternary conflict in coal-fired power industry chain.

DM_i	O	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}	s_{16}	s_{17}	s_{18}
DM_C	A_1	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y
	A_2	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N
	A_3	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N
DM_P	A_4	N	N	N	N	Y	Y	N	N	N	N	Y	Y	N	N	N	N	Y	Y
DM_G	A_5	N	N	Y	Y	N	Y	N	N	Y	Y	N	Y	N	N	Y	Y	N	Y
	A_6	N	Y	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	Y	N	N

strategies are recorded as $O_G = \{A_5, A_6\}$. Specifically: 1) The government should ensure the supply of thermal coal and maintain the stability of its market, denoted by A_5. For example, the government should strengthen the communication and coordination among the three parties of production, transportation, and demand, which promote the signing of medium- and long-term contracts for thermal coal. Also, they should supervise the medium- and long-term contract system of coal and optimize pricing mechanisms such as "benchmark price + floating price," "reasonable price range," et al. 2) Ensure the security of electricity production and stable supply, noted as A_6. In order to achieve this goal, on the one hand, the government needs to supervise coal-fired power generation enterprises to implement safe production and equipment maintenance; on the other hand, it needs to take measures to increase the feed-in tariff of coal-fired power to avoid the shortage of power supply caused by the closure of coal-fired power enterprises.

Feasible State and its Transfer of Ternary Conflict in Coal-Fired Power Industry Chain

Decision-makers choose one or more strategies in their strategy set (O_i) and dynamically adjust their own strategies according to the strategies of other decision-makers, and the strategies of all decision-makers at the same moment form a specific conflict situation or state (s). In the ternary conflict of coal-fired power industry chain, $O = \{O_C, O_P, O_G\}$ contains six strategies, each with two states, i.e., choice (Y) and non-choice (N), and theoretically, there are 2^6 conflict states, but not all of them conform to the factual logic. For example, coal enterprises choose to increase the coal price while choosing to reduce the coal supply strategy, which is not in line with the assumption of a rational economic man, so the state ($YYN\ N\ NN$) is considered irrational and deleted. In view of the above considerations, there are 18 feasible states of conflict, which are detailed in **Table 3**.

Conflict state transfer is the process by which decision-makers move from a current conflict situation to another by changing their own strategies. The feasible states of decision-makers and their transfer characteristics in GMCR can be represented by a directed graph. In detail, **Figures 3A–C** show the state transfer of DM_1, DM_2, and DM_3 in the ternary conflict of coal-fired power industry chain, respectively. The circle represents the feasible state (s), and the directed arc represents the state transition process. For example, in **Figure 3A**, the conflict state s_1 means that the coal company reduces the coal quality $\{(A_1, A_2, A_3) = (N, N, Y)\}$, the coal-fired power plant maintains the current electricity supply $\{(A_4) = (N)\}$, and the government maintains the current regulatory policy and supervision $\{(A_5, A_6) = (NN)\}$. s_7 indicates that coal company has changed their strategy to reduce coal supply $\{(A_1, A_2, A_3) = (N, Y, N)\}$, while power plant and the government have made no strategic adjustments $\{(A_4, A_5, A_6) = (N, N, N)\}$, i.e., coal enterprises change the conflict state from s_1 to s_7 by unilaterally changing their strategies.

Strategy Preference Statement and Conflict State Preference

Conflict state preference is the prioritization of the decision maker's feasible states, which is often determined in practice using the method of strategy preference statement (Xu et al., 2018). Based on the characteristics of decision-makers' conflict mechanism, conflict environment, decision-making goals, and other characteristics in the ternary conflict of coal-fired power industry chain, the order of decision-makers' strategy preferences are declared, and the conflict feasible state ranking of different decision-makers is obtained. The strategy preference statements of DM_1, DM_2, and DM_3 are shown in **Table 4**, where the symbols "-" and "IFF" indicate the inverse strategy and conditional strategy preference statement (if and only if), respectively. Specifically, the strategy preference statement for DM_1 is $-5,\ 1\,IFF-5,\ 3\,IFF-5,\ 2\,IFF-5,\ -4,\ 6$, indicating a strong to weak strategy preference ranking of government deregulation (-5), raising coal prices under relaxed government regulation ($1\mathrm{IFF}-5$), lowering coal quality under relaxed government regulation ($1\,IFF-5$), lowering coal supply levels under relaxed government regulation ($2\,IFF-5$), coal-fired power plants maintaining stable power supply (-4), and the government raising feed-in tariffs for coal-fired power generation (6). In a similar manner, the strategy preference statements of DM_2 and DM_3 are declared to be $6,\ 5,\ -1,\ -3,\ -2,\ 4\,IFF-6$, and $-4,\ -1,\ -3,\ -2,\ 5,\ 6$, respectively.

