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Article

Time varying characteristics of factors affecting carbon price in emission trading scheme in China: Evidence from SV-TVP-VAR approach

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Abstract: Analysis of the factors influencing the price of carbon emissions trading in China and its time-varying characteristics is essential for the smooth operation of the carbon trading system. We analyse the time-varying effects of public concern, degree of carbon regulation, crude oil price, international carbon price and interest rate level on China's carbon price through SV-TVP-VAR model. Among them, the quantification of public concern and the degree of carbon emission regulation is based on microblog text and government decisions. The results show that all the factors influencing carbon price are significantly time-varying, with the shocks of each factor on carbon price rising before 2019 and turning significantly thereafter. The short-term shock effect of each factor is more significant compared to the medium- and long-term, and the effect almost disappears at a lag of six months. Thanks to public environmental awareness, low-carbon awareness and the progress of carbon market management mechanisms, public concern has had the most significant impact on carbon price since 2019. With the promulgation of relevant management measures for the carbon market, relevant regulations on carbon emission accounting, financing constraints, and carbon emission quota allocation for emission-controlled enterprises have become increasingly mature, and carbon price signals are more sensitive to market information. The above findings provide substantial empirical evidence for all stakeholders in the market, who need to recognize that the impact of non-structural factors on the price of carbon varies over time. Government intervention also serves as a key aspect of carbon emission control and requires the introduction of relevant constraints and incentives. In particular, emission-controlling firms need to focus on the policy direction of the carbon market, and focus on the impact of Internet public opinion on business production while reducing carbon allowance demand and energy dependence.

Keywords: carbon price; carbon regulation; public concern in China; SV-TVP-VAR model

1. Introduction

Climate change has been the global focus throughout the world (Wu and Wang, 2022). In response to the mounting threat of climate change, the adoption of a low-carbon development model has emerged as the preferred approach to achieving sustainable societal progress (Den Elzen et al., 2011). The carbon emission trading scheme (ETS), regarded as a vital market-driven carbon mitigation instrument, could trigger technology innovation and accelerate green economy transition (Li et al., 2022; Wu, 2022). China is the top emitter of carbon and energy consumer (Wu et al., 2023), which, coupled with the relatively nascent state of China's carbon market, inadequate regulatory frameworks, and imperfect allowance allocation mechanisms, exposes it to inherent risk factors and challenges (Weng and Xu, 2018). These factors contribute to the susceptibility of carbon prices to increased instability and pronounced volatility. In response, enterprises, whose production activities require carbon credits, may resort to distorting their decision-making processes in an attempt to shield themselves from the effects of carbon price fluctuations, ultimately limiting the carbon market's effectiveness in resource allocation (Song et al., 2015). It is for this reason that the carbon trading price is able to portray the supply and demand for carbon emission rights, making it one of the core indicators of the carbon trading market. This further makes us want to discuss what makes carbon prices volatile.

The formation of carbon price is ultimately a balance between the supply of carbon allowances and the demand for carbon emissions. The mechanism of carbon price formation is extremely complex, involving multiple stakeholders such as governments, businesses and consumers. Scholars have explored its association with carbon price volatility based on structural factors such as energy price changes, financial market situation, and macroeconomic regulation (Wang and Guo, 2018; Yang et al., 2023; Zhang et al., 2015). Such factors regulate enterprises' demand for carbon emission allowances by influencing their production costs, emission reduction costs, and production factor inputs, which in turn cause carbon price fluctuations. However, unstructured factors such as government carbon regulation and public demand for low-carbon environmental protection are also important components of the environmental regulatory system. On the one hand, the government regulates carbon price by strengthening scientific management and low-carbon advocacy on both the supply and demand side of carbon allowances, and on the other hand, the expression of the public will also promote the government to strengthen carbon emission control or indirectly influence the amount of carbon emission reduction and carbon allowance demand of enterprises (Wilson et al., 2018). Carbon price is not only influenced by structured factors such as energy price and financial product price, but also the impact of unstructured government policy regulation and public concern. At present, China's carbon market still takes enterprises as the main body of market transactions, but local governments have also initially explored some forms of individual carbon transactions, and with the improvement of carbon emission measurement and management capabilities, carbon trading mechanisms among individual members of the public can also be launched (Tang et al., 2023). This paper aims to investigate the link between government carbon regulations, public environmental concerns, and carbon price among corporate entities. Additionally, it seeks to understand the social determinants of carbon price fluctuations. These findings have implications for the future operation of carbon trading systems among the general public, providing valuable insights for government policymakers.

