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Energy price bubbles and extreme price movements: Evidence from China's coal market

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ABSTRACT

This study investigates the factors behind the extreme price movements in China's coal market, with a particular focus on the impact of climate risk and energy transition in recent years. The Generalized Sup Augmented Dickey-Fuller (GSADF) method is employed to detect coal price bubbles, and a dynamic model averaging (DMA) approach is then used to analyze the causes of these price bubbles. The findings reveal that price bubbles in the Chinese coal market are mainly triggered by fluctuations in international energy prices. The extreme prices are rooted in supply-demand imbalances resulting from energy transition, economic development, and geopolitical conflicts. Policies aimed at adjusting coal supplies can effectively mitigate abnormal coal price fluctuations in China, while normal coal price fluctuations are significantly influenced by changes in energy demand driven by macroeconomic development. During the green transition towards renewable energy, the current high prices of fossil energy present challenges to China's energy supply security but also offer opportunities for the development of the renewable energy market. However, energy transition has facilitated the spread of price bubbles across coal, natural gas, and renewable energy markets, potentially leading to contagion effects.

1. Introduction

Coal plays a significant role in China's energy market and energy transition. Studying the extreme price movements in China's coal market is crucial not only for domestic energy security and energy market risk management but also for the international energy market. Historically, coal has dominated China's energy mix, accounting for nearly two-thirds of its primary energy sources (Li et al., 2019). Extreme fluctuations in coal prices can potentially lead to supply shortages or surpluses, posing a threat to the stability of China's energy supply and adversely affecting various aspects such as electricity supply, heating, and industrial production. Therefore, understanding the drivers and impacts of coal price bubbles and fluctuations is essential for shaping economic policies and maintaining economic stability.

From the perspective of the broader international energy market and coal trade, China stands as the top producer and consumer of coal globally (Li et al., 2022b). Particularly from the demand side, China is one of the world's largest consumers of coal, with its annual coal consumption accounting for over half of the global total. Changes in the supply and demand dynamics and price fluctuations in the Chinese coal market can significantly impact on the fundamentals of the international coal market and consequently affects international coal trade.

Regarding climate change and energy transition, China is the world's largest emitter of greenhouse gases. The Chinese government has taken significant measures to reduce its carbon footprint and transition towards a more sustainable, low-carbon economy. A crucial aspect of achieving China's dual carbon goals of carbon peaking and carbon neutrality is the transformation of the energy consumption structure towards clean energy sources. Coal is the primary contributor to carbon emissions and is a major driver of climate change (Gao et al., 2023). As a result, phasing out coal is a crucial element of China's ongoing energy transition process (Jia and Lin, 2021; Wang et al., 2022). Policies aimed at phasing out coal give rise to the bridging role of substitute energy sources, especially natural gas, which can lead to risk contagion across these energy markets home and abroad (Wang et al., 2022).

We focus on China's coal market as the case of China could be generalized to other markets, especially the emerging markets, against the backdrop of global energy transition and the battle against climate

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change. In retrospect, the price of coal in China has exhibited fluctuations over the past decade (Guo et al., 2016a). Initially, from 2010 to 2013, the price of coal increased due to robust demand from industries such as steel and cement, coupled with limited supply resulting from mine closures and safety inspections. Subsequently, between 2014 and 2016, the coal price declined because of oversupply and a slowdown in economic growth. The government's efforts to address overcapacity in the coal industry also contributed to the price decline. However, between 2016 and 2018, coal prices rebounded due to increased demand from industries like steel and electricity, along with supply-side reforms that aimed to reduce overcapacity and enhance safety in the coal industry. From 2019 to 2021, the coal price experienced fluctuations influenced by various factors, including the COVID-19 pandemic, changes in government policies, and global economic conditions.

Overall, the price of coal in China has been shaped by a diverse range of factors throughout the past decade. The extreme coal prices in China observed over the past decade have posed significant uncertainties and risks to the economy, industries, and firms. Various factors contribute to these extreme price fluctuations and the formation of coal price bubbles in the Chinese coal market, including supply and demand dynamics in the domestic market, government policies, transportation bottlenecks, extreme weather conditions, global economic conditions, and spillover effects from other markets, most notably, crude oil and the global coal market (Li et al., 2019).

Over the past decade, the Chinese government has implemented a range of policies to control coal production capacity, address environmental concerns and promote the use of clean energy. Even before the introduction of the dual carbon goals, significant coal-related policies were put into effect. In 2013, China established a coal consumption cap of 4.2 billion tons by 2020, with the aim of reducing coal usage to combat air pollution and lower greenhouse gas emissions. Starting in 2016, a series of measures were implemented to tackle safety issues, overcapacity and pollution within the coal industry. This included the close of outdated and inefficient coal mines. On one hand, the government announced plans in 2016 to shut down 1000 coal mines, with the goal of eliminating 500 million tons of coal production capacity by 2020. On the other hand, the construction of new coal-fired power plants has been prohibited in 15 regions since 2016. Consequently, the utilization rate of coal capacity rose from 59.55% in 2016 to 74.05% in 2021, and the growth rate of coal production slowed down to 2.57% in 2021.[1]

Alongside these efforts to reduce coal consumption, China has made significant strides in promoting clean energy and tackle pollution in recent years. In 2015, the country initiated the "Three-Year Action Plan for Air Pollution Prevention and Control" aimed at reducing air pollution in major cities. This comprehensive policy included measures to support the adoption of clean energy sources such as wind, solar and nuclear power. Furthermore, in 2017, China introduced a national emission trading scheme (ETS) to regulate carbon emissions. The ETS covers industries including power generation, iron and steel, and cement, and encourages companies to lower their emissions by allocating tradable carbon allowances. This market-based approach incentivizes emission reductions. Additionally, China launched the "12th Five-Year Plan for Energy Conservation and Emission Reduction" in 2011 to enhance energy efficiency in buildings, transportation and industry. These multifaceted efforts demonstrate China's commitment to promoting clean energy and reducing greenhouse gas emissions.

These policies have played a crucial role in reducing China's reliance on coal and promoting the adoption of clean energy sources. However, given China's resource endowment, coal accounts for 92.1% of the country's fossil fuel reserves (Li et al., 2019) and continues to dominate the country's fossil fuel reserves. Consequently, coal remains a significant source of energy in China. Limiting coal consumption poses challenges due to the limited availability of oil and gas resources, and the renewable energy sector's current inability to fully compensate for the energy gap resulting from the transition. Even during the COVID-19 pandemic, while coal consumption declined in North America and Europe, China's demand for coal remained high (Drachal, 2021). These factors highlight the ongoing importance of addressing coal consumption and further advancing clean energy alternatives in China's energy landscape.

The implementation of these policies has had repercussions on the coal market, resulting in potential supply-demand imbalances, price bubbles, and extreme fluctuations. In the domestic market, the Chinese government's policies to reduce reliance on coal and promote cleaner energy sources have led to a decrease in coal production and an increase in production costs. As a result, the cost of coal has risen, impacting its price in the market. Meanwhile, stricter environmental regulations on coal production have prompted the closures of many small and inefficient mines, reducing the overall supply of coal and subsequently driving prices higher. Also, despite efforts to shift towards cleaner energy sources, China's growing economy and industrial sector have led to an increased demand for coal. This sustained demand contributes to price dynamics, influenced by supply and demand fundamentals and government policies. The tension between ongoing "de-coaling" efforts and the continued dependence on coal during the energy transition process can create significant volatility in energy prices. Additionally, coal transportation in China faces bottlenecks due to limited rail and truck capacity, leading to higher transportation costs and, consequently, higher coal prices.

It should be noted that climate risk plays a non-negligible role in driving extreme price movements in coal, through influencing supply and demand fundamentals, transportation, and government policies (Liu and Chen, 2013; Bell et al., 2020). First, China is a vast country with diverse climatic conditions, and extreme cold or hot weather can be experienced in certain regions. Extreme weather conditions can impact coal demand patterns and power generation. Coal is a primary heating fuel in China, especially in rural areas, and coal-fired power plants are the primary source of electricity generation in China. The demand of coal tends to surge due to increasing heating demand during cold spells or soaring electricity demand for powering air conditioning during heatwaves. The increased demand can put pressure on the coal supply and lead to higher prices (Wang et al., 2022).

Second, extreme weather conditions, such as droughts and floods, are not uncommon in China. Heavy rainfall, flooding or severe storms can induce disruption of coal mining operation and coal production in China. Mines may be forced to temporarily shut down or reduce production due to safety concerns or logistical challenges. One example is the incessant heavy rain in 2021 that flooded 60 mines in Shanxi, a top coal producing province in China. The subsequent coal supply crunch contributed to surging prices of thermal coal in China. Third, extreme weather conditions can damage transportation infrastructure, including roads, railways, and ports, leading to transportation disruptions that hamper the movement of coal from mines to power plants or other destinations. Limited transportation capacity can result in delays in coal delivery, leading to potential supply shortages and extreme price fluctuations. Furthermore, extreme weather events can draw attention to the importance of public health and environmental sustainability. This increased focus on mitigating climate change and reducing vulnerability to extreme weather may influence environmental regulations and policies to aim at reducing coal consumption and demand for coal while promoting renewable energy sources, therefore putting downward pressure on coal prices.

Changes in global economic conditions and energy market fundamentals induced by systemic events such as the COVID-19 pandemic and geopolitical conflicts have also played a role in driving significant price movements in the Chinese coal market. The dynamics and fundamentals in the international energy market, particularly international coal prices (Li et al., 2019), play a significant role in shaping coal prices within

[1] Based on the official data of the National Bureau of Statistics.

China. A recent example highlighting the impact of global factors is the severe power shortage experienced in China during the summer of 2021. This shortage resulted in power usage restrictions being imposed as a response to a combination of domestic and global factors. On the domestic front, there was a high demand for energy, exacerbated by extreme weather conditions (droughts), which led to a decrease in hydropower generation. Additionally, supply chain disruptions caused by the COVID-19 pandemic further strained the energy sector. Internationally, there was a surge in global energy prices, which directly affected the cost of energy in China. Coal-fired plants in China faced significant challenges, including declining coal imports, curtailed domestic coal production, and rising coal prices (He et al., 2010; Peng, 2011). These factors led to substantial losses for coal-fired power plants and reluctance to generate power, ultimately necessitating power usage restrictions imposed by Chinese provinces (Liu et al., 2022). The power usage restrictions were gradually lifted as the situation improved, and the government has taken steps to increase the country's energy efficiency and transition towards cleaner energy sources, including renewable energy. However, the power usage restrictions experienced in 2021 underscore the detrimental effects of extreme coal prices on the power industry and highlight the challenges of balancing economic growth and energy security in a rapidly developing country like China.

There is also rich empirical evidence of an increasing level of integration between energy commodities and the risk and volatility spillover from crude oil to coal, for example, in the European energy market (Ji et al., 2018). Serletis and Libo (2016) study volatility spillovers across three primary energy markets (crude oil, natural gas and coal) over a long span between 1870 and 2014 and find that negative shocks to the oil markets have significant impacts on volatility of coal returns. The spillover effect from crude oil to coal may be driven by an inter-fuel substitution effect (Li et al., 2019). When crude oil prices rise, energy consumers may switch to cheaper alternatives such as coal, leading to increased demand for coal and a subsequent increase in its price.

Another potential driver of the extremely high coal prices in China is the complex and ever-changing global geopolitical environment, particularly geopolitical tensions that impact both global energy markets and political relationships between countries. A recent example is the bombing of the Nord Stream pipeline during the Russia-Ukraine conflict in 2022, which resulted in severe disruptions to energy supplies and trade. The Nord Stream pipeline played a significant role in meeting Europe's energy demand. The damage to the pipeline has caused a disruption in natural gas supply to European countries that heavily rely on it, leading to energy shortages and higher prices. This not only exacerbates geopolitical tensions and impacts the Russian economy, which heavily depends on natural gas exports as a significant source of revenue, but also could result in a more prolonged disruption in the global supply of natural gas. The damage to the pipeline sparks discussions about the need to diversify Europe's energy sources. Consequently, there is an urgent need for alternative energy sources to rapidly shift to coal, which further stimulates the ongoing surge in coal prices in the European region.

Extremely high coal prices, driven by these multiple factors, can create conditions conducive to the formation of a bubble in the coal market. A bubble occurs when the price of coal rises rapidly and surpasses its fundamental value, exhibiting bubble-like properties (Stiglitz, 1990). During the periods of high coal prices, there is often a perception that prices will continue to rise, which can lead to a speculative buying frenzy. Investors may purchase coal as a speculative investment rather than based on its intrinsic value. This speculative activity can further drive up prices and contribute to the formation of a bubble. However, if prices rise excessively, there is a risk that demand will eventually decrease. Buyers may turn to alternative energy sources or reduce their consumption of coal, which can result in a decline in prices and the eventual bursting of the bubble.

Coal price volatility and bubbles can have significant effects on China's economy and energy security. From an economic standpoint, a coal price bubble can result in higher production costs for industries heavily reliant on coal, such as steel, cement, and manufacturing sectors (Burke and Liao, 2015). This can further lead to increased prices for consumers and a slowdown in economic growth (Guo et al., 2016a). In terms of energy security, a coal price bubble in China can have profound impacts on the power industry (Peng, 2011) and the country's energy security. As the largest consumer of coal globally, China heavily relies on coal-fired power plants for electricity generation. Disruptions in coal supply or volatile coal prices can pose significant threats to the country's energy security. During a coal price bubble, the cost of coal can skyrocket, making it expensive for power plants to generate electricity. If power plants struggle to secure a stable supply of affordable coal, they may be compelled to reduce output or shut down completely. Consequently, power outages and blackouts may occur, which can have serious consequences for businesses and households reliant on a consistent electricity supply, such as the aforementioned power shortage in China in 2021.