The preference scores of all feasible states of coal companies, coal-fired power plants, and governments are calculated with the help of the conflict state ranking method based on strategy preference statements (Hou and Xu, 2016), and the preference sequences of feasible states are determined accordingly. Specifically, the conflict state

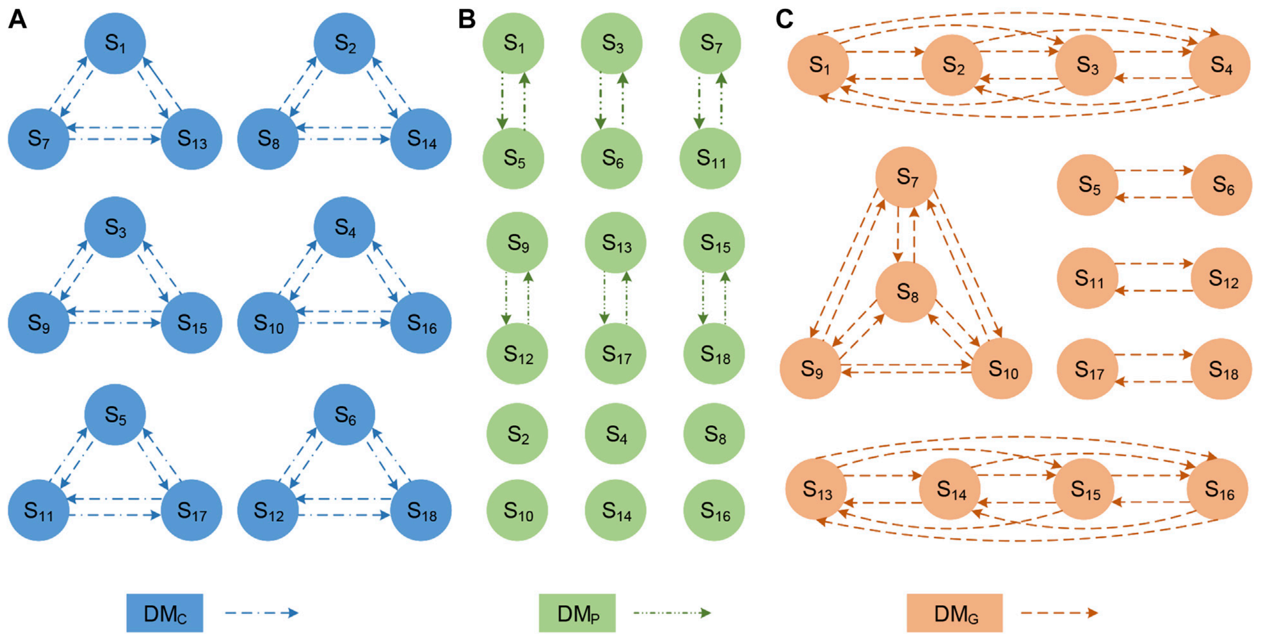

FIGURE 3 | Feasible state transfer of ternary conflict in coal-fired power industry chain.

TABLE 4 | Preference statement of feasible conflict states.