Our study contributes significantly in three key dimensions. To begin, it strives to elucidate the multifaceted impact of unstructured variables on carbon prices. Going beyond the established insights into structured factors available in the extant literature, this research embarks on a comprehensive exploration of the dynamic forces influencing carbon prices and compares their varying levels of volatility. Moreover, it employs a robust quantification approach for unstructured factors. This entails a rigorous assessment of the scientific rigor underpinning carbon market management in China, drawing insights from policy releases and media coverage.

Additionally, the study quantifies public sentiment regarding low-carbon initiatives and environmental protection through an in-depth sentiment analysis of microblog texts, offering valuable insights into public perceptions and concerns. Lastly, the paper unveils the nuanced, time-evolving effects of both structural and non-structural factors on carbon prices, using the SV-TVP-VAR method. This method effectively addresses the limitations inherent in traditional vector autoregression models by accommodating variable parameters and mitigating endogeneity issues during model construction.

The subsequent sections of this paper are structured as follows: section 2 encompasses the literature review, section 3 outlines the theoretical analysis, section 4 introduces the research methodology, and section 5 presents the empirical analysis along with the corresponding results. The final section is the conclusion.

2. Literature review

With the continual global expansion of carbon trading markets, there has been a growing body of research examining the underlying causes of fluctuations in carbon prices (Li et al., 2023). In general, the volatility of carbon prices can be attributed to two primary factors: structural and non-structural factors (Wang and Guo, 2018; Deeney et al., 2016). The primary aim of this paper is to explore the influence of non-structural factors, specifically carbon regulations and public concern, on carbon prices. Consequently, in this section, we will review pertinent literature on the intricate relationship between carbon regulations and carbon prices, the impact of public concern on carbon prices, and the empirical analysis techniques commonly employed in this area of research.

2.1. Carbon regulation policy and public concern

The carbon market is a policy-led market, where market policies can convey certain price signals to market participants (Kearney et al., 2014), and changes in carbon quota expectations caused by quota issuance as well as mechanism design have a significant impact on carbon price (Lin and Jia, 2019). Scholars have verified that European policy regulation can have an impact on European carbon trading price through reports on climate change related issues, policy announcements by the European Parliament, and policy enactments in carbon trading markets (Deeney et al., 2016; Hartvig et al., 2023; Ye and Xue, 2021; Zhang and Xia, 2022). However, there are few studies on the impact of China's carbon market policies on carbon price. In terms of public concern, the increase of public concern about the environment can form an effective constraint on the behavior of both government and enterprises (Zhang et al., 2018), which is an important factor to influence the amount of carbon emission reduction of enterprises and regulate the demand for carbon quotas. Some scholars have quantified public concern through the Baidu Index (Huang and He, 2020; Wang et al., 2022), and found that the increase in public concern has a positive impact on carbon price (Li et al., 2020). However, the Baidu index is only generated based on user search behavior statistics, while microblog sentiment information can more accurately and in real time reflect the overall psychological and behavioral changes in society (Kim et al., 2022), and can better reflect public demands for environmental protection and ecological governance (Wu et al., 2022). In the financial market, textual information from social media platforms can often reveal the changing trends of asset price (Derakhshan and Beigy, 2019). Quantitative analysis of microblog texts has been effectively utilized in various areas, including stock market analysis, reflecting public sentiment towards significant events, and assessing corporate image and reputation (An et al., 2021; Bao et al., 2023; Sun et al., 2019). Currently, studies on how public concern affects carbon price are only quantified based on the Baidu index and ignore the public's emotional demands regarding environmental protection and low-carbon governance on the microblogging platform.

2.2. The identification of the factors influencing carbon price

In terms of comprehensive identification of the factors influencing carbon price in China, some studies have attempted to identify which of the many influencing factors are the most significant, as opposed to the previous single factor discussions. Wen et al. (2022) analyzed the dynamic connectivity algorithm to obtain that the fluctuation of carbon price in the Hubei province of China. Hubei's carbon market is mainly affected by electricity. Liu et al. (2023) utilized the ICEEMDAN-HC method and quantile regression analysis to examine the factors influencing carbon price in China, concluding that the fluctuations in carbon price were mainly driven by market forces such as the financial and energy markets. Zhou and Li (2019) and Lin and Xu (2021), using the VAR-VEC model and non-parametric analysis method respectively, found that macroeconomic factors had a more significant impact on carbon price. Song et al. (2019) conducted a study on the Chinese carbon market using the Logit model, revealing that environmental policies and CO_2 emission policies had important short-term effects on carbon price. General equilibrium model results also indicated a close relationship between carbon price and carbon market mechanisms (Lin and Jia, 2019). Li et al. (2023) use the SV-TVP-VAR model to verify the time-varying influence of crude oil price and weather changes on China's carbon prices, the results show that carbon prices are more prone to fluctuations due to weather changes. The existing research has an apparent problem of failing to differentiate the factors with the greatest impact on the carbon price. Furthermore, China's carbon trading market exhibits distinct stages (Weng and Xu, 2018), imperfections in the trading mechanisms and significant carbon price fluctuations may result in changes to the influencing mechanisms of various factors on carbon price (Batten et al., 2020). This implies that the evolving process of how the force of each factor on carbon price changes over time has become difficult to reveal.