A coal price bubble in China can have complex impacts on the country's energy transition. It is commonly perceived that a coal price bubble can make coal-fired electricity generation more expensive, potentially accelerating the shift towards cleaner energy sources like natural gas, renewables, or nuclear power. Higher coal prices can make the alternative energy sources more economically viable, thus encouraging investment in renewable energy technologies. However, if coal prices remain artificially low due to government subsidies or other factors, it may discourage the transition to cleaner energy and perpetuate China's reliance on coal. This could hinder the growth of renewable energy industries and delay the transition to a cleaner energy system. Gu et al. (2020) find significant volatility spillover between the steam coal market and the returns of clean energy stocks in China. The authors emphasize that the co-movement between China's steam coal market and the investments in environmental protection concept stocks is subject to the influence of policies and regulations that restrict the supply and demand of steam coal. Therefore, the fundamentals and volatility in the coal market not only have a dominant impact on China's economy but also significantly affect the financing of the clean energy industry.

To mitigate the risks posed by coal price bubbles and promote a faster transition to cleaner energy sources, the Chinese government has implemented various policies and initiatives. First, China has taken measures to enhance its energy security, such as diversifying its energy mix, investing in renewable energy, and increasing domestic coal production. Due to the country's heavy reliance on coal, any disruptions in the coal market can still have significant implications for its energy security. Thus, ensuring a stable and affordable coal supply remains a key priority for China's energy planners. Second, the government is actively supporting and facilitating energy transition through subsidies for renewable energy projects, promoting the adoption of electric vehicles, and implementing carbon pricing mechanisms. However, the persistence of coal price bubbles and the complex political and economic challenges associated with transitioning to a cleaner energy system make it difficult to accurately predict the future trajectory of China's energy transition.

From a broader perspective, it is also crucial to closely monitor the risk and bubbles in the coal market in China, considering their impact on the returns and volatility of other energy types and the global energy market (Li et al., 2019; Khan et al., 2021a). Batten et al. (2019) study the level of integration in the global coal market and provide evidence of the volatility spillover from the Chinese coal market to the global coal market. This spillover represents a significant source of risk for the international energy market. Li et al. (2019) find that changes in China's coal prices influence both crude oil prices and international coal prices, while the volatility in China's coal market is impacted by the international coal market through a contagion effect, as well as by crude oil markets through a substitution effect. These interrelationships highlight the interconnected nature of the coal market with other energy markets and underscore the importance of considering these dynamics when assessing risks and bubbles in China's coal market.

Despite the significance of coal price volatility for China's economy, energy security, and the global energy market, there is a limited number of studies specifically focusing on the question of price bubbles in the Chinese coal market. To fill this gap, this study seeks to explore the time-varying determinants of price bubbles in China's coal market. The findings of this research hope to provide valuable insights and policy implications to enhance energy security, facilitate the green transition, and promote stability in the global energy market. To achieve this objective, we first employ the Generalized Supremum Augmented Dickey-Fuller (GSADF) test to identify bubble periods in China's coal market. We then analyze the time-varying determinants of these bubbles based on the Dynamic Model Averaging (DMA) method. The determinants considered in this analysis encompasses a wide range of factors, including supply and demand dynamics in the coal industry, prices of alternative energy sources, conditions in the power market, and the macroeconomic and financial market conditions.

The study's main contributions are twofold. First, by using the DMA model, we are able to identify the factors that influence China's coal price bubbles from a dynamic perspective. Previous research on the factors driving coal price bubbles has often taken a static approach, as seen in Li et al. (2022b) and Khan et al. (2021a). Using a Logit model, Li et al. (2022b) propose that China's coal price bubble is linked to policy adjustments related to coal capacity reduction and environmental regulations. Khan et al. (2021a) suggest that the major drivers of the bubbles of the benchmark prices of global coal markets include oil prices, economic growth, supply security concerns, geopolitical conflicts, and overproduction. In contrast, the DMA approach employed in this study equips us with a robust tool not only to identify the elements responsible for coal price bubbles but, more importantly, to delve into the evolving nature of these drivers.

Determinants of price bubbles tend to shift over time, particularly during periods marked by significant events. These pivotal events include but are not limited to the introduction of marketization and coal de-capacity policies in the Chinese coal industry, the outbreak of the COVID-19 pandemic, the announcement of China's dual carbon goals, and the Russia-Ukraine conflict. The introduction of the DMA model allows us to discern variations in the determining factors of Chinese coal prices under the influence of different events shocks.

Specifically, during the different periods segmented by these prominent events, we find clear time variations in the level of influence of each factor on China's coal prices. Prior to the marketization of the coal industry in 2013, the overcapacity of China's coal sector and the power generation industry emerged as the primary drivers of coal prices in China. After the implementation of coal de-capacity policies in 2016, price risks in the international coal, natural gas, and renewable energy markets became significant drivers of the Chinese coal prices, especially with the increasing complexity of the international energy landscape following the outbreak of the Russia-Ukraine conflict. The extreme coal prices are fundamentally caused by supply-demand imbalances resulting from energy transition, economic development, and geopolitical conflicts. Notably, over the full sample period, macroeconomic developments and stock market volatility serve as significant determinants of Chinese coal prices during non-bubble periods, while alternative energy price volatility serves as the primary driver during coal price bubble periods.

Second, we examine the potential for the extreme price volatility in the coal market to propagate to other energy markets and vice versa, particularly in the context of energy transition. We compare price bubble periods in the coal market with those in alternative energy markets and analyze the evolving risk contagion across energy markets during the energy transition process. The risk connection between China's coal market and international coal market is influenced by the country's coal de-capacity policies. As part of the energy transition, there is a need to reduce the production of coal, which may increase the demand for imported coal and promote the impact of international coal prices on Chinese coal prices. The risk correlation between coal and renewable energy markets may also increase as the consumption of renewable resources expands. Furthermore, the risk contagion between the coal and liquefied natural gas (LNG) markets is expected to strengthen, given that natural gas plays a bridging role in the energy transition. By analyzing these dynamics, we aim to enhance understanding of the risk propagation across different energy markets during the energy transition process, with a specific focus on the coal market bubbles and their connections with alternative energy market bubbles.

The remainder of this paper is structured as follows. Section 2 provides a review of the relevant literature on coal price bubbles and their underlying determinants. Section 3 outlines the methodology employed in this study. Section 4 describes the data used in the study and presents and discusses the empirical results. Section 5 concludes the paper and offers policy implications based on the findings.

2. Literature review

2.1. Energy price bubbles

This study is first related to the strand of literature on the causes of energy price bubbles. A sudden rise or rapid fall in the price of a commodity, deviating from its fundamental value, is a key sign of its bubble formation (Stiglitz, 1990). An energy price bubble is a situation where energy prices rise rapidly and significantly above their fundamental value, driven by speculative demand from investors and traders (Li et al., 2020). These bubbles can occur in various energy markets, including oil, gas, and coal. Energy price bubbles can have significant economic impacts, leading to higher energy costs for consumers and businesses, increased inflation, and market instability.

Energy price bubbles are often associated with periods of strong economic growth and high demand for energy, which can cause supply constraints and create a perception of scarcity (Khan et al., 2022). This perception can lead to a speculative demand for energy commodities, driving up prices beyond their fundamental value. Besides, irrational capital market exuberance caused by economic crises (Khan et al., 2022), geopolitical conflicts (Khan et al., 2021a), and rising commodity prices, such as oil price (Khan et al., 2021b; Khan et al., 2022), weather-related disruptions to energy supply chains (Bell et al., 2020), and changes in government policies (Li et al., 2022a) are often significant drivers of energy price bubble formation.

Driven by strong economic growth and the global financial crisis, crude oil, natural gas, and coal prices in international markets experienced significant structural disruptions and formed bubbles during 2007–2008 (Khan et al., 2022). The oil price spiked in the early 2000s, which saw the price of crude oil rise from around $20 per barrel in the late 1990s to over $100 per barrel in 2008, driven by increased demand for oil from emerging economies, supply disruptions caused by geopolitical events in the Middle East, and speculation by traders and investors. Significant negative financial bubbles are detected in international crude oil prices during the oil price crash in 2014–2015 (e.g., Fantazzini, 2016). Sharma and Escobari (2018) point out that U.S. crude oil and thermal oil prices underwent structural disruptions and formed bubbles during the economic crisis in 2008 and the oil price crash phase in 2014. Recently, Khan et al. (2021b), Umar et al. (2021), and Gharib et al. (2021) focus on the bubble performance of crude oil prices during the COVID-19 epidemic and point out that the oversupply of the OPEC, the production of U.S. shale oil, and the mismatch between oil supply and demand are the primary factors that generated price bubbles in crude oil. Concerning price bubbles in the natural gas market, Li et al. (2020) conduct a cross-country study and detect multiple episodes of bubbles respectively in the EU, Asian and US natural gas markets.

To detect the drivers of coal price bubbles, the contagion effect of price bubbles across the above-mentioned energy markets should not be ignored. Zhang et al. (2018) and Wang and Kim (2022) suggest that the natural gas pricing mechanism linked to crude oil prices is the primary reason for the overlap of oil and gas price bubble ranges in Asian markets, in response to price risk contagion among different energy commodities. The propagation of price bubbles also extends into the oil and coal market, resulting from a combination of speculative influences and economic and political factors, as observed in Khan et al. (2022).

The extant evidence further shows that determinants of energy price bubbles vary across regions. Li et al. (2020) investigate the determinants of natural gas price bubbles and point out that the primary driver of European gas prices is geopolitical factors. They find that the US market gas price bubbles are attributable to speculative behavior, while bubbles in Asian gas prices stem from supply-demand imbalances and international oil price fluctuations. On the other hand, the patterns of energy price bubble contagion may also be affected by the determinants that form the bubbles. Li et al. (2022b) compare coal price bubble intervals in different regions of China and find that policy interventions in terms of environmental regulations, such as de-capacity policies, cause bubbles to spread from coal-producing regions to coal-consuming regions, while bubble propagations triggered by demand-side factors are from an opposite direction.

2.2. Drivers of coal price volatility

Shown in the extant literature, the price volatility of coal is influenced by a variety of factors. The supply and demand dynamics of the coal market can have a significant impact on its price fluctuations. Fundamentals in the coal market, including production, consumption, storage and overcapacity, contribute significantly to coal price fluctuations (Guo et al., 2016a; Wang et al., 2018; Zhang et al., 2019; Teng et al., 2019). On the other hand, coal price decline can be caused by factors such as coal imports (Wang et al., 2020a, 2020b). On the demand side, the price of coal is influenced by factors such as the impacts from the power industry (Li et al., 2015; Cui and Wei, 2017), and the availability and prices of alternative energy sources (Yang et al., 2012; Ma and Wang, 2019). Macroeconomic factors, the global economic environment (Punzi, 2019), and government policies (Guo et al., 2016b; Li et al., 2022a) also exert significant impacts on coal demand and price fluctuations. Based on these findings, related literature on these key factors is reviewed in this section, namely, alternative energy resources, the power generation industry, macroeconomic environment, energy policy, and climate risk.

2.2.1. Alternative energy sources

Fuel substitutability can lead to price interactions between coal and other energy sources. Due to fuel substitutability, natural gas, renewables, and nuclear power can provide competition to coal in the energy market. When the price of coal is high, other energy sources can become more competitive, resulting in a shift in the energy mix (Li et al., 2019). The availability and price of alternative energy sources can thus impact the demand for coal and its price, and vice versa. In terms of price correlations, Joëts and Mignon (2012) utilize a nonlinear panel cointegration framework and find a positive correlation among oil, natural gas, and coal prices. During special economic periods, such as the 2008 global financial crisis, international energy commodity prices demonstrate strong linkage characteristics (Zolfaghari et al., 2020; Ferrari et al., 2021).

With the increasing shift towards market-based global pricing of fossil fuels, there is a growing correlation observed among fossil energy prices (Yang et al., 2012). In examining bubble periods across various energy sources, Khan et al. (2022) identify crude oil prices and economic growth as significant factors in the volatility of coal prices. Li et al. (2019) suggest that the linkage between Chinese coal prices and international crude oil prices primarily depends on China's energy structure, while the linkage with international coal prices depends on the size of China's coal trade. Therefore, a sudden rise or fall in international oil and coal prices can have a substantial impact on Chinese coal prices (Xue and Huang, 2017). The ongoing marketization of China's natural gas pricing is expected to enhance the interaction between natural gas and coal markets, leading to a significant correlation between the two energy prices once the reform is completed (Li et al., 2017; Li et al., 2021; Wang et al., 2022).

In addition to fossil fuels, the utilization of non-fossil energy can exert a substantial substitution effect on coal-fired power generation, thereby impacting the price of coal (Guo et al., 2016a). Renewable energy sources such as wind and solar power have become increasingly competitive with coal in terms of cost. As the cost of renewable energy technologies continues to decrease, they have emerged as an appealing option for power generation. Consequently, their usage has increased, leading to a reduction in the demand for coal and contributing to a decline in its price. Ding et al. (2021) identify the renewable energy price index as one of the most reliable predictors of Qinhuangdao power coal prices.

Based on these findings, the present study considers the influence of conventional fossil energy sources on China's coal prices and incorporates renewable energy indicators to analyze the impact of the renewable energy sector on China's coal price bubbles.