DMi	Strategy statements	DMi	Strategy statements	DMi	Strategy statements
Coal Enterprises (DM_C)	–5	Coal-fired Power Plants (DM_P)	6	Government (DM_G)	–4
	1IFF-5		5		–1
	3IFF-5		–1		–3
	2IFF-5		–3		–2
	–4		–2		5
	6		4IFF-6		6

preference of coal enterprises is: P_C={$s_{14} \succ s_{13} \succ s_{17} \succ s_2 \succ s_1 \succ s_5 \succ s_8 \succ s_7 \succ s_{11} \succ s_{10} \succ s_9 \succ s_{12} \succ s_4 \succ s_3 \succ s_6 \succ s_{16} \succ s_{15} \succ s_{18}$}; The conflict state preference of coal-fired power plants is P_P = { $s_{10} \succ s_4 \succ s_{16} \succ s_8 \succ s_2 \succ s_{14} \succ s_{12} \succ s_9 \succ s_6 \succ s_3 \succ s_{18} \succ s_{15} \succ s_{11} \succ s_7 \succ s_5 \succ s_1 \succ s_{17} \succ s_{13}$}. The conflict states preference of government is P_G = {$s_{10} \succ s_9 \succ s_8 \succ s_7 \succ s_4 \succ s_3 \succ s_2 \succ s_1 \succ s_{16} \succ s_{15} \succ s_{14} \succ s_{13} \succ s_{12} \succ s_{11} \succ s_6 \succ s_5 \succ s_{18} \succ s_{17}$}.

5 CONFLICT EQUILIBRIUM STATE ANALYSIS OF TERNARY CONFLICT IN COAL-FIRED POWER INDUSTRY CHAIN

The rational economic man hypothesis of decision-makers indicates that their decision-making goal is to pursue the maximization of their own interests, but the conflict state cannot usually be decided by any one decision-maker. Each decision-maker must consider the conflict overall situation and predict what all decision-makers may accept as the solution to the conflict and stability. Conflict equilibrium state analysis based on GMCR theory usually relies on four kinds of stability: *NASH*, *GMR*, *SMR*, and *SEQ*. **Table 5** shows the four stability characteristics of all feasible states in the ternary conflict of coal-fired power industry chain. Among them, "$\surd$" indicates that the feasible state satisfies the corresponding stability conditions; "*" indicates that the feasible state satisfies the corresponding stability condition for all decision-makers, i.e., the feasible state is the equilibrium point (E) under the corresponding stability.

As presented in **Table 5**, presents the stability characteristics of different conflict states, where s_1, s_2, s_5, s_7, s_8, s_9, and s_{11} satisfy GMR and SMR. Among them, when DM_i is in the equilibrium state of GMR, any strategy adjustment DM_i taken to try to change the current state will suffer from the opponent's counterattack behavior making its own interests damaged. In the equilibrium state of SMR, DM_i adjusts its strategy to change the conflict state and can still make further counterattacks after suffering counterattacks from the opponent, but all counterattacks of DM_i cannot make its own interests better than the current state. s_{10} and s_{12} satisfy four kinds of

TABLE 5 | Equilibriums of ternary conflict in coal-fired power industry chain.

State	NASH				GMR				SMR				SEQ			
	DM_C	DM_P	DM_G	E	DM_C	DM_P	DM_G	E	DM_C	DM_P	DM_G	E	DM_C	DM_P	DM_G	E
s_1					√	√	√	*	√	√	√	*	√	√		
s_2		√			√	√	√	*	√	√	√	*	√	√		
s_3						√	√			√	√					
s_4		√	√			√	√			√	√			√	√	
s_5		√			√	√	√	*	√	√	√	*	√	√		
s_6		√	√			√	√			√	√			√	√	
s_7					√	√	√	*	√	√	√	*	√	√		
s_8		√			√	√	√	*	√	√	√	*	√	√		
s_9	√				√	√	√	*	√	√	√	*	√			
s_{10}	√	√	√	*	√	√	√	*	√	√	√	*	√	√	√	*
s_{11}		√			√	√	√	*	√	√	√	*	√	√		
s_{12}	√	√	√	*	√	√	√	*	√	√	√	*	√	√	√	*
s_{13}	√				√				√				√			
s_{14}	√	√			√	√			√	√			√	√		
s_{15}						√				√						
s_{16}		√	√			√	√			√	√			√	√	
s_{17}	√	√			√	√			√	√			√	√		
s_{18}		√	√			√	√			√	√			√	√	