In conclusion, existing literature has thoroughly investigated the factors impacting carbon price in the research field. Although existing studies have mainly discussed the impact of structural factors such as energy markets, financial markets and macroeconomics on carbon price in China. However, in terms of unstructured factors, theoretical explanations of the impact of carbon market regulations and public concern are insufficiently detailed. Existing literature does not precisely explain how carbon market policies and public environmental concern affect carbon price in China. Several studies have found a positive association between increased public concern and environmental governance (Li et al., 2020). Furthermore, it has been measured using the Baidu Index to assess its impact on carbon price (Zhang et al., 2021). However, the Baidu index is only generated based on user search behavior, while the microblog sentiment information better reflects the public's concern to environmental protection and ecological management. Meanwhile, existing literature exhibits certain discrepancies in the overall analysis results of the factors influencing carbon price. One possibility is due to the scientific insufficiency of the management of the carbon trading market at that time and the small sample data may lead to bias in the research results, and the research findings vary widely. Another factor is that the research methods employed in existing literature are more suitable for static analysis. For example, VAR-VEC models, nonparametric analysis methods, and general equilibrium analysis methods have been utilized. However, due to the potential time-varying nature of factors influencing carbon prices, the effectiveness of these methods in analysis may be limited.

Therefore, through the empirical facts and SV-TVP-VAR model, the study elucidates the impact of unstructured factors on carbon prices. It analyzes the effects and directions of unstructured factors such as carbon market policies and public concern, as well as structured factors such as energy markets, financial markets, and macroeconomics on carbon prices. It further reveals the correlation between unstructured factors such as carbon regulation policies, public concerns and carbon prices. Finally, it provides more robust empirical evidence for the causes of carbon price fluctuations. This contributes to the good and smooth operation of the carbon trading market, to better achieve the economic leverage to pry key emission units to take the initiative to reduce emissions. The results of theoretical and empirical analyses will provide policy makers with sufficient decision-making references and evidence to effectively achieve carbon emission reduction goals. It will also provide theoretical references for the construction and improvement of various carbon markets in China and other developing countries in the future.

3. Theoretical analysis

As China's unified carbon market prepares to be established, carbon emission rights have improved in terms of liquidity and transaction price after the gradual improvement of trading management methods, the inclusion of industry categories, and the setting of total allowances (Weng and Xu, 2018). It is worth noting that since the official adoption of the Paris Agreement and the government's work objectives have placed more emphasis on the pursuit of natural harmony, the public has further demanded for environmental friendliness. Carbon emissions and low-carbon living have become hot topics in society, and the carbon trading market has become the place where the public expects to build a green and low-carbon development in the future. The shift in the development stage of the carbon trading market also means that the impact of various factors on carbon price may show time-varying characteristics.

Although China currently has a carbon reserve system to regulate the carbon market, allowing allowances to be bought or sold based on a set percentage, the supply of carbon emission allowances can still be considered relatively constant in the short term and adjustable in the long term (Weng and Xu, 2018). The carbon price can respond to market conditions, changing both with changes in government planning and regulation of carbon emissions and as companies respond to clean development, low-carbon advocacy, and rising public demand for low-carbon. This effect of carbon regulation policies and public concern on carbon price has been verified in many studies (Hartvig et al., 2023; Li et al., 2020). The government's planning and control of carbon emissions through scientific management and low-carbon advocacy, as well as the public's concern for expressing their concern for environmental protection and low-carbon living through social media platforms can cause carbon price changes. **Figure 1** shows the mechanism diagram of the impact of carbon regulations and public concern on carbon price fluctuations.