2.2.2. The power generation industry

From the demand side, the power generation industry plays a crucial role as a major consumer of coal. The price of coal holds significant influence on the power industry, as steam coal (also known as thermal coal) is widely used as a fuel source for power generation worldwide (Batten et al., 2019). This is especially true in China, where the electric power industry accounts for over 40% of total coal consumption (Yuan et al., 2017), with thermal power generation contributing to 70% of the country's total electricity generation.

Since the cost of coal is a significant component of the total cost of electricity generation, fluctuations in the coal price can have substantial economic spillover effects on the power industry (Yuan et al., 2016). When coal prices rise, the cost of electricity generation increases, subsequently reducing the profitability of power generators. This can results in higher electricity prices for consumers and negatively impact overall output, gross domestic product (GDP), and the consumer price index (CPI) (He et al., 2010; Yang et al., 2012).

The price of coal not only impacts the cost of electricity generation but can also be influenced by the power generation industry itself. The demand for coal in the power sector is influenced by various factors, including the price of electricity, elasticity of electricity demand, and forecasted elasticity of power companies. These factors play crucial roles in determining coal prices in China (Liu et al., 2013; Cui and Wei, 2017). Conversely, when the price of coal rises, it enhances the competitiveness of alternative energy sources, prompting the power generation industry to adjust its fuel mix or increase the utilization of more efficient power plants. This, in turn, impacts the demand for coal as well as its price.

Additionally, changes in environmental regulations or policies aimed at promoting clean energy can result in a shift away from coal-fired power generation. This, in turn, can lead to a decrease in demand for coal and subsequent drops in coal prices. With the introduction of the dual carbon goals and China's Action Plan to Achieve Carbon Peak by 2030, promoting the substitution, transformation, upgrading, and development of new energy sources to reduce coal consumption has become a crucial aspect of China's strategy (Shi et al., 2020). The construction of a new power system that gradually increases the share of renewable energy has become a key focus of China's power system reform. In the long run, the power generation industry will gradually transition its production and consumption of fossil fuels towards cleaner energy alternatives, with renewable energy generation replacing some of the coal-fired power plants (Shi et al., 2020). However, due to the current insufficient installed capacity of renewable energy, coal-fired power plants continue to play a crucial role in ensuring electricity supply, particularly in providing deep peaking (DPR) services (Li et al., 2022a). Therefore, there will still be a significant need for coal-fired power plants to support the development of renewable energy (Yin and Duan, 2022).

Based on the close link between the power generation industry and the coal industry in China and the trend of adopting increasing clean energy to generate power, two factors in China's power generation industry are included in our empirical analysis: the total output of China's thermal power and the volume of renewable energy power generation.

2.2.3. The macroeconomic environment

Economic growth plays a vital role in determining the demand for energy, including coal. When an economy is experiencing growth, there is usually an increased need for energy, leading to higher demand for coal and subsequently driving up its prices. On the other hand, during economic downturns or recessions, the demand for coal tends to decrease, resulting in a drop in its price. Khan et al. (2022) study the price of coal in the US between 2000 and 2021, and identify three bubble periods between 2003 and 2004, 2007 and 2008, and from October to December in 2016. These bubbles are found to be influenced by economic growth, coal demand, and oil prices.

The correlation between energy consumption and economic growth varies across countries due to differing industrial development structures and energy consumption patterns (Lei et al., 2014). In the case of emerging economies like China, economic growth and industrial production play pivotal roles in driving coal demand. China has been the world's largest producer and consumer of coal in recent years, and its remarkable economic development has been a major factor behind the increase in coal demand and prices (Lei et al., 2014). The overall coal demand elasticity in China shows a gradual upward trend in China (Burke and Liao, 2015). However, there are regional disparities in coal demand elasticity within China. According to urban-level evidence presented by Chen et al. (2022), coal plays a critical role in the development of resource-based cities in China, particularly in the Northeast region, where there is a high dependence on coal consumption and significant pressure to reduce carbon emissions. Conversely, high-income cities in the eastern region have more energy consumption options, resulting in relatively higher coal demand elasticity (Teng et al., 2019).

The impacts of coal price fluctuations on the macroeconomy can vary depending on a country's economic structure. For example, based on the 2007 Chinese input-output data, Chen (2014) shows that the coking industry is most responsive to changes in coal prices, while the agriculture and service sectors are least sensitive. In general, high coal prices increase the production costs for industries heavily reliant on coal, which can impact the profitability and financial positions of relevant firms (Lin and Wang, 2021). Furthermore, as coal serves as the primary fuel for power generation in China, an increase in coal prices directly affects the operations of enterprises and the livelihoods of residents due to the higher costs in the power industry. This can have negative consequences for the macroeconomy (Yang et al., 2012; He et al., 2010). Conversely, a decline in coal prices would encourage the development of non-resource industries while hindering the growth of the coal chemical industry (Wang et al., 2017).

2.2.4. Energy policy

Energy policy has a substantial influence on the demand for and price of coal. In China, energy policies have played a crucial role in shaping the country's coal market by impacting the supply and demand fundamentals within the industry. In recent years, the Chinese government has implemented various policies aimed at reducing the country's reliance on coal and promoting the adoption of clean energy sources. One such policy is the "Coal Cap" policy, which was initiated in 2016. This policy established a target to cap coal consumption at 4.2 billion tons by 2020 and decreased the proportion of coal in the country's energy mix to below 58%. Another notable policy is the "Blue Sky Defense" campaign, launched in 2018, which focused on reducing air pollution by restricting the use of coal and other high-emission fuels. These policies have had a significant impact on the demand for coal in China, subsequently affecting its price. The concerted efforts to reduce coal consumption and promote cleaner energy sources have led to changes in the supply and demand dynamics within the coal market. As a result, the implementation of these policies has influenced the price of coal in China.

In the short term, policies aimed at reducing coal usage can lead to a decrease in demand and subsequently lower coal prices. However, in the long term, policies that promote clean energy alternatives can result in an increased demand for alternative energy sources like natural gas or renewables, leading to a decline in coal prices. Furthermore, the implementation of policies focused on reducing carbon emissions can drive the demand for cleaner coal technologies, such as carbon capture and storage, which can increase the production costs of coal and result in higher prices for consumers. Li et al. (2022b) conduct a study on the steam coal price in China between 2012 and 2020 using Logit regression and identify the existence of multiple bubble periods in 2013, 2014, 2015, 2016 and 2020. The authors argue that changes in government policies related to coal de-capacity and environmental protection are critical drivers of these coal price bubbles. These policies restrict coal production, reduce market supply, and consequently contribute to the increase in coal prices.

While changes in supply and demand serve as the foundation for coal price volatility, the level of marketization also plays a crucial role in influencing the transmission effect of supply and demand (Zhang et al., 2019). In 2013, China fully liberalized its price restrictions on coal, leading to a gradual and increasing impact of supply and demand factors, such as production volume and macroeconomic development (Guo et al., 2016b). However, due to excess coal capacity resulting from insufficient demand, market failures, and institutional distortions, the price of coal in China remained low until 2016 (Yang et al., 2018; Wang et al., 2018). In early 2016, the State Council issued a guidance policy to address excess capacity in the coal industry, aiming to facilitate its transformation. This policy had a significant positive effect on coal prices, contributing to a 3.44% increase (Wang et al., 2020a, 2020b). Consequently, under the guidance of the central and local government policies, China's coal production growth rate declined from 5.2% in 2018 to 0.9% in 2020 (National Bureau of Statistics of China (NBS), 2021).

Energy policies may distort the transmission effects of supply and demand factors on coal prices, inevitably leading to decreased social welfare in the short term (Zhang et al., 2021). Some studies have highlighted local government intervention as a major driver of China's coal overcapacity in earlier years (Zhang et al., 2017). Continued efforts to reduce coal capacity, however, can lead to a shortage of coal supply to meet the energy demand and support economic growth, resulting in a surge in coal prices. Shi et al. (2018) argue that capacity reduction policies should be tailored to accommodate different situations across regions and different types of coal mines. The authors emphasize the importance of adopting market-based approaches that outperform command and control instruments and eliminate policy distortions that contribute to overcapacity. Only when driven by market forces can enterprise capacity plans align with market demands, effectively curbing overcapacity (Zhang et al., 2017). In the long run, as China aims to achieve its dual carbon goals, the phase-out of fossil fuels becomes a natural outcome. However, policymakers still face severe challenges in formulating energy transition policies that do not adversely impact the economy (Zhang et al., 2021).

2.2.5. Climate risk

Climate risk poses significant challenges to the coal industry, affecting coal prices on multiple fronts. First, extreme weather conditions directly affect the demand for coal and further affect its prices. Wang et al. (2022) point out that there are two potential mechanisms through which climate factors can affect fuel prices: a direct mechanism where the climate factor directly increases energy demand and raises its price, and an indirect mechanism where the climate factor first boosts the demand for an alternative energy source generated by the fuel in question. In the case of coal, these mechanisms respectively correspond to the surging coal demand during cold winter months and the increasing demand for electricity generated by coal during heatwaves. Second, the increasing frequency and intensity of extreme weather events, such as hurricanes, floods, and wildfires, affect the supply of coal, through disrupting coal mining operations and transportation infrastructure (Bell et al., 2020). This disruption can lead to reduced coal production and supply shortages, thereby driving up coal prices in affected regions.

Third, as the world grapples with the consequences of climate change, extreme weather events and the urgent need to reduce greenhouse gas emissions have profound implications for coal pricing. The global push for mitigating climate change has resulted in stricter environmental regulations and policies aimed at reducing carbon emissions. As governments implement measures to transition to cleaner energy sources, the demand for coal decreases, negatively impacting coal prices. The transition towards renewable energy alternatives, driven by the imperative to decarbonize, further reduces the competitiveness and attractiveness of coal (Wang et al., 2020a, 2020b).

Moreover, climate risk amplifies market uncertainties and affects investor sentiment towards the coal industry (Ji and Zhang, 2019). Institutional investors and financial institutions are increasingly factoring climate-related risks into their decision-making processes. Concerns about stranded assets and potential liabilities associated with coal operations can lead to divestment and reduced access to capital for coal companies. This, in turn, can impact production capacity and exert pressure on coal prices.

Overall, the interplay between climate risk and coal prices is complex. While extreme weather events can cause short-term supply disruptions and price volatility, the long-term trend is moving towards a reduced reliance on coal due to climate change mitigation efforts. As the world transitions to a low-carbon economy, coal prices face an uncertain and challenging future, heavily influenced by climate-related factors. On the other hand, China's great coal demand for winter heating and summer power generation purposes cannot be sufficiently met by alternative energy sources at least in the short term. Climate factors should therefore be considered important potential drivers of coal demand and coal prices in China. We follow Wang et al. (2022) to include the extreme weather indicators, heating degree days and cooling degree days, in this study to explore how climate risks may influence the coal prices in China.

3. Methodology

3.1. The generalized sup augmented dickey-fuller (GSADF) test

In terms of detecting bubbles in energy and other asset prices, this study adopts the Generalized Supremum Augmented Dickey Fuller (GSADF) method, as proposed by Phillips and Jun (2011) and Phillips et al. (2015). This approach has been shown to have advantages in simultaneously detecting multiple bubble intervals in commodity prices over a long span, accounting for structural changes, and is applicable to data of any frequency (Khan et al., 2021b). It has been widely used for detecting explosive behaviors in energy prices. For example, Su et al. (2017) employ the GSADF approach and find that the dates of WTI crude oil price bubbles often correspond to specific political or financial market events. In this paper, the GSADF method is applied to detect bubbles in Chinese coal prices, and the characteristics of bubble risk contagion in the energy market are explored by comparing them with the bubble periods of alternative fuels. Khan et al. (2021a) also utilize the GSADF method and detect multiple bubble periods between 1979 and 1982, during 2004, and between 2007 and 2008 in global coal benchmark prices from 1971 to 2020. The Logit regression results suggest that the major drivers of these bubbles include oil prices, economic growth, supply security concerns, geopolitical conflicts, and overproduction.

A smooth price series should indicate that commodity prices will return to their fundamental values, while a non-smooth price series with a unit root indicates a persistent deviation in the price of a commodity from its fundamental value, indicating the presence of a bubble. Building on this concept, Phillips and Jun (2011) and Phillips et al. (2015) propose a generalized recursive testing procedure known as the backward ADF (BSADF) detection, which utilizes flexible window widths. The BSADF statistic at point r is the supremum (sup) value of the ADF statistic across the feasible range of r_1 and r_2, given by:

$$\mathrm{BSADF}_r(r_0) = sup_{r_1=[0,r_2-r_0],r_2=r}\left[\mathrm{ADF}_{r_1}^{r_2}\right] \tag{1}$$

where r_0 represents the minimum window size required to initiate the regression. When changing the endpoint (r) of BSADF, the Generalized SADF (GSADF) statistic is given by:

$$\mathrm{GSADF}(r_0) = sup_{r_2=[r_0,1]}\left[\mathrm{BSADF}_{r_2}(r_0)\right] \tag{2}$$

Thus, the GSADF can be seen as a series consisting of the BSADF statistics. Phillips et al. (2015) define the initiation date of the bubble as the point when the BSADF statistic exceeds its corresponding critical value, and the bubble bursts when the BSADF statistic falls below the critical value. The critical values are obtained from Monte Carlo simulations with 1000 replications. This paper utilizes the GSADF method to detect bubbles in Chinese coal prices and compares them with the bubble periods of alternative fuels to explore the characteristics of bubble risk contagion in the energy market.