equilibrium at the same time. In the NASH equilibrium state, all decision-makers have no desire to change the current state. In SEQ equilibrium, the decision-maker adjusts the strategy and whether the opponent takes counterattack behavior will consider the change for its own gain. If the counterattack can make its own gain greater than the case of no counterattack, it takes counterattacking behavior, otherwise, it abandons counterattacking. In fact, the SEQ equilibrium is based on the GMR with the addition of the counter attacker's rationality factor, i.e., the counter attacker will consider its own income situation when making decisions.

In **Figure 4**, the evolution paths of conflict equilibrium states s_{10} and s_{12} reveal the game process of coal enterprises, coal-fired power plants, and government from a dynamic perspective. The equilibrium state s_{10} connotes that coal enterprises reduce coal supply, and government strengthens the regulation of coal enterprises and moderately increases the feed-in tariff of coal-fired power generation. The conflict evolution stabilization situation is in line with the coal power industry supply chain price transmission law in the context of energy decarbonization transition strategy. Specifically, the unstable coal production capacity under the constraint of dual carbon targets will intensify the market price volatility. In the short term, coal companies will maintain coal supply due to the cost of defaulting on long-term coal contracts and government regulatory pressure. However, when prices of coal supplied for power generation are frequently lower than market coal prices and free-market profits exceed regulatory and long-term contract default costs, coal companies will reduce coal supply and switch to the free market for higher profits. The reduction of coal supply beyond a certain limit will inevitably lead to higher operating costs for downstream coal-fired power plants, and even long-term loss-making operations and bankruptcy, ultimately jeopardizing the security of the power supply. In particular, if the external environmental impact leads to a sharp increase in power demand, the above-mentioned power security supply problems will be more prominent. In view of this, the government, in order to ensure a stable supply of electricity, needs to continuously improve the coal price monitoring mechanism to effectively regulate the coal supply capacity of coal enterprises in a timely manner, and take severe punishment for enterprises that illegally reduce the supply of coal for coal-fired power generation. At the same time, when the reduction of upstream coal supply for coal-fired power generation has caused the cost of coal-fired power plants to continue to rise above the maximum alarm rate, it should appropriately increase the feed-in price of coal-fired power or reduce the operating costs of coal-fired power plants through tax incentives, etc., to promote the safe and stable supply of electricity.

Conflict equilibrium state s_{12} means that coal enterprises and coal-fired power plants reduce the supply level at the same time, and the government imposes strict supervision on coal enterprises. Specifically, the reduction of coal supply for coal-fired power generation by coal enterprises will lead to an increase in the fuel cost of downstream coal-fired power plants for power generation and induce the bankruptcy of units with outdated equipment and low power generation efficiency because they cannot bear the increased operating costs caused by the increase in fuel costs. Finally, the advantageous capacity of coal-fired power generation will be released to make up for the power supply gap caused by the elimination of backward production capacity. Government should strengthen the supervision of coal enterprises and punish enterprises that maliciously reduce the supply of coal for power generation.

The future energy structure system tends to reduce carbon emissions under the dual carbon target constraints, and the ternary conflict mediation strategy of "coal-power-government" should fully grasp the rhythm of energy change. Objectively, the combination of strategies corresponding to the above conflicting equilibria s_{10} and s_{12} is not absolutely superior or inferior in promoting the low-carbon transition of the energy structure system, but is determined by the energy demand and the dual carbon targets at different stages of the low-carbon energy