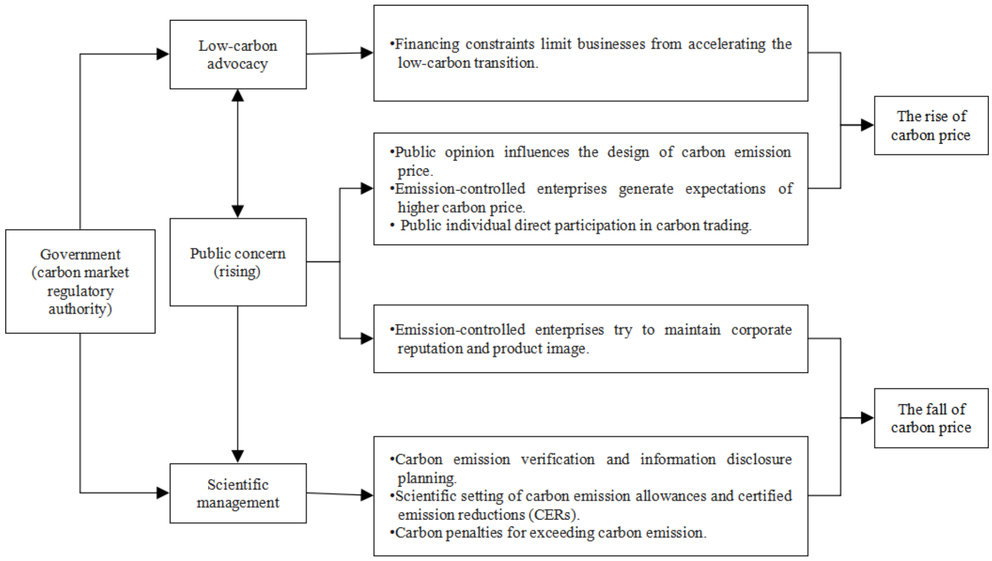


Figure 1. The impact of carbon regulation policies and public concern on carbon price.

Concerning the formulation of carbon regulation policies by the government, China's carbon trading pilots adhere to a total-control trading system framework. These pilots incorporate carbon credit offset mechanisms to bolster market liquidity, and meticulous provisions are in place delineating the industry coverage scope, total carbon allowance allocation, and compliance verification protocols (Zhang et al., 2020). Functioning as a regulatory authority within the carbon market landscape, the government wields influence over corporate decisions. Through the promotion of low-carbon practices and scientific management, it actively regulates corporate carbon emission demand. Additionally, the government formulates management practices pertaining to carbon market trading, thereby exerting an impact on carbon prices.

First of all, concerning financial constraints, the government can support high energy-consuming enterprises through green credit policies to complete the green and low-carbon transition and reduce their carbon emission needs in addition to directly managing the carbon trading market (Khan and Johansson, 2022). Increasing banks' green credit financing constraints can also put pressure on high energy-consuming and high-polluting industries, further forming a financing incentive and financing constraint mechanism for borrowing enterprises by influencing credit customer preferences and capital allocation directions (Huang et al., 2022). However, when enterprises' cleaner production standards cannot meet the green credit regulations, they may also turn to the carbon market to purchase carbon emission allowances due to the pressure to reduce emissions, as some enterprises cannot adjust their production plans or transform to cleaner production modes in the short term.

Second, regarding to the verification of carbon emissions and the planning of information disclosure, the construction of an effective carbon market requires the development of standards for greenhouse gas emission accounting, emission reduction effect assessment, and information disclosure (Weng and Xu, 2018). As an important part of the carbon trading system, the carbon verification system can ensure the authenticity, accuracy, and reliability of the greenhouse gas data emitted by enterprises, which can directly affect the allocation and trading of their carbon quotas. For the carbon emissions that are missed or under-checked to do a good job of verification statistics, the demand for carbon emission rights by enterprises may increase as a result, driving up the carbon price.

Third, in terms of the scientifically grounded establishment of carbon emission allowances and certified emission reductions (CERs), the carbon market policy design contains multiple constraint mechanisms for emission control subjects, and the tightness of the limits, the different ways of quota allocation, and the difficulty of issuing certified emission reductions will affect the supply capacity of carbon emission rights (Song et al., 2019). If there is a contraction in the supply of carbon allowances, the carbon price may face greater upward pressure.

Fourth, concerning penalties for exceeding carbon emissions, penalty rules and legal liability provisions can regulate the carbon reduction obligations of emission control enterprises. At the end of the compliance cycle, enterprises are required to surrender carbon allowances equal to their emissions or face penalties such as fines (Seifert et al., 2008). When companies do not complete their compliance obligations and do not face severe penalties for doing so, they may choose to pay fines for excess emissions rather than purchasing carbon credits in the market. If carbon penalties are increased, the carbon price may rise.

The content of social concern in China follows closely the national carbon market construction situation (Weng and Xu, 2018). The public can indirectly influence carbon price by expressing their concern for environmental protection and low-carbon living on social media platforms, as well as by supporting environmentally friendly products in their consumption through green consumption behaviors, or by opening personal accounts in the carbon trading market and directly participating in carbon emissions trading. It mainly includes the following aspects.