3.2. The dynamic model averaging (DMA) method

Most of the extant literature attempting to identify the drivers of coal price bubbles adopts a static perspective, using approaches such as Logit regression (Li et al., 2022b). In this study, we employ the dynamic model averaging theory to analyze what factors drive the formation of coal price bubbles in China over time. This dynamic perspective fills the gap in the literature by illustrating the time variations in the bubble dynamics in China's coal market.

The dynamic model averaging (DMA) theory based on spatial measures allows for the calculation of the influencing weight of each factor on energy prices at each point in time. In the DMA estimation process, the price of coal in China (Y_t) is the dependent variable, while N influencing factors are included as explanatory variables ($X_t^{(N)}$), resulting in $K = 2^N$ different forecasting models. The parameter corresponding to the k^{th} model at time t is denoted as $\theta_t^{(k)}$, and the probability that model k is adopted conditional on $Y_{t-1}$is represented by $\pi_{t|t-1,k} = P(L_t = k|Y_{t-1})$. The resulting probability matrix $\Pi\_(K \times T)$ measures the importance of model k at each point in time. The optimal model at each time point is selected to fit the estimation of the coal price in China:

$$\hat{y}_t^{DMA} = \sum_{k-1}^{K} \pi_{t|t-1,k} \hat{y}_t^{(k)} = \sum_{k-1}^{K} \pi_{t|t-1,k} \left(x_t^{k}\right)^T \hat{\theta}_{t-1}^{(k)} \tag{3}$$

The final step involves constructing the weight matrix of the influencing factors. The selected set of explanatory variables is represented by a matrix $M_{N\times K}$, which consists of zeros and ones. The k^{th} row of the matrix indicates the k^{th} linear model, and $M(n,k) = 1$ indicates that the n^{th} variable element is present in the k^{th} model. We use $v_{n,t}$ to measure the level of influence of the k^{th} variable on the coal price in China at time t. The matrix of influence weights is constructed as follows:

$$V_{N\times T} = M_{N\times K} \times \Pi_{K\times T} = \begin{bmatrix} v_{1,1} & v_{1,2} & \cdots & v_{1,T} \\ v_{2,1} & v_{2,2} & \cdots & v_{2,T} \\ \vdots & \vdots & \ddots & \vdots \\ v_{N,1} & v_{N,2} & \cdots & v_{N|T} \end{bmatrix}_{N\times T} \tag{4}$$

In this paper, we estimate the probability of the presence of each influencing factor in the optimal forecasting model of the coal price in China. This information, combined with the analysis of bubble periods of related energy prices, helps us identify the sources of risk that drive abnormal energy price volatility and structural changes within the risk-driven framework.

3.3. Variable selection

A summary of original variables included in this study is shown in Table 1. The Qinhuangdao Q5500 thermal coal price (QHD) is selected to represent the price of coal in China. As the largest coal storage and transportation port in China, the QHD coal price is widely used in the literature as a proxy for the coal price in the Chinese market (Fan et al., 2016; Shi et al., 2018). Then, the spot price of coal at the port of Newcastle (NEWC), Australia, is chosen as a proxy for international coal prices in this study. Australia is the world's largest exporter of thermal coal, and China has been the largest buyer of its resources (Ma and Wang, 2019; Li et al., 2019; Ding et al., 2021). The risks and volatility in NEWC are considered a significant source of risk spillover in the international coal market (Batten et al., 2019) as well as in the Chinese coal market.

Furthermore, to address the roles of alternative fossil energy sources in forming coal price bubbles, we consider the influences from crude oil prices (Serletis and Libo, 2016; Xue and Huang, 2017; Khan et al., 2022) and adopt Brent and WTI crude oil prices as proxies for international crude oil prices (Joëts and Mignon, 2012; Li et al., 2019; Wang et al., 2022). Additionally, we use the average price of Chinese liquefied natural gas imports (LNG) as a proxy for the price level of natural gas in the China (Joëts and Mignon, 2012; Li et al., 2017; Li et al., 2021; Ferrari et al., 2021) to explore the influences of alternative energy sources on coal price bubbles.

Table 1
Summary of original variables.

Variable	Description of variables	Unit
Pabel A: Explained Variable		
QHD	Qinhuangdao Q5500 thermal coal price	USD/ton
Pabel B: Explanatory Variables-Alternative energy prices		
NEWC	Australia Newcastle steam coal spot price	USD/ton
WTI	WTI crude oil spot price	USD/Barrel
Brent	Brent crude oil price	USD/Barrel
LNG	Average LNG import price in China	USD/ton
Pabel C: Explanatory Variables-Fundamental factors		
Consumption	China's coal consumption	10,000 tons
Storage	Coal inventory of Qinhuangdao Port	10,000 tons
Overcapacity	Coal overcapacity in China	10,000 tons
Pabel D: Explanatory Variables-Power industry factors		
ELE_FIRE	China's thermal power output	Billion KWH
REPG	Renewable energy power generation index	Point
Pabel E: Explanatory Variables-Macroeconomic and financial market factors		
MCI	Macroeconomic climate index	Point
SHI	Shanghai Stock Exchange Index	Point
Panel F: Climate factors		
HDD	heating degree days	Days
CDD	cooling degree days	Days

Several aspects of China's coal market fundamentals are addressed in the analysis. The decline in Chinese coal prices from 2012 to 2016 has been attributed to economic downturn, overproduction, weak demand, and inventory changes (Zhang et al., 2019). To examine the influences of coal supply and demand fundamentals on the coal price in China, the impacts of coal consumption volume (Burke and Liao, 2015; Teng et al., 2019), thermal coal storage (Guo et al., 2016a), and coal industry overcapacity (Wang et al., 2018; Yang et al., 2018) are discussed. Here, the overcapacity in China's coal industry is calculated as OC=C-P=P/CU-P, where OC refers to the scale of excess capacity, C represents the total capacity of coal production in China, P denotes the actual coal production in China, and CU represents the coal capacity utilization rate, based on previous studies of Wang et al. (2018) and Yang et al. (2018).

Coal serves as the primary fuel for thermal power generation in China, and higher coal prices can lead to increased costs for the power industry. The development of the renewable power generation industry plays a crucial role in reducing the power industry's dependence on fossil fuels and is considered one of the most reliable predictors of coal prices in China (Ding et al., 2021). To examine the influences from the power industry from a demand-side perspective, two variables are included in the analysis: China's thermal power output volume (ELE_FIRE) (Liu et al., 2013; Yuan et al., 2016; Cui and Wei, 2017; Lin and Wang, 2021; Yin and Duan, 2022), and renewable energy power generation index (REPG) (Ding et al., 2021; Yin and Duan, 2022).

Through changes in the costs of the power industry, fluctuations in coal prices can further impact the operations and profitability of enterprises, and the livelihoods of residents, consequently influencing related industries and the broader macroeconomy (Liu et al., 2022; Yang et al., 2012; He et al., 2010; Wang et al., 2017). Conversely, risks originating from the macroeconomic environment and the financial market may spread to the coal industry, leading to price volatility (Ding et al., 2021). To address the risk spillover and impacts from the macroeconomic environment and financial market dynamics, the macroeconomic climate index (MCI) (Lei et al., 2014; Chen, 2014; Chen et al., 2022) and the stock market performance represented by the Shanghai A-share Stock Exchange Index (SHI) (Ding et al., 2021) are included in the analysis.

Finally, we include climate factors in the analysis to address the impact of climate risks and extreme weather conditions on driving the price movements of coal in China. To proxy the climate conditions, we include two proxies following Wang et al. (2022): heating degree days (HDD) and cooling degree days (CDD).[2] HDD, which measures how cold the weather is, is included to address that extremely cold weather conditions can directly lead to increasing heating fuel demand during cold winter months, which are particularly common in the northeast and northwest in China. Coal has historically been a major fuel for heating in China. China has a long history of using coal for heating homes, buildings, and industrial processes. The abundance of coal reserves in China, coupled with its affordability, made it a popular choice for heating purposes, especially in rural areas. Although China has been actively working to reduce its reliance on coal due to environmental concerns, air pollution, and climate change in recent years through various policies and initiatives to promote cleaner and more sustainable energy sources for heating, such as natural gas, electricity, and renewable energy, coal still plays a significant role in heating, especially in less developed regions. On the other hand, CDD, which measures how hot the weather is, is included to capture the impacts of increased use of air conditioning powered by electricity during hot months. Coal is a

[2] Following Wang et al. (2022), HDD equals the difference between 18 °C and the mean temperature during a given day, or zero if the mean temperature is higher than 18 °C; CDD equals the mean temperature of a given day subtracted by 26 °C, or equals zero if the mean temperature is lower than 26 °C. The HDD and CDD in this study are monthly averages.

dominant fuel in the process of power generation in China, as about 70% of the country's electricity demand is met by thermal power generation. The demand and price of coal can inevitably increase during seasons with soaring power demand. The demand and price of coal can inevitably increase during seasons with soaring power demand. Even though China has actively sought to reduce its reliance on coal in recent years due to environmental concerns, coal continues to play a significant role in heating and power generation, especially in less developed regions (Teng et al., 2019; Chen et al., 2022).

4. Empirical results

4.1. Data and descriptive statistics

This study uses monthly data between July 2007 and March 2023. Table 2A presents the descriptive statistics for the first difference series of the log-transformed original variables (as shown in Table 1), calculated as $(lnx_{t+1} - lnx_t) \times 100$, therefore approximating each original variable's growth rate between any two consecutive periods. Following Drachal (2016) and Wang et al. (2022), the growth rates of the original series are used in the following DMA model analysis, while the original price series are adopted to identify bubble periods in energy prices, the descriptive statistics of which are reported in Table 2B.

In Table 2A, LNG and QHD exhibit the highest and lowest standard deviations, respectively. The Jarque-Bera test statistics significantly reject the null hypothesis of normality for all series, except for REPG. All series show excess kurtosis. The Augmented Dickey-Fuller (ADF) test statistics suggest that all growth rate series are stationary. We notice that the mean values of both Consumption and Storage are positive, indicating that China's coal usage and storage have continued to grow during the sample period. This suggests that although China's green transition and de-capacity policies have aimed to reduce coal consumption, they have not reversed the dominance of coal yet, nor have they curbed the increasing trend in China's coal storage. Additionally, China's macroeconomic index and the financial market index have negative growth rates over the sample period, implying an overall slowdown of the macroeconomic and financial market development. When looking at the climate factors, the mean value of CDD is zero in Table 2A, indicating that the growth rate of the cooling degree days has not increased during the sample period but remained stable. In contrast, a positive mean value of HDD implies growing demand for heating during wintertime over the full sample. In other words, increasing pressure may have been imposed on securing the fuel supply for the winter heating purpose year after year.

For the original variables used in the GSADF analysis for detecting bubble periods, their descriptive statistics are reported in Table 2B. The international crude oil benchmark prices (WTI and Brent), NEWC coal price, and LNG import price series are all denominated in US dollars. We therefore convert the unit of the Qinhuangdao thermal coal price to dollars per ton. Compared with other energy markets, the original coal price of QHD and NEWC both show relatively higher Skewness (positive) and Kurtosis. The ADF test statistics show that the original price series of Chinese coal, LNG, and international crude oil prices are non-stationary, while the NEWC price is stationary.

4.2. Bubble periods of the coal price in China

We first detect the bubble periods in the Qinhuangdao thermal coal price (in USD/ton) using the GSADF method. The results are depicted in Fig. 1. The blue line shows the BSADF statistics, while the critical value of the GSADF test is marked by a red line. By comparing the temporal positions of the blue and red lines, it is not hard to spot five intervals where the blue line is above the red line, indicating greater BSADF statistics than the critical values and suggesting the existence of price bubbles. These five bubble intervals are marked by gray bars.

Seen in Fig. 1, the first coal price bubble period starts in May 2011 and quickly bursts before 2012. The coal price initially rises during this period and then continues to drop until 2015 when the second price bubble is detected. Intuitively, this first bubble period in 2011 and the subsequent downturn of the price of coal in 2012 occured just before the end of the golden period of China's coal industry, which lasted from 2003 to 2012 and was driven by the country's rapid industrialization and urbanization (Li et al., 2022b). After nearly a decade of rapid development and expansion, the coal industry faced severe overcapacity problems, leading to restrictions on bank loans to coal enterprises, closure of coal mines, and a slump in the price of thermal coal at the Qinhuangdao Port (Wang et al., 2020a, 2020b). Furthermore, in 2013, the State Council of China issued the China Air Pollution Control Action

Table 2A
Descriptive statistics (growth rate).