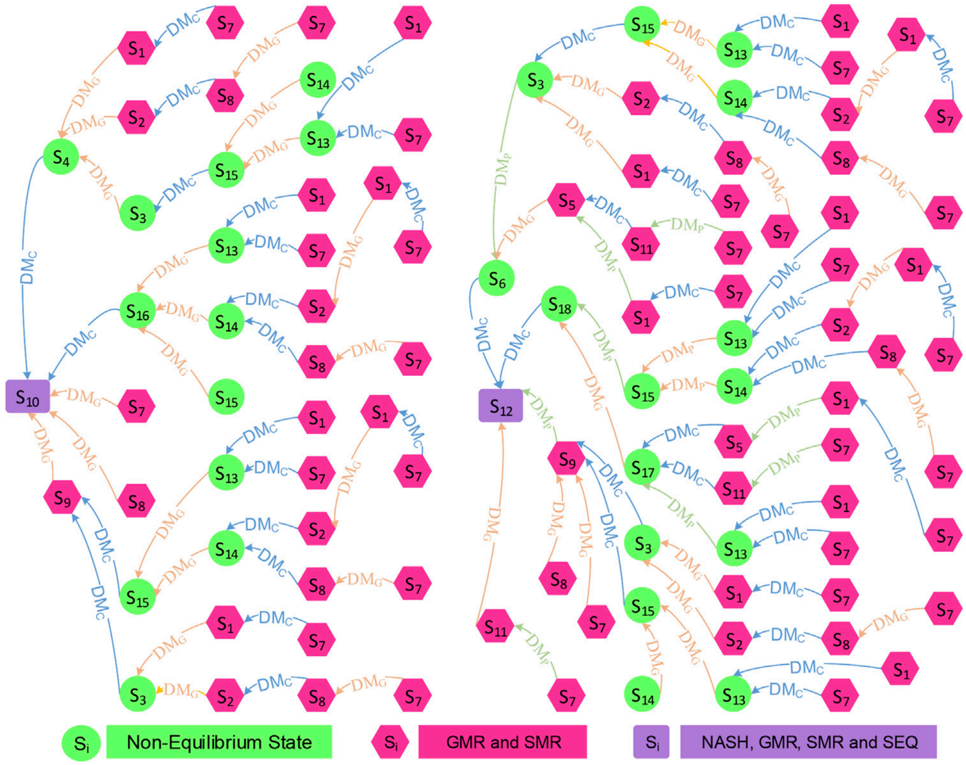

FIGURE 4 | Evolution path of conflict equilibrium states.

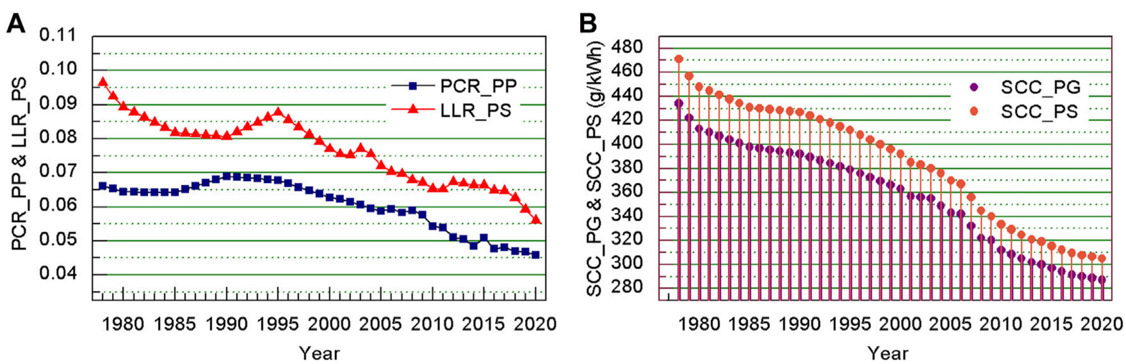

FIGURE 5 | Power generation efficiency and coal consumption of China's power plants. Source: The data were obtained from CHINA ELECTRICITY STATISTICAL YEAR BOOK 2021.

transition. For example, increasing the feed-in price for coal-fired power generation in the conflict equilibrium s_{10} may mislead investors in coal-fired generation and thus reduce the energy decarbonization transition process. However, increasing the feed-in tariff of coal-fired power generation can help alleviate the risk of power supply shortage in the process of power decarbonization. In addition, the ternary conflict mediation strategy of coal-fired power industry chain should reflect regional differences. In regions where the green energy supply is not yet able to fill the gap of coal-fired power plants and where the conflict between coal companies and coal-fired power plants seriously endangers the stable power supply, the government can set the conflict mediation strategy according to the evolutionary path of s_{10}. In regions with a higher level of green energy supply, the government should refer to the evolution path of s_{12} precise governance to accelerate the elimination of backward coal power production capacity and build a safe, green, and efficient energy system. It is worth noting that inter-regional carbon transfer may result in "efficiency losses" exceeding "efficiency gains" (Jiang et al., 2015; Lejano et al., 2020), so the government's regional carbon emission reduction policy needs to comprehensively evaluate its negative benefits before specific implementation.