(1) Public opinion influence. Individual members of the public can browse and publish articles or related discussions about low-carbon advocacy, environmental regulation, and pollution prevention through platforms such as Baidu and Weibo, and when the heat of the topics discussed by the public rises, the government can understand the direction of public opinion about the current ecological environment through the degree of public opinion at this time (Li et al., 2019). If the government fails to effectively regulate and restrain enterprises that exceed the carbon emission

standards, the public will question the government's ability to govern and affect the government's credibility. Therefore, the government may require enterprises to make corresponding rectifications and shrink their carbon emissions.

(2) Emission-controlled enterprises' price expectations. Some industries such as iron and steel, chemical, cement, electric power, non-ferrous metals, glass, paper and other high energy-consuming industries have a high potential for emission reduction, but the effectiveness of emission reduction is limited in the short term due to production cycle, production factor use, and production technology limitations (Weng and Xu, 2018). When faced with rising public concern for environmental protection, such enterprises may generate expectations of rising carbon price and may purchase certain carbon emission rights in advance to hedge the risk of rising carbon price.

(3) Public individual direct participation in carbon trading. Individual members of the public can purchase a certain share of carbon credits by opening an account in the carbon trading market, potentially contributing to higher carbon price. It can also influence product market price as well as financial market price by purchasing stocks or other financial derivatives through companies or financial markets based on individual expectations of product price, and other investments in carbon financial markets by residents can also directly affect carbon spot price (Wang and Guo, 2018).

(4) Emission-controlled enterprises' corporate reputation and product image. If the government strengthens publicity on energy conservation and emission reduction and guides consumers to generate low-carbon consumption habits, then the public may prefer cleaner products (Wei et al., 2023). As residents' low-carbon awareness increases, the consumption of low-carbon products will increase, and enterprises will tend to produce more low-carbon products to maintain their corporate image and product image, which in turn will influence their future investment expectations. If enterprises pass a low-carbon green transformation, they can in turn reduce the demand for carbon emissions and cause a decrease in carbon price.

4. Research design

4.1. Data

Non-structural and structural factors exert diverse influences on carbon pricing. Our study aims to assess which of these unstructured and structured factors holds the most substantial sway over carbon pricing, and to conduct a comprehensive analysis of the extent, direction, and time-dependent characteristics of each factor's impact on carbon pricing. During the data collection process for these influencing factors, we were attentive to the differing developmental stages and regional disparities within China. However, the efficacy of market data has been somewhat constrained due to the limited operational history of China's national carbon emissions trading system, known as China's National ETS, which has only completed two compliance years. It is worth noting that the Hubei Province Carbon Emission Rights Trading Market, established in 2014, is a noteworthy case. As one of the pioneer provinces in carbon trading, Hubei Province stands as a representative model concerning industrial structure, energy composition, and economic development stage in China. In our analysis, we draw on existing research regarding the impact mechanisms of carbon regulation and the influence of public concern among the unstructured factors, taking into account the studies conducted by Wang et al. (2022), Zhu et al. (2018), and Yang et al. (2023). The selected influencing factors include the level of carbon regulation, public awareness, crude oil prices, international carbon pricing, and interest rates.

The Carbon Trading Network includes carbon regulation policies and news media reports on carbon finance, carbon sinks, carbon markets, carbon inventories, carbon quota indicators, etc. Therefore, the study measures the degree of carbon regulation by the number of policies and news reports included on the carbon trading website. The data of public concern indicators are collected from the text content of microblogs on topics such as environmental pollution, low-carbon life and climate change. Among the structured influencing factors, the energy price is selected from Brent crude oil futures price as a reference, and the data is obtained from Sina Finance. The EUA futures price is used as a reference for the European carbon price, and the data comes from the Investing website (Investing, 2003). We select the Shanghai Interbank Offered Rate to measure the interest rate level. All data are collected from China Stock Market & Accounting Research Database (CSMAR).

4.2. Quantification of public concern

We aim to measure public concern indicators using sentiment analysis on microblogging platforms. Microblogs, as popular social media platforms, are known for their high responsiveness and extensive user participation, owing to their open sharing and dissemination mechanisms. They wield significant influence in facilitating information exchange and interaction. The quantification of public concern on microblogging platforms regarding topics such as environmental pollution, low-carbon living, climate change, and more, allows for a more accurate reflection of public sentiment towards environmental issues. Additionally, it provides valuable insights into public demands for environmental protection. **Figure 2** illustrates the process of quantifying public concern in detail.

Step 1: based on the Baidu index on energy saving and environmental protection, low carbon advocacy, pollution prevention and control through the demand mapping function to determine the keywords that are highly relevant to carbon emissions, to expand the scope of keyword selection. A total of 21 keywords were obtained, such as greenhouse gas, environmental protection, carbon neutral, carbon footprint, etc. The keywords were filtered by the Person correlation coefficient.