	Mean	Maximum	Minimum	St. Dev.	Skewness	Kurtosis	J.B.	ADF
QHD	0.005	0.461	−0.638	0.096	−0.504	17.868	1739.465***	−6.058***
NEWC	0.473	36.512	−53.93	10.141	−0.607	8.505	248.926***	−4.135***
WTI	−0.006	54.562	−56.813	11.563	−0.898	10.356	449.065***	−6.061***
Brent	0.01	46.905	−55.479	11.415	−1.136	9.49	370.375***	−6.047***
LNG	0.59	98.487	−75.285	17.467	0.353	10.759	475.429***	−7.655***
Consumption	0.345	29.321	−38.106	11.144	−0.567	4.684	32.29***	−9.097***
Storage	0.283	45.939	−32.898	8.592	0.428	7.788	185.294***	−4.562***
Overcapacity	0.416	26.158	−32.426	10.347	−0.364	3.385	5.3*	−11.474***
ELE_FIRE	0.958	89.353	−49.834	11.522	1.948	22.56	3115.981***	−5.87***
REPG	0.06	54.561	−49.457	15.679	0.033	3.741	4.337	−7.455***
MCI	−0.024	5.295	−4.293	1.284	0.567	6.996	135.155***	−4.736***
SHI	−0.11	18.891	−22.02	6.086	−0.177	4.77	25.525***	−4.87***
HDD	0.743	224.257	−249.01	84.974	0.169	4.773	25.508***	−7.752***
CDD	0	144.927	−196.08	57.791	−0.962	6.897	147.939***	−8.477***

Note: In this table, all the series are first difference of the log-transformed original variables reported in Table 1, calculated as $(lnx_{t+1} - lnx_t) \times 100$, indicating the growth rate of the original variables. QHD denotes the Qinhuangdao Q5500 thermal coal price (USD/ton); NEWC denotes the Australia Newcastle steam coal spot price (USD/ton); WTI denotes the WTI crude oil spot price (USD/Barrel); LNG denotes the Average LNG import price in China (USD/ton); Consumption denotes China's coal consumption (in 10,000 tons); Storage denotes coal inventory of Qinhuangdao Port (in 10,000 tons); Overcapacity denotes coal overcapacity in China (in 10,000 tons); ELE_FIRE denotes China's thermal power output (in Billion KWH); REPG denotes the Renewable energy power generation index (in Point); MCI denotes the Macroeconomic climate index (in Point); SHI denotes the Shanghai Stock Exchange Index (in Point); HDD means heating degree days and is the monthly average of the difference between each day's mean temperature and 18 °C, which equals zero if the mean temperature is higher than 18 °C); CDD means cooling degree days and is the monthly average of each day's mean temperature subtracted by 26 °C, which equals zero if the mean temperature is lower than 26 °C. St. Dev. denotes standard deviation; J.B. denotes the Jarque-Bera test statistics; ADF denotes the Augmented Dickey Fuller test statistics. ***, ** and * represent the 99%, 95% and 90% level of significance, respectively.

Table 2B
Descriptive statistics (original series).

	Mean	Maximum	Minimum	St. Dev.	Skewness	Kurtosis	J.B.	ADF
QHD	104.268	328.647	56.58	36.238	2.169	10.853	633.877***	−1.547
NEWC	110.248	434.02	48.27	76.255	2.826	10.802	731.005***	−4.241***
WTI	72.888	133.88	16.55	23.408	0.123	2.233	5.111*	−2.875
Brent	77.992	132.72	18.38	26.075	0.115	1.941	9.259***	−2.67
LNG	453.799	978.88	160.92	174.845	0.68	3.579	17.198***	−2.505
Consumption	28,508.28	38,748.1	13,965	4801.729	−0.295	2.974	2.741	−2.282
Storage	591.457	895.09	270.04	117.878	−0.082	2.942	0.241	−3.585**
Overcapacity	10,476.42	20,134.1	2385.826	4630.172	−0.334	2.186	8.728**	−2.171
ELE_FIRE	3642.934	5989.3	1994.82	917.72	0.336	2.498	5.549*	−4.194***
REPG	3483.354	7010.49	1321.14	1549.54	0.482	2.154	12.945***	−3.484**
MCI	99.497	116.52	86.37	4.451	0.55	5.426	55.894***	−4.012***
SHI	3126.517	6114.06	1970.66	707.177	1.177	5.827	106.605***	−5.637***
HDD	5.233	25.958	0	6.738	0.914	2.509	28.239***	−12.922***
CDD	0.919	7.413	0	1.934	1.98	5.513	173.207***	−7.772***

Note: In this table, all the series are the original series of the variables reported in Table 1. QHD denotes the Qinhuangdao Q5500 thermal coal price (USD/ton); NEWC denotes the Australia Newcastle steam coal spot price (USD/ton); WTI denotes the WTI crude oil spot price (USD/Barrel); LNG denotes the Average LNG import price in China (USD/ton); Production denotes China's coal production (in 10,000 tons); Consumption denotes China's coal consumption (in 10,000 tons); Storage denotes coal inventory of Qinhuangdao Port (in 10,000 tons); Overcapacity denotes coal overcapacity in China (in 10,000 tons); ELE_FIRE denotes China's thermal power output (in Billion KWH); REPG denotes the Renewable energy power generation index (in Point); MCI denotes the Macroeconomic climate index (in Point); SHI denotes the Shanghai Stock Exchange Index (in Point); HDD means heating degree days and is the monthly average of the difference between each day's mean temperature and 18 °C, which equals zero if the mean temperature is higher than 18 °C); CDD means cooling degree days and is the monthly average of each day's mean temperature subtracted by 26 °C, which equals zero if the mean temperature is lower than 26 °C. St. Dev. denotes standard deviation; J.B. denotes the Jarque-Bera test statistics; ADF denotes the Augmented Dickey Fuller test statistics. ***, ** and * represent the 99%, 95% and 90% level of significance, respectively.

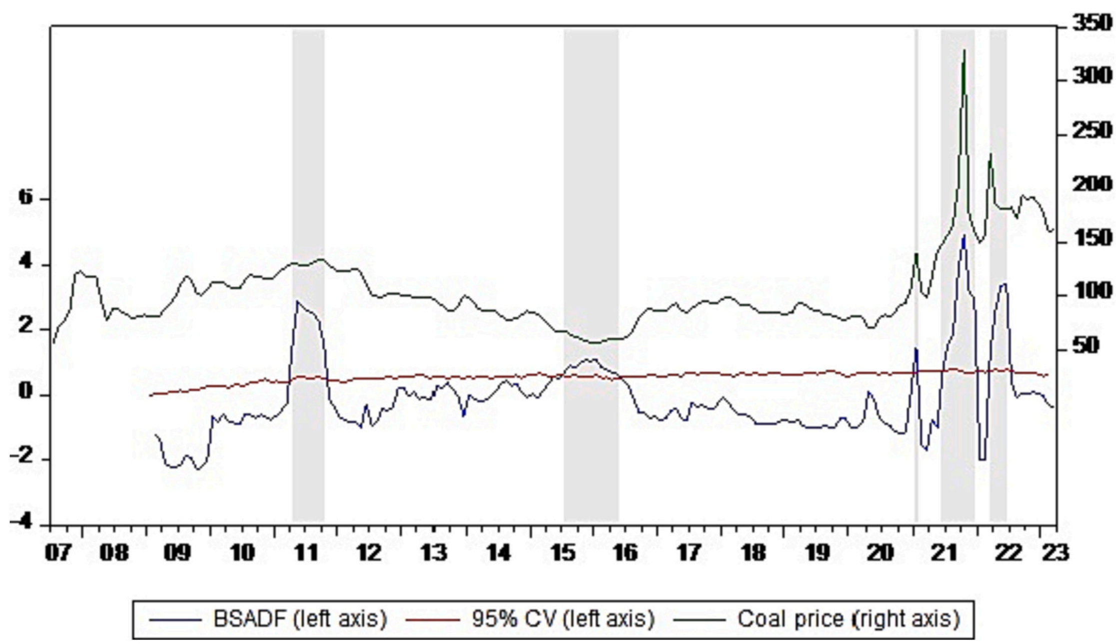


Fig. 1. Bubble periods of the price of coal (USD/Ton) in China.
Note: In this figure, bubble periods are marked by gray bars; CV denotes the critical value of the GSADF test at the 95% level of significance obtained from Monte Carlo simulations with 1000 replications; BSADF denotes the BSADF statistics; Coal price is in USD/Ton.

Plan, which aimed to limit the proportion of coal in total energy consumption to 65% by 2017. This policy also contributed to a plummet in coal demand and a subsequent drop in coal prices. It is therefore not hard to understand the burst of this initial bubble in 2012.

After the first bubble bursts, the price of coal exhibits a generally decreasing trend until the formation of the second bubble in July 2015. The second bubble period lasts until May 2016, lasting longer than the first one. The formation of this bubble can be linked to the policy released by the National Development and Reform Commission (NDRC) in 2015, which sets an ambitious goal for CO2 emission reduction goal through controlling coal consumption and promoting clean coal. This was accompanied by several regulation and policy measures, such as the Action Plan for Clean and Efficient Utilization of Coal issued by the National Energy Administration (NEA) in 2015. Subsequently, the supply-side structural reform of the coal industry, which commenced in February 2016, further emphasized the objective of reducing capacity, leading to capacity reduction measures implemented by major coal production provinces in China. These policy efforts resulted in a reduction in coal production and a decrease in coal supply, leading to a period of price bubbles due to a temporary imbalance between supply and demand in the market.

The coal price then remains stable until three price peaks appearing in 2021 and 2022. A notable and long bubble period occurs in the second half of 2021. These identified bubble periods will be further discussed in the next subsection, with a special focus on analyzing the drivers of each bubble during their respective periods. In the above analysis, the Qinhuangdao thermal coal price is denominated in USD/ton. To assess the robustness of the bubble test results, the price of Qinhuangdao thermal coal in USD/ton is replaced with the price in RMB/ton. The corresponding results are presented Fig. A.1 in the Appendix. The significant bubbles in 2011 and 2015 are still observed, and bubbles that occur after 2021 are also visible in Fig. A.1. Furthermore, between 2011 and 2015, there are four other abnormal fluctuations that can be spotted.

4.3. Key drivers of China's coal price bubbles

After identifying several bubble periods in the price of coal in China during the sample period, we proceed to explore the drivers behind these price bubbles over time. Since alternative energy prices (WTI, Brent, NEWC and LNG import prices) are all denominated in USD, the Qinhuangdao thermal coal price in USD/ton is used in the following analysis. Fig. 2 illustrates the time-varying probability of each potential bubble driver's presence in the optimal coal price forecasting model throughout the entire sample period. A higher probability value indicates a greater influence of a specific factor in driving the temporal movement of the coal price. According to previous literature (Drachal, 2021), a horizontal dotted line is drawn in Fig. 2 as a reference level, which corresponds to the 50% probability threshold for a driving factor to be included in the optimal coal price forecasting model. The average probability of each factor's presence in the optimal models over the full sample period is also provided in parentheses in Fig. 2.

4.3.1. The overall trend

Over the full sample, we find that the top three drivers of China's coal price are NEWC, HDD and Overcapacity. Among these three factors, only the average probability of NEWC being included in the optimal coal price forecasting models exceeds 50%, while the probabilities for the others are lower. This suggests that on average, the best forecast for the coal price in China during the sample period can be obtained by considering the dynamics in the international coal market, while the impacts of cold weather conditions and coal overcapacity within China should not be ignored. Another implication is that the price of coal in China tends to lack a consistent dominant force over the full sample, except for the information derived from the international coal market. This finding aligns with evidence from the literature, which highlights the important role of coal imports in influencing China's coal price (Ma and Wang, 2019). As the world's largest coal consumer and importer, fluctuations in international coal prices have a direct impact on the cost of coal used in the Chinese market. Furthermore, the significant influences of international coal prices and HDD on China's coal prices are primarily observed during bubble periods, implying their role in the formation of price bubbles in the coal market.

In addition to these three top driving factors, other variables intermittently but significantly influence China's coal prices over time. Compared to the top three coal price drivers, ELE-FIRE, MCI and SHI are, on average, three less important but still notable contributors. Prior to the first bubble period in 2011, ELE-FIRE was the leading driver of China's coal price. This suggests the significant role of the thermal power generation industry in influencing coal prices before 2011 when China launched the "12th Five-Year Plan for Energy Conservation and Emission Reduction". This policy design aims to enhance energy efficiency, promote clean energy, and reduce emissions, potentially leading to a decoupling of the strong connection between the power generation and coal industries.

While international coal prices and HDD are the primary drivers of coal prices during bubble periods, the macroeconomic and stock market factors, MCI and SHI, inconsistently demonstrate notable influences on the coal price in China during non-bubble periods. This observation adds further evidence to the exiting findings indicating that the price of coal in China is primarily and fundamentally influenced by the macroeconomic environment and development (Lei et al., 2014; Khan et al., 2022). The stock market is closely linked to a country's overall economic growth and industrial activity. A thriving stock market often signals robust industrial activity and increased energy demand, which can impact coal prices. The stock market also reflects investor sentiment and overall market confidence, which influences investor decisions on capital allocation (Ji and Zhang, 2019). Positive stock market performance typically indicates a favorable economic outlook and boosts investor confidence, leading to greater investments in sectors such as manufacturing and infrastructure. This increased investment subsequently drives up the demand for coal and raises its price. Conversely, during stock market downturns, when investors perceive higher risks, they may seek alternative investment options, leading to decreased demand and potentially lower coal prices. Moreover, the stock market can also influence government policies and regulations (Lin and Chen, 2019). Governments may introduce measures to stabilize the market or stimulate economic growth during periods of stock market volatility or downturns. These measures may include changes in energy policies, subsidies, or regulations, directly or indirectly affecting the coal industry and its pricing.