For the A_6 strategy in the equilibrium state s_{10}, the government can consider formulating guiding policies from the perspective of encouraging green innovation (Sun et al., 2019). As depicted in **Figure 5A**, power consumption rate of power plants (PCR_PP) decreases more while in loss rate of power system (LLR_PS) decreases less, so the technological innovation in the power transmission process needs to be further enhanced in order to facilitate further compression of LLR_PS. The government should further strengthen policy inducement in this regard. Moreover, although both standard coal consumption for power generation (SCC_PG) and power supply (SCC_PS) being reduced, there is still a gap between SCC_PG and SCC_PS. This gap can be understood as the space for technologies related to reducing SCC_PS. Therefore, the government needs to formulate systematic policies to support coal-fired power plants to carry out targeted technological research on reducing SCC_PG and SCC_PS, so as to improve their power generation efficiency and carbon emission reduction capabilities.

CONCLUSIONS AND DISCUSSIONS

Grasping the main contradictions in the current energy transition process according to specific national conditions and proposing a practical implementation path for low-carbon energy transition is the key to achieving the development of energy transition. Against the backdrop of the tight time frame for carbon-peaking and carbon-neutral targets, the Chinese government has outlined an ambitious blueprint for promoting climate and environmental governance and sustainable development with a series of important emission reduction strategies, demonstrating China's strategic determination to adhere to green and low-carbon development and actively address climate change. Overall, the ternary conflict among coal enterprises, coal-fired power plants, and the government is essentially an outward manifestation of the multiple pressure shifts faced by these three parties in the process of decarbonizing the energy system in the context of China's macro strategy for high-quality development.

Coal enterprises, coal-fired power plants, and the government are placed under a systematic analysis framework from the perspective of coal-fired power industry chain conflict to explore the formation mechanism of the above ternary conflict in the process of decarbonization transformation of energy system. Further, a conflict analysis model of the coal-fired power industry chain is constructed based on the theory of GMCR to analyze the possible coping strategies and conflict states of different decision-makers. The feasible conflict states are ranked based on the state preference statement method, and then the NASH, GMR, SMR, and SEQ equilibrium characteristics of conflict states for all the decision-makers are explored. It is found that among all feasible conflict states, s_{10} and s_{12} satisfy the above four equilibrium conditions at the same time. Therefore, taking s_{10} and s_{12} as the strategic basis for ternary conflict mediation in the coal-fired power industry chain and drawing its evolution path, a reasonable conflict mediation path is proposed accordingly.

Finally, this paper provides some useful insights for future research on the transformation and upgrading of energy systems under the background of carbon-peaking and carbon-neutral targets. Future research could draw more on big data and its management and application tools to assist in determining the strategic preference characteristics of coal enterprises, coal-fired power plants, and governments, especially in identifying the pace of energy reform and conflict characteristics in different regions. In particular, it is critical to use technological innovation to promote the low-carbon transformation of the energy system to achieve the carbon reduction goal (Cai et al., 2021). For example, the energy system needs to transform from high-carbon to deep low-carbon or zero-carbon, from mechanical electromagnetic systems to power electronic devices, and from deterministic controllable continuous power sources. The decarbonization process of the energy system is radical but realistic in some respects, and further development and diffusion of green technologies facilitate more efficient decarbonization. Overall, the systematic design of optimal energy system low-carbon transition pathways is a complex process of continuous refinement.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

YF conceived the project and wrote the manuscript; HX designed the GMCR model and edited the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.930322/full#supplementary-material

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