Step 2: The sentiment analysis method was introduced to select the terms with the absolute value of correlation coefficient greater than 0.5 as the subsequent microblog search keywords, and the collected microblog text data were analyzed to understand the current public emphasis on environmental protection, low-carbon life and ecological governance. Additionally, preprocess the microblog text, and eliminate irrelevant information such as network links, animations, videos and pictures in the microblog.

Step 3: Divide the microblog text into words through Jieba word segmentation, and identify them through the Boson sentiment dictionary, HowNet degree dictionary, negative dictionary and Harbin Institute of Technology Stopwords. Calculate the sentiment score of each microblog sentence. After obtaining the quantified text sentiment data of each Sina microblog, the microblog sentiment data is sorted into time series data according to the release date of the microblog.

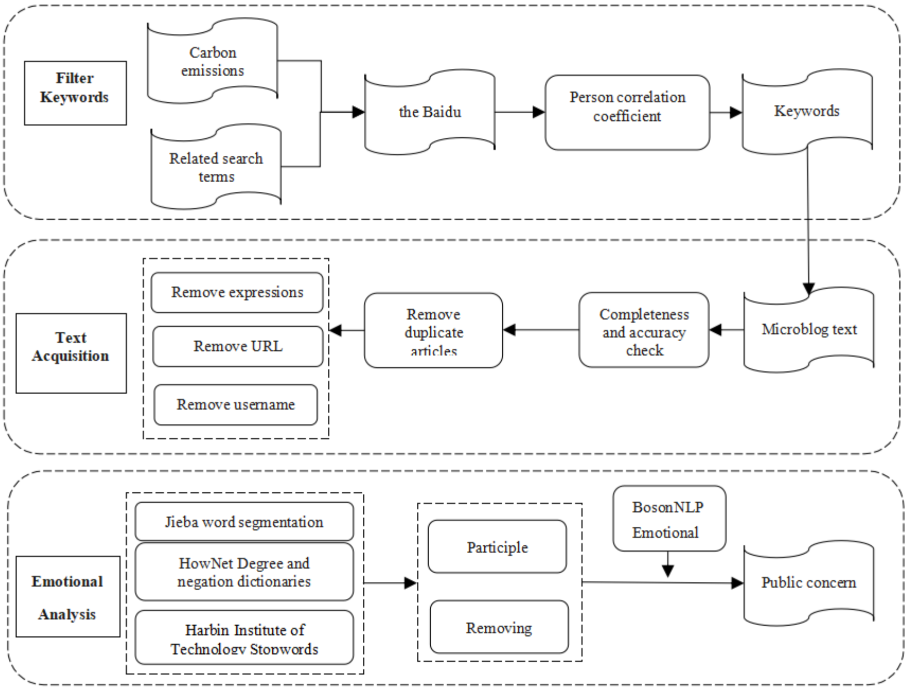


Figure 2. Flow chart of public concern quantification.

4.3. The SV-TVP-VAR approach

The transition in China's carbon trading market development stage introduces a dynamic element, indicating that the influence of various factors on carbon prices may exhibit time-varying characteristics. Notably, carbon trading activities among emission-controlled enterprises in China are constrained by compliance years, necessitating consideration of the evolving nature of carbon price fluctuations. Traditional quantitative analysis methods, such as VAR and SVAR, commonly utilized in prior research, assume constant relationships among variables, potentially overlooking vital time-varying insights. In contrast, the SV-TVP-VAR model, which is free from mean squared error assumptions and inherently characterized by time-varying parameters, offers greater flexibility and precision in capturing the nuanced connections between different factors and carbon prices across varying time periods. This approach has already proven its efficacy in domains like the European carbon market, electricity market, and energy market, as evidenced by Zhong et al. (2023), Qiao et al. (2023), and Guo et al. (2022). In our study, we enhance the traditional VAR model by introducing time-varying features and construct an SV-TVP-VAR model to dynamically analyze the evolving relationships between variables. This innovative approach provides a more accurate depiction of how the correlation between carbon prices and various influencing factors evolves over time.

Based on Primiceri (2005), and Nakajima (2011), the model can be derived progressively from the VAR model. Assume that the basic form of Structural VAR model follows:

$$Ay_t = F_1 y_{t-1} + \cdots + F_S y_{t-s} + \varepsilon_t, t = s+1, \cdots, n \quad (1)$$

$$A = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ a_{21} & 1 & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ a_{k1} & \cdots & a_{k,k-1} & 1 \end{bmatrix}, \Sigma = \begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & \sigma_k \end{bmatrix} \quad (2)$$