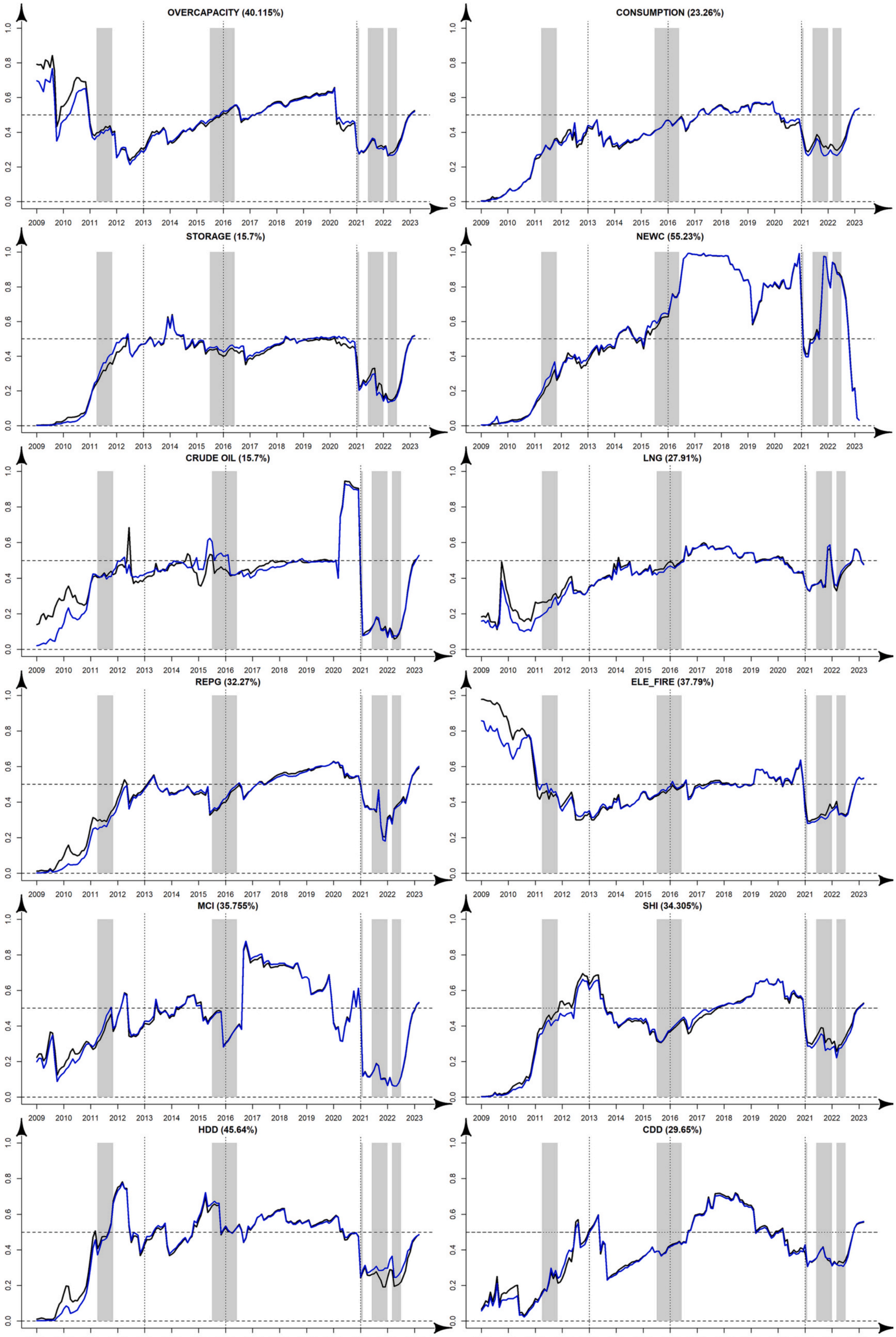
It is worth noting that the significant impact of CDD on the coal price is also generally pronounced during non-bubble periods. Given that the influence of CDD is not prominent during bubble periods while HDD shows significant influence during the first two bubble periods, and the influence of thermal power output has been declining over the sample period, we can argue that the demand for electricity for cooling purposes is not a key driver of coal price bubbles. Instead, winter heating demand tends to be a key determinant of coal price bubbles in China during the sample period. This is consistent with the evidence recently noted by Su et al. (2023), who find that changes in heating demand during extremely cold winter weather can drive the formation of a bubble in a country's energy prices. Therefore, between the two potential mechanisms through which climate factors affect energy prices (Wang et al., 2022), the direct mechanism significantly contributes to the formation of the price bubbles in China's coal market.

4.3.2. Time-varying coal price drivers

The above findings highlight the significant roles played by international coal price fluctuations, the heating demand during cold winters within China, and the progress in coal industry de-capacity, in influencing coal prices over the full sample period. When examining the time-varying drivers of coal price bubbles, our focus is on assessing the level of influence exerted by each factor, particularly during bubble periods. If a factor's probability of being included in the best coal price forecasting model during bubble periods is higher than other factors, we consider it a major bubble driver. The key drivers of coal price bubbles are summarized in Table 4. At least the top three variables with the highest probabilities of being included in the optimal DMA model during each bubble period are reported in Table 4.

Most notably, the dominant role of NEWC in the formation of coal price bubbles is confirmed, as it consistently emerges a top contributor during coal price bubble periods, except for the first one between April and October 2011. Additionally, after 2016, price risks associated with alternative energy sources, not only in the international coal market but also in the natural gas and renewable energy markets, emerge as significant drivers of the Chinese coal market bubbles.

The changes in the drivers of the coal price bubbles over time can be linked back to significant policy changes. In Fig. 2, three vertical dotted lines are drawn to indicate the initiation of three important policy changes proposed by the Chinese government: marketization of the coal industry in 2013, coal de-capacity in 2016 and the dual-carbon goals in 2021. These three critical years divide the entire sample period into four intervals. As observed in Figs. 2, the influence of each factor on the price of coal clearly varies across the four intervals.



(caption on next page)

Fig. 2. Drivers of China's coal price.
Note: The vertical axis of the figure indicates the probability that each indicator is present in the optimal coal price forecasting model. The percentages in parentheses report the average of this probability for each factor over the full sample period. The gray vertical bars indicate the coal price bubble periods. The horizontal dotted line marks the 50% probability threshold for a driving factor to be included in the optimal coal price forecasting model. Three vertical dotted lines mark the initiation of three important policy changes proposed by the Chinese government: coal marketization, coal de-capacity and the dual-carbon goals, respectively in 2013, 2016, and 2021. The black and blue lines represent the results based on WTI and Brent, respectively, as proxies for international crude oil prices. NEWC denotes the Australia Newcastle steam coal spot price (USD/ton); Crude Oil denotes the WTI or Brent crude oil spot price (USD/Barrel); LNG denotes the Average LNG import price in China (USD/ton); Consumption denotes China's coal consumption (in 10,000 tons); Storage denotes coal inventory of Qinhuangdao Port (in 10,000 tons); Overcapacity denotes coal overcapacity in China (in 10,000 tons); ELE_FIRE denotes China's thermal power output (in Billion KWH); REPG denotes the renewable energy power generation index (in Point); MCI denotes the macroeconomic climate index (in Point); SHI denotes the Shanghai Stock Exchange Index (in Point); HDD means heating degree days and is the monthly average of the difference between each day's mean temperature and 18 °C, which equals zero if the mean temperature is higher than 18 °C; CDD means cooling degree days and is the monthly average of each day's mean temperature subtracted by 26 °C, which equals zero if the mean temperature is lower than 26 °C.

Table 4
Key drivers of coal price bubbles in China.

Bubble periods of QHD	Duration (month)	Key drivers of coal prices
April–October 2011	7	HDD (46.61%); ELE_FIRE (46.10%); SHI (42.37%)
July 2015–May 2016	11	NEWC (65.74%); HDD (56.11%); Overcapacity (50.34%); Crude oil (47.55%); ELE_FIRE (46.88%)
January 2021	1	NEWC (71.97%); REPG (49.49%); MCI (48.52%)
June–December 2021	8	NEWC (67.72%); LNG (42.64%); CDD (37.22%)
March–June 2022	4	NEWC (90.59%); LNG (40.22%); REPG (35.15%)

Note: The percentages in the parentheses are the mean probability of the presence of each variable in the optimal DMA model during the bubble period. At least three variables with the highest probabilities are reported here. QHD denotes the Qinhuangdao Q5500 thermal coal price (USD / ton); NEWC denotes the Australia Newcastle steam coal spot price (USD / ton); Crude Oil denotes the WTI or Brent crude oil spot price (USD / Barrel); LNG denotes the Average LNG import price in China (USD / ton); Consumption denotes China's coal consumption (in 10,000 tons); Storage denotes coal inventory of Qinhuangdao Port (in 10,000 tons); Overcapacity denotes coal overcapacity in China (in 10,000 tons); ELE_FIRE denotes China's thermal power output (in Billion KWH); REPG denotes the renewable energy power generation index (in Point); MCI denotes the macroeconomic climate index (in Point); SHI denotes the Shanghai Stock Exchange Index (in Point); HDD means heating degree days and is the monthly average of the difference between each day's mean temperature and 18 °C, which equals zero if the mean temperature is higher than 18 °C; CDD means cooling degree days and is the monthly average of each day's mean temperature subtracted by 26 °C, which equals zero if the mean temperature is lower than 26 °C.

4.3.2.1. Prior to the marketization of the coal industry. As evident from Fig. 2 and Table 4, prior to the marketization of the coal industry in 2013, the climate factor HDD and thermal power output emerge as the primary drivers of coal price bubble in 2011. Seen in Fig. 2, between 2011 and 2021, China's coal price was notably affected by HDD, primarily due to the country's reliance on coal for winter heating purposes, particularly in the northern regions. Historically, coal has been the primary fuel source for heating in many households, industries, and power plants. The increased demand for coal during the winter season puts upward pressure on coal prices. It is not hard to understand that HDD appears as the top driver of the coal price bubble in 2011. Back then, alternative energy sources for heating, such as natural gas and renewables, were not as widely available or developed in China. The reliance on coal for heating purposes was more prevalent, leading to a strong correlation between heating demand and coal prices.

Before 2013, the influence of the power generation industry on coal prices is much higher than all the other factors, being a dominant driver of coal prices. The significant influence of the power generation industry on coal prices before coal marketization can be explained by several reasons. First, before the marketization of the coal industry, the power generation industry in China was primarily dominated by state-owned enterprises (SOEs) which had significant control over coal production, distribution, and pricing. The coal price was therefore heavily influenced by the policies and practices of these state-owned power generation companies. Second, the government's integrated energy planning and policies played a crucial role in determining the demand for coal from the power generation sector, leading to a close relationship between the performance of power generation industry and coal consumption. Price controls, subsidies, and other regulatory interventions in the power sector had a direct impact on the cost of coal and, subsequently, its price in the market. Third, competition in the coal market was limited prior to the marketization of the coal industry and state-owned coal mines were the primary suppliers with few alternative sources of coal. This lack of competition further allowed the power generation industry to exert significant influence over the coal price. Its influence, however, keeps declining sharply prior to coal marketization, as shown in Fig. 2. With the progress of coal marketization reforms, the coal industry in China has gradually transitioned towards a more market-oriented system. This has led to increased competition, price liberalization, and a reduced direct influence of the power generation industry on coal prices.

Before the first bubble emerged in 2011, Overcapacity exerted significant influence on the coal price in China, as shown in Fig. 2, especially before 2010. However, the influence of Overcapacity declined sharply before 2013. The diminishing role of Overcapacity can be explained by the supply and demand dynamics in the coal market. During the golden period from 2003 to 2012, there was a significant increase in coal production capacity over the years, driven by factors such as government support, rapid industrialization, and increased energy consumption (Li et al., 2022b). However, as China's economy shifted to a slower and more sustainable growth pattern, the demand for coal started to weaken, largely influenced by efforts to curb pollution, promote renewable energy sources, and improve energy efficiency. Additionally, China's economic restructuring and focus on reducing reliance on heavy industries further impacted the demand for coal. With the decline in demand and the presence of excess supply, the Chinese coal industry faced an oversupply situation by the end of 2012 (Li et al., 2022a). In conjunction with the slowdown of China's economic growth under the "new normal", Chinese coal prices exhibited a downward trend. It is therefore not surprising to spot the quick burst of the first price bubble in 2011 and a subsequent downturn of the coal price in 2012.

Moreover, the probability of China's financial market development indicator (SHI) in the DMA forecasting model during 2012 and 2014 is relatively high. The Chinese stock market experienced significant fluctuations and volatility in the first half of 2012, influenced by the concerns over the global and domestic economic challenges, but started to recover from the second half of the year. A steady upwards trend was seen in SHI in 2013 and the first half of 2014, driven by supportive government policies and investor optimism. SHI began a steep and sharp decline from mid-2014, mainly due to concerns over China's economic slowdown, tighter liquidity conditions, and regulatory changes aimed at curbing speculative trading, eventually leading to the stock market crash in mid-2015, which had a significant impact on both domestic and global markets (Wu, 2019). Combining these dynamics in stock market performance and changes in SHI's influence in corresponding years shown in Fig. 2, it is evident that stock market optimism and good performance are accompanied by a greater influence of SHI on China's coal prices. This confirms that sound stock market performance can positively impact coal prices through boosting investor sentiment, overall market confidence, and directing capital towards coal-dependent industries (Ji and Zhang, 2019).

4.3.2.2. Prior to coal de-capacity policies. While existing evidence shows that coal prices in China are affected by global oil prices (Xue and Huang, 2017; Li et al., 2019), we observe from Fig. 2 and Table 4 the increasing influence of international oil prices since 2009.

From 2011 to 2012, oil production started to decline due to political uncertainty in OPEC countries (Khan et al., 2021b), resulting in relatively high international crude oil and potentially risk spillover from crude oil prices to China's coal prices. The second bubble period in 2015–2016 coincides with notable impact of international crude oil prices. This bubble is largely driven by the information spillover from the international oil market. Prior to that, the supply of oil from non-OPEC countries experienced robust growth due to high oil prices, while Saudi Arabia, instead of defending oil prices, began increasing crude oil production. The combination of diminishing oil demand resulting from slowing economic growth and oversupply led to a sharp decline in oil prices. Between January 2014 and January 2015, WTI and Brent crude oil prices plummeted by 60% and were identified as a significant negative bubble (Fantazzini, 2016). During that period, strong linkages and bubble overlaps were observed between international coal and oil markets according to the literature (Ferrari et al., 2021; Khan et al., 2022). A recent study by Guo and Zhao (2024) also points out that there is a long-term cointegration relationship between crude oil and coal in China. These findings are consistent with our observations of the increasing bubble contagion from international oil to Chinese coal market.

The main reason for the low coal prices during that period is also attributed to the imbalance between supply and demand in the coal market caused by overcapacity (Li et al., 2022b). Wang et al. (2018) report that China's coal capacity utilization rate has been continuously declining since 2013 due to the slowdown in economic growth, reaching a historical low of 59.55% in 2016. The situation of overcapacity in the coal industry highlighted the need for adjustments and reforms to align production capacity with market demand. The Chinese government implemented various measures to address overcapacity, including production cuts, mine closures, and promoting industry consolidation. These initiatives aimed to rebalance the market, reduce excess supply, and support more sustainable development in the coal industry. These policy efforts may lead to a temporary supply crunch and higher coal prices, which explains that Overcapacity is among the top three key drivers of the coal price bubble between 2015 and 2016.

The significant impact of MCI on the coal price in 2021 can also be linked to the country's commitment to achieving environmental goals and the continued policy efforts on coal de-capacity and green transition. In early 2016, the Chinese government outlined a specific plan for coal de-capacity and assigned the task to local provinces and coal companies. Following this, Chinese coal prices experienced a brief period of recovery and then remained relatively stable. There were no significant price fluctuations or detected bubbles until 2021. Throughout this period, MCI played a crucial role as a determinant of Chinese coal prices, with a high probability of being included in the optimal coal price forecasting model shown in Fig. 2.

4.3.2.3. The impact of green transition and the proposal of the dual carbon goals. The most notable trend during the green transition in China is the declining influence of the power generation industry and the rising roles played by international coal prices and alternative energy sources, including natural gas, renewable energy sources and international crude oil prices (during the COVID-pandemic period).

Fig. 2 shows that the influence of the international coal market represented by NEWC on Chinese coal has steadily increased since 2011 and becomes increasingly significant, until a plummet occurs close to end of the sample period. China's coal industry relies on both domestic production and imports to meet its demand. This increasing influence of NEWC can be attributed to the rise in coal imports by China when the domestic production was significantly reduced due to the de-capacity policies. Additionally, the coal market has become more interconnected globally with increased trade and integration between countries. Information spillover across domestic markets has been largely enhanced (Batten et al., 2019). As a major player in the global coal market and an information recipient of the international coal market returns (Li et al., 2019), China's coal prices are susceptible to volatility in international coal prices, which can reflect global supply and demand dynamics, as well as geopolitical factors, market speculation, and changes in trade policies.

The NEWC's influence is shown to be determined by the import volume of coal to China. Seen in Fig. 2, there was a temporary sharp decline in NEWC's influence in early 2021, following the unofficial ban on coal imports from Australia by the Chinese government from December 2020, driven by diplomatic rather than economic considerations. The combination of continuous efforts to reduce coal production capacity and the reduction in imports contributed to reduction in supply and the explosive growth of China's coal prices in 2021.

Besides the generally increasing influence of NEWC, the rising roles of LNG and REPG are observed in Fig. 2 and Table 4 in the three most recent coal price bubbles. While Wang et al. (2022) provide evidence that coal prices in China exert significant influence on the LNG import prices, we further find that from the opposite direction, LNG import prices are increasingly important in driving the prices of coal and the formation of its price bubbles in recent years.

In terms of LNG and REPG's rising roles, one explanation is the substitution effect of natural gas and renewables over coal, especially against the backdrop of the green transition. As a major substitute of coal, the natural gas market is closely linked and gradually integrated with the coal market (Wang et al., 2022). Consistent with Wang et al. (2022), we find a positive role played by China's green energy transition in enhancing the connection between the natural gas and coal markets in China. Natural gas is an important bridging fuel during China's implementation of the "coal-to-gas" policy aiming at reducing carbon emissions and improving the energy consumption structure to eventually phase out coal. This switching from coal to natural gas substantially raises the demand for natural gas, while China's natural resource endowment is poor in gas but rich in coal reserves. It is well expected that gas shortage, such as the one in 2017, can inevitably lead to the country's greater dependence on LNG imports, resulting in a greater influence from the international gas market on China's domestic energy markets, including coal and LNG. On the other hand, coal prices in China have become substantially market-oriented after ten years of efforts to marketize the coal industry. The natural gas market, however, is currently undergoing reforms towards price marketisation. As the reform progresses, both energy prices will become increasingly market-oriented and therefore more closely linked (Wang et al., 2022), leading to enhanced volatility and risk spillover across these energy prices.

It is not hard to understand the rising role of REPG also from the perspective of inter-fuel substitution effect. The use of non-fossil energy to replace coal-fired plants is a future direction in the power generation industry during China's green transition. The increasing proportion of renewables in power generation contributes to the phasing-out of coal (Guo et al., 2016b). With the advancement of renewable energy technologies and declining costs, renewable energy sources such as wind and solar power will become increasingly popular and competitive with coal. The adoption of renewables therefore affects the demand and price of coal, which is consistent with the findings of Ding et al. (2021) that the renewable energy price index can be a reliable predictor of Qinhuangdao power coal prices.

Seen in Fig. 1, the price of coal in China started to rise from early 2020. This can be attributed to the increased demand for coal and the insufficient supply to meet it, as the outbreak of the COVID-19 pandemic in the beginning of 2020 led to delayed production for coal enterprises nationwide, resulting in reduced coal supply and inventory. This coal price surge can be linked to the prolonged risk spillover from the global crude oil market following the COVID-19 pandemic, which caused international crude oil prices to plummet to historically low levels. For example, on 20 April 2020, the WTI crude oil futures contract for May delivery experienced an unprecedented drop into negative territory, highlighting the severe imbalance between supply and demand and risks in the global oil market. The risk spillover from the crude oil market inevitably led to sharply increased influence of crude oil on China's coal prices.

In the latter half of 2020, as the COVID-19 pandemic was effectively controlled, enterprises gradually resumed operations and production, leading to another sharp increase in coal demand for electricity generation. This resulted in the subsequent surge of coal prices as shown in Fig. 1. During this period, there was a sudden increase in the level of influence of ELE-FIRE on coal prices, as observed in Fig. 2. This short interval of coal price rise therefore stems from the increasing pressure imposed by the power generation sector on coal supply.

In 2021, the economic recovery from the coronavirus pandemic resulted in an even greater surge in the demand for coal, leading to a spike in the price of coal shown in Fig. 1. From the supply side, amid China's emission reduction campaign and green transition, the coal supply was much tightened in 2021. In September 2020, China announced its target of achieving a carbon peak in 2030 and carbon neutrality in 2060, making coal reduction and the promotion of renewable energy development crucial aspects of the energy transformation agenda. Another driver of the coal supply crunch is China's ban on Australian coal imports, which was announced by the Chinese government on 14 December 2020. This ban forced buyers in China to pay steep premiums for imports from other farther sources. Meanwhile, the temperature drop in December 2020 in China boosted the heating demand. These factors jointly pushed up the coal price in China and enabled the forming of a price bubble in January 2021 as well as the second half of 2021.

As mentioned above, from early 2021, global energy demand experienced a rapid recovery due to increased socio-economic activities following the containment of the COVID-19 epidemic. However, there was a lack of investment in traditional upstream energy sources amid the energy transition. Similar to the situation in China, the development of the global renewable energy sector could not sufficiently meet the energy demand in a short term, resulting in a global intensification of the energy supply-demand imbalance. Consequently, the prices of three conventional fossil energy sources (crude oil, natural gas, and coal) subsequently surged in the second half of 2021. This explains the substantial increase in the influence of international coal prices (NEWC) and LNG during the periods of coal price bubbles in 2021 and 2022, as shown in Fig. 2 and Table 4.

During the second half of 2020, the probability of the power sector indicator REPG being included in the optimal coal price forecasting model temporarily rises, and then falls remarkably since the beginning of 2021 (seen in Fig. 2). The announcement of the dual carbon goals in September 2020 contributed to the temporary rise of the influence of REPG, as developing renewable energy sources to eventually phase out coal in power generation should be a crucial step during the green transition. It therefore temporarily enhanced the influence from the renewable energy side on coal prices. However, the coal supply crunch in late 2020 and the coal price bubbles in 2021 indicate that the current development of the renewable energy sector could not bridge the energy gap at least in in a short time, nor could it resolve the problem of coal supply-demand imbalance. We therefore observe a declining influence of REPG on coal prices until 2022. Notwithstanding, developing renewable energy sources is an irreversible trend, we observe an increasing trend in its influence on coal prices from 2022 till the end of the sample period, implying the growing significance of renewables in the energy mix in China as the green transition continues.

The price of Chinese coal continued to rise and reached a record high in October 2021, reaching approximately \$328 per ton, which is three times the coal price in 2020. The GSADF analysis indicates that the coal price bubble emerged in June 2021 and persisted for eight months. Seen in Table 4, CDD is among the top three key drivers of the coal price bubbles during this period. This can be related to the power shortage during the summer in 2021 that was induced by the coal price surge. The heatwaves led to increased demand for power, while the soaring coal prices caused higher costs and huge losses for power plants. This combination led to the worst power shortage nationwide in history. The situation was then relieved after a series of government measures were implemented to enhance coal supply and improve the power pricing system. These facts explain the important roles played by the climate factor during the formation of the coal price bubble in June 2021.

4.3.2.4. The Russia-Ukraine conflict. As discussed above, the last two bubble periods in 2021 and 2022 are mainly characterized by a dominant influence of NEWC and a notable contribution of LNG prices, implying growing influences of the global coal market and natural gas import prices. From the geopolitical risk perspective, the outbreak of the Russia-Ukraine conflict in February 2022 has a significant impact on the global fossil fuel supply chain (Nerlinger and Utz, 2022). It carries the potential to incite explosive behavior within energy market prices (Su et al., 2023). As a major energy exporter, any restrictions or policies affecting Russian energy trade directly influenced the global energy supply and subsequently led to higher energy prices. The sustained increase in international coal prices significantly influences the high prices observed in the Chinese coal market. Our study finds that international coal prices represented by NEWC were the most influential factor contributing to the Chinese coal price bubble in 2022. Meanwhile, the impact of LNG and renewable energy sources is rapidly increasing due to their substitutability and potential as alternatives to coal.

The on-going Russia-Ukraine conflict may continue to push international coal prices upward. For example, in September 2022, the bombing of the Nord Stream natural gas pipeline further exacerbated the already tense global energy supply situation. This event resulted in a sharp decrease in Russian pipeline gas exports to Europe, a significant reduction in upstream production, and a substantial surge in gas prices on the European market. As winter approached, many European countries began replenishing their energy stocks at soaring gas prices and restarted their coal-fired power plants to ensure energy supply. In the Chinese market, we observe a clear rising trend in the influence of LNG on China's coal prices during 2022, partly reflecting the risk spillover from the international natural gas market to the Chinese energy market.

4.4. Price bubble periods of alternative energy sources

In the above analysis, the key drivers of coal price bubbles in China clearly exhibit time-varying characteristics. Prior to the launch of the coal industry de-capacity measures, the formation of coal price bubbles was primarily driven by extreme weather conditions and the power generation industry factors. We then find the important role of international crude oil price fluctuations in 2015. From 2016 onwards, international coal prices, LNG import prices, and renewable energy market indicators (REPG) are significant drivers of the Chinese coal market bubbles.

The above analysis identifies the impacts of individual factors on coal price volatility and the formation of coal price bubbles. Due to the substitutability between different types of energy commodities, the risk of price fluctuations in the coal market may be transmitted to other energy markets such as oil and natural gas, and vice versa. Also, the risk correlation between coal and renewable energy markets may increase as the consumption of renewable resources expands. The risk contagion between the coal and liquefied natural gas (LNG) markets is expected to strengthen as well, given that natural gas plays a bridging role in the energy transition. To address these potential cross-market risk contagion effects, we extend our analysis with an attempt to identify the mechanism of coal price bubble formation from a cross-market bubble contagion perspective. By comparing the price bubble periods between coal and alternative energy sources and identifying overlapping bubble periods, we can detect the co-occurrence of price bubbles, which, at least in part, contributes to the formation of coal price bubbles.

We conduct bubble period tests for those key variables, including NEWC, Brent, WTI, LNG, and REPG. Although the international crude oil prices are not the drivers of the coal price bubbles in 2021 and 2022, we also include them here to address the notably increasing influence from the crude oil side on China's coal prices during 2020 as well as after early 2022. The results are presented in Fig. 3 and Table A.1.

The gray shaded areas in Fig. 3 indicate the bubble periods for each alternative energy price. NEWC and the international crude oil prices (Brent and WTI) both exhibit significant bubbles in 2011, appearing earlier than the Chinese coal price bubble. During that period, energy price fluctuations in the international market exhibit steadily increasing influences on the coal prices in China, though not becoming major bubble drivers yet. Our results therefore confirm the findings of Yang et al. (2012) that the substitution effect between different fuels can facilitate the contagion of energy price risk across markets, and the high dependence of the Chinese economy on coal is considered to be the main reason for the strong correlation between coal and crude oil at that time.