where y_t is the $(k \times 1)$ vectors of observable variables, and the disturbance $\varepsilon_t \sim N(0, \Sigma\Sigma)$ represents the structural shock. A is the $(k \times k)$ coefficient matrix, and $F_1, \cdots, F_S$ are the $(k \times 1)$ coefficient matrices respectively. The $\sigma_i (i = 1, \cdots, k)$ is the standard deviation of the structural shock. This paper specifies the simultaneous relations of the structural shock by recursive identification and assumes that the correlation coefficient matrix A of the same period is lowertriangular. The Equation (1) can be can be expressed as:

$$y_t = B_1 y_{t-1} + \cdots B_p y_{t-s} + A^{-1}\Sigma\epsilon_t, \epsilon_t \sim N(0, I_k) \quad (3)$$

where $B_i = A^{-1}F_i$ for $i = 1, \cdots, s$. Stacking the elements in the rows of the B_i to form $\beta(k^2 s \times 1)$, and defining $X_t = I_k \otimes (y'_{t-1} \cdots y'_{t-p})$, the Equation (3) can be written as

$$y_t = X_t \beta + A^{-1}\Sigma\epsilon_t \quad (4)$$

All parameters in Equation (4) are time-invariant. Primiceri (2005) proposed a time-varying parameter vector autoregressive model, assuming that the parameters can change with time, in order to identify the possible time-varying structure among economic variables. The above model is further transformed into:

$$y_t = X_t \beta_t + A_t^{-1}\Sigma_t \epsilon_t, t = s+1, \cdots, n \quad (5)$$

Equation (5) is the expression form of the SV-TVP-VAR model. Different from Equation (4), the coefficients β_t, the parameters A_t and Σ_t are all time varying. Supposing that column vectors $a_t = (a_{21}, a_{31}, a_{32}, a_{41}, \cdots, a_{k,k-1})$ and $h_t = (h_{1t}, \cdots, h_{k,k-1})$ is the stack of the elements a and $h_{jt} = \log(\sigma_{jt}^2)$ in A_t. We assume that the parameters in Equation (5) follow a random walk process as follows:

$$\beta_{t+1} = \beta_t + u_{\beta t}, a_{t+1} = a_t + u_{at}, h_{t+1} = h_t + u_{ht}, \begin{bmatrix} \epsilon_t \\ u_{\beta t} \\ u_{at} \\ u_{ht} \end{bmatrix} \sim N\left(0, \begin{bmatrix} I & 0 & 0 & 0 \\ 0 & \Sigma_\beta & 0 & 0 \\ 0 & 0 & \Sigma_a & 0 \\ 0 & 0 & 0 & \Sigma_h \end{bmatrix}\right) \quad (6)$$

where $t = s+1, \cdots, n$, $\beta_{t+1} \sim N(\mu_{\beta 0}, \Sigma_{\beta 0})$, $a_{t+1} \sim N(\mu_{a0}, \Sigma_{a0})$, and $h_{t+1} \sim N(\mu_{h0}, \Sigma_{h0})$. The shocks to the innovations of the time-varying parameters are assumed uncorrelated among the parameter β_t, a_t and h_t. The shocks can also catch sudden changes in the structure of the economy.

In order to avoid the over-identification problem easily caused by the least square method or the maximum likelihood method to estimate the SV-TVP-VAR model. Nakajima et al. (2011) believe that the Markov chain Monte Carlo (MCMC) method estimation is more accurate and effective. Let $y = \{y_t\}_{t=1}^n$, $\omega = (\Sigma_\beta, \Sigma_a, \Sigma_h)$. We set the prior probability density as $\pi(\omega)$ for ω, then Gibbs sampling of given data is conducted from the posterior distribution according to:

(1) Initialize β, a, h, and ω.

(2) Sample $\beta|a, h, \Sigma_\beta, y$.
(3) Sample $\Sigma_\beta|\beta$.
(4) Sample $a|\beta, h, \Sigma_a, y$.
(5) Sample $\Sigma_a|a$.
(6) Sample $h|\beta. a, \Sigma_h, y$.
(7) Sample $\Sigma_h|h$.
(8) Go to Equation (2).

5. Empirical results

We analyzed the historical trends of carbon price and public concern. Subsequently, in this section, we presented the impact response results of carbon regulation degree, public concern level, crude oil price, international carbon price, and interest rate level on carbon price using the SV-TVP-VAR model. We examined the relationship between time-varying impulse response, cumulative impulse response, and point-wise impulse response. Finally, we compared and reflected on the research findings with some similar studies.