In 2015, the Brent crude oil price and renewable energy power generation index were both found to have bubble overlapping with the coal price bubble in China. This is consistent with Khan et al. (2022) that the low oil prices and the rapid development of the renewable energy market caused to decline in coal demand, which in turn affected the coal price in 2016. Li et al. (2019) additionally point out that Brent crude oil had a significantly positive net spillover effect on Chinese coal prices during that period, acting as an information transmitter for the Chinese coal market. Our DMA results also show that there is a surge in the influence of international crude oil prices and REPG on the price of coal in China (Seen in Fig. 2). The low coal prices during this period are partly due to the declining international oil prices and the rapid growth of renewable energy generation. As shown in Fig. 3, there are significant declines in crude oil prices of Brent and WTI and a surge in the renewable energy power generation index from 2014 to 2016.

We further observe in Fig. 3 that international coal, Chinese LNG import prices, and renewable energy generation indices have all shown significant upward trends since 2021. First, the GSADF test results show that NEWC's significant bubble intervals are detected from May to October in 2021 and from February 2022 to January 2023, emerging just earlier than the Qinhuangdao thermal coal price bubbles starting in June 2021 and March 2022, respectively, and lasting longer. The observed patterns of bubbles in the international and Chinese coal markets align well with the DMA results, implying that the bubbles in China's coal prices are driven by the international coal prices during these periods. There is evidence that the linkage between Chinese coal and international coal prices depends on the size of the coal trade (Li et al., 2019). As the world's largest coal importer, the sustained increase in international coal prices is a significant reason for the two recent sharp price fluctuations in the Chinese coal market.

Second, there are two significant abnormal volatilities in China's LNG import prices since 2021 (From November 2021 to January 2022 and in August 2022). Our results also show that the coal price bubble overlapped with China's LNG import price bubble in the second half of 2018. Natural gas is considered a "bridge fuel" for the energy transition. Both energy structure optimization and energy marketization will further promote price risk contagion between coal and natural gas markets (Wang et al., 2022). It is therefore not surprising to see the increasingly important role of LNG import prices in influencing the coal price in China.

Third, potential bubble contagion between fossil energy and the renewable energy generation industry should not be ignored either. Fig. 3 shows that China's renewable energy generation index is detected with a price bubble overlapping with China's coal price bubble at the end of 2015 and 2021. The bubble in the REPG in 2015 may have partly been influenced by the then-overly-booming Chinese stock market (Wang et al., 2020a, 2020b), while the volatility in 2018 and 2021 mainly stems from increasing fossil energy prices. Unstable fossil energy prices facilitate a shift in market investment towards the renewable energy sector, and high fossil energy prices present many opportunities for the development of renewable energy markets (Maghyereh et al., 2019; Corbet et al., 2020). In the context of the global efforts to reduce carbon emissions and the complex geopolitical situation, the risk contagion among different fuels may become more complex in the future.

5. Conclusion and policy implications

The dynamics in China's energy landscape have evolved fast in recent years, with efforts to reduce coal consumption, promote cleaner energy sources, and improve air quality. The paper employs the GSADF approach and dynamic model averaging theory to identify bubbles in Chinese coal prices and analyze their causes. We find that supply-demand imbalances resulting from the energy transition, economic development, and geopolitical conflicts serve as fundamental causes of extreme coal prices in the Chinese market. According to our results, the dynamics of the power generation industry and winter heating demand used to be two primary drivers of price bubbles in the Chinese coal market, while in recent years the coal price bubbles are mainly driven by the dynamics of international coal prices, while alternative energy sources, including natural gas and renewables, are gaining increasing importance.

Specifically, the coal price bubble observed since 2021 can be attributed to the imbalance of coal supply and demand under the dual carbon goals, as well as the escalating international coal prices stemming from the Russia-Ukraine conflict. The year 2021 marks the initiation of China's 14th Five-Year Plan and the implementation of the dual carbon goals, which aims to reduce coal consumption. Although the development of renewable energy sectors has not yet compensated for the persistently high energy demand, the influence of the renewable energy sources is gradually gaining prominence during the formation of coal price bubbles. Furthermore, the post-COVID-19 economic recovery and disruption in the energy supply chain caused by the Russia-Ukraine conflict have led to significant increases in traditional fossil energy prices. The growing importance of LNG import prices on the formation of coal price bubbles well reflects the enhanced risk spillover between these two traditional fossil duels.

Our findings provide evidence to the argument that substitutability between different fuels may facilitate the contagion of bubble risks across various energy sources (Wang et al., 2022). Since the implementation of the dual carbon goals, China's LNG import price and the renewable energy generation sector index have exhibited significant abnormal volatility. While the energy transition presents numerous opportunities for renewable energy development, high prices of fossil fuels also pose challenges to China's economic growth and energy supply security. Given China's abundant coal resources and relatively limited oil and gas resources, thermal power and coal will remain crucial for China's energy security until renewable energy becomes the predominant source of energy supply. Particularly in the current complex international landscape, high international energy prices will continue to impact coal prices in China, and the mismatch of coal supply and

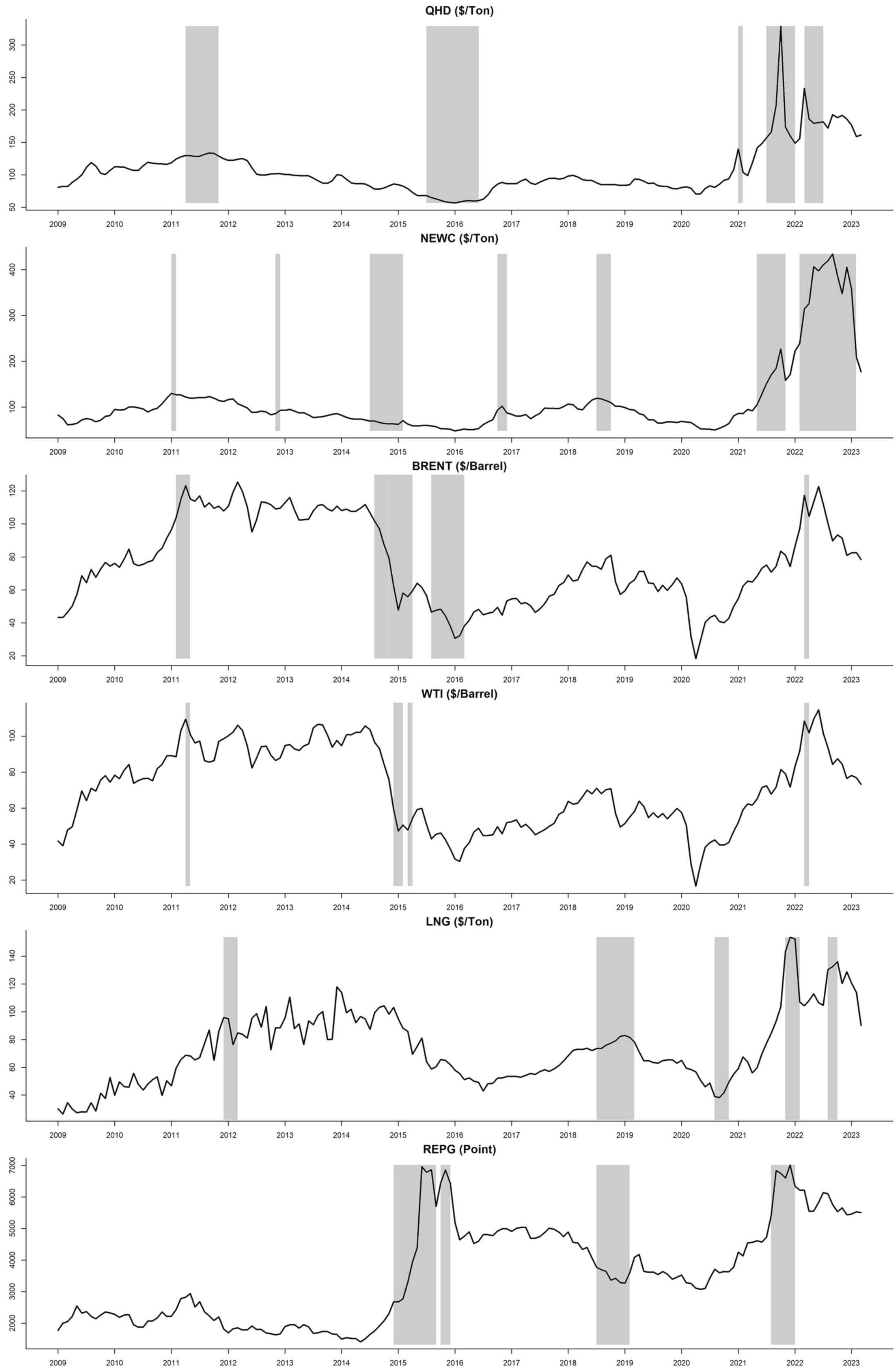


Fig. 3. Bubble periods in coal and alternative energy markets.
Note: The vertical axis of the figure indicates the price of each variable, with the unit shown in parentheses. The gray vertical bars indicate the price bubble periods in each market. QHD denotes the Qinhuangdao Q5500 thermal coal price (USD/ton); NEWC denotes the Australia Newcastle steam coal spot price (USD/ton); Brent and WTI denote the Brent and WTI crude oil spot prices (USD/Barrel), respectively; LNG denotes the Average LNG import price in China (USD/ton); REPG denotes the renewable energy power generation index (in Point).

demand may persist.

Lastly, macroeconomic developments and stock market volatility serve as significant determinants of Chinese coal prices during non-bubble periods. The regular fluctuations in coal prices in China are closely linked to the energy demand driven by economic environment and development. Additionally, measures such as coal de-capacity implemented in 2016 play a crucial role in influencing China's coal prices. Therefore, while it is important to monitor abnormal price fluctuations caused by international energy prices, China should also prioritize assessing the fundamental supply and demand conditions of the coal market. Efforts should be made to minimize the impact of energy price fluctuations on the economy, finance, and the daily lives of residents.

CRediT authorship contribution statement

Tiantian Wang: Conceptualization, Data curation, Methodology, Formal analysis, Software, Writing – original draft, Funding acquisition. **Fei Wu:** Conceptualization, Writing – original draft, Writing – review & editing, Validation, Funding acquisition. **David Dickinson:** Supervision, Writing – review & editing. **Wanli Zhao:** Visualization, Investigation, Software.

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Appendix A. Appendix

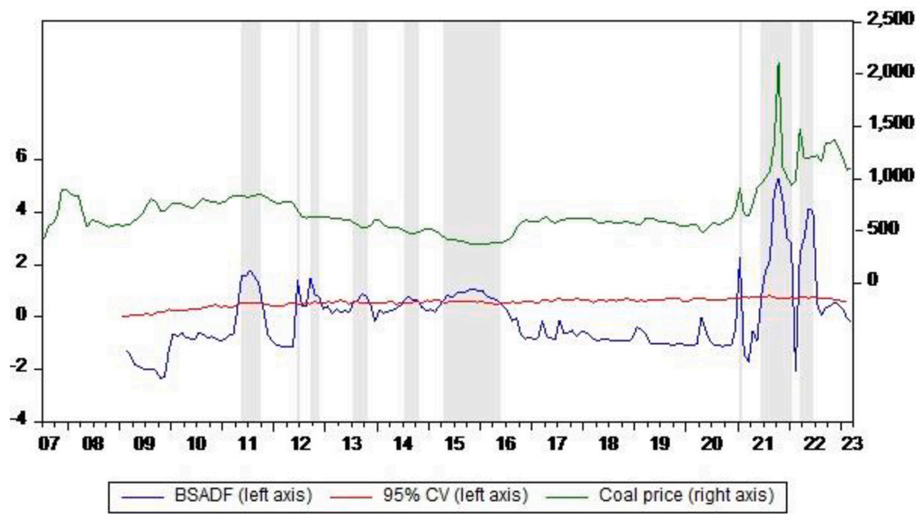

Fig. A.1. Bubble periods of the price of coal (RMB/Ton) in China.
Note: In this figure, bubble periods are marked by gray bars; CV denotes the critical value of the GSADF test at the 95% level of significance obtained from Monte Carlo simulations with 1000 replications; BSADF denotes the BSADF statistics; Coal price is in RMB/Ton.

Table A.1
Bubble periods of alternative energy sources.

Alternative energy source	Bubble period	Duration (Month)
QHD	April–October 2011	7
	July 2015–May 2016	11
	January 2021	1
	June–December 2021	7
	March–June 2022	4
NEWC	January 2011	1
	November 2012	1
	July 2014–January 2015	7
	October–November 2016	2
	July–September 2018	3
	May–October 2021	6
	February 2022–January 2023	12
WTI	April 2011	1
	December 2012–January 2015	2
	March 2015	1
	March 2022	1
Brent	February–April 2011	3
	November 2014–March 2015	5
	August 2015	1

(continued on next page)

Table A.1 (*continued*)

Alternative energy source	Bubble period	Duration (Month)
	December 2015–February 2016	3
	March 2022	1
LNG	December 2011–February 2012	3
	July 2018–February 2019	8
	August–October 2020	3
	November 2021–January 2022	3
	August 2022	1
REPG	December 2014–August 2015	9
	October–November 2015	14
	July 2018–January 2019	7
	August–December 2021	5

Note: In this table, QHD denotes the Qinhuangdao Q5500 thermal coal price (USD/ton); NEWC denotes the Australia Newcastle steam coal spot price (USD/ton); Brent denotes the Brent crude oil spot price (USD/Barrel); LNG denotes the Average LNG import price in China (USD/ton); REPG denotes the Renewable energy power generation index (in Point).

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2023.107253.

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