5.1. Trend analysis

Figure 3 shows the trend of carbon price and public concern since the start of the carbon market in Hubei Province, China. The increase or decrease of the value corresponds to the increase or decrease of the carbon price and public concern respectively, and the time frequency is monthly and the period when no trading occurs has been excluded. It is easy to see that the public concern index constructed based on the Baidu index can better reflect the degree of public concern about low carbon advocacy, environmental regulation and pollution prevention. The trend of public concern and carbon price are generally similar. Especially from 2019 onwards, when the Hubei carbon market enters the sixth compliance period and the Interim Regulation on the Management of Carbon Emission Trading is introduced, the change of public concern and the trend of the carbon price is more compatible, further verifying that there is indeed a correlation between public concern and the change of carbon price. Specifically, the level of public concern has increased slightly since 2016 compared to 2014 and 2015, probably due to the successful adoption of the Paris Agreement in December 2015 and the fact that the public is more concerned about the environment and climate change due to the several "explosions" of haze in Beijing during the same period. Later, on 22 September 2020, the goals of "carbon peaking" and "carbon neutral" were proposed, further guiding public awareness of greenhouse gases and the low-carbon economy, and public awareness of low-carbon green living has increased.

From the perspective of the operation of the carbon market, since the launch of the pilot carbon market in Hubei, the sudden change point of carbon price often occurs around the annual deadline of compliance from May to July every year. Especially from 2015 to 2017, due to the lack of market information at the beginning of the compliance year, companies often adopt a wait-and-see attitude to capture market trends and thus lack enthusiasm for transactions. The total amount is set too high, leading to the sale of carbon emission allowances at low price before the end of the compliance year, and the carbon price has dropped sharply. Not only that, most of the pilot carbon markets have the problem that the proportion of the Chinese Certified Emission Reduction (CCER) offsets is too large (Huang et al., 2022). Too many total carbon allowances and offsetting emission reductions make the carbon market less effective, and the carbon price signal does not truly reflect market information. With the gradual introduction of relevant management measures for the carbon market, on 14 March 2017, the China National Development and Reform Commission announced the suspension of CCER transactions, and organized the revision of the Interim Measures for the Administration of Greenhouse Gas Voluntary Emission Reduction Transactions. On 19 December 2017, the National Development and Reform Commission issued the National Carbon Emissions Trading Market Construction Plan (Power Generation Industry), the construction of China's unified carbon emission trading market system has officially started, and the development of China's carbon market has gradually become standardized.

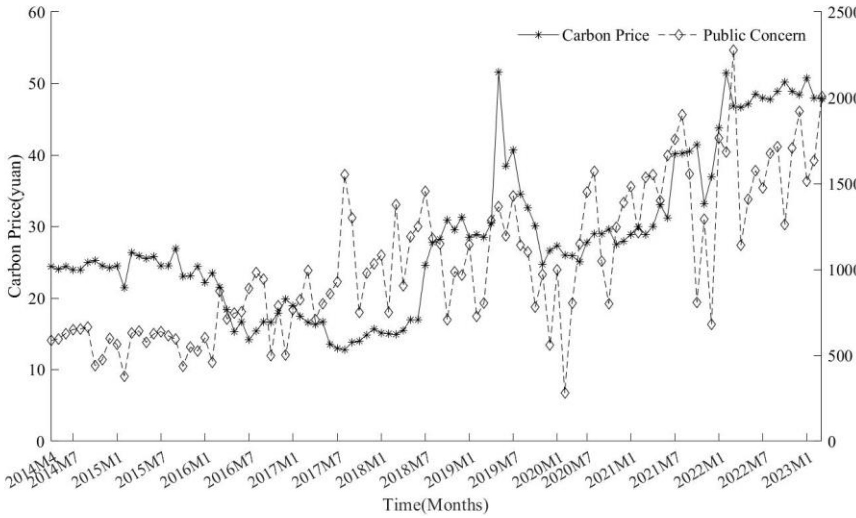


Figure 3. Historical trend of the carbon price and public concern.

5.2. Variable testing and model setting

We adopted a vector autoregressive model with time-varying parameters to examine the dynamic relationships among the variables by constructing SV-TVP-VAR models with six variables: carbon price in Hubei (Hbea), public concern (Gpr), carbon regulation degree (Pec), Brent crude oil futures price (Brent), European EUA futures price (Eua), and Shanghai Interbank Offered Rate (Shibor). Therefore, ADF test were performed for the required variables. Considering that log-differencing of the smooth variables does not affect the reliability of the statistical inference of the VAR, but putting non-smooth variables into the VAR as smooth variables creates statistical inference problems (Guo et al., 2023), the log-differencing treatment was taken for the raw data (see **Table 1**). After log-differencing, the variables all remained stationary.

We set the parameters of the SV-TVP-VAR model as follows: $u_{\beta 0} = u_{a0} = u_{h0} = 0$, and $\Sigma_{\beta 0} = \Sigma_{a0} = \Sigma_{h0} = 10 \times I$, and set the a priori assumptions of the model $\left(\Sigma_\beta\right)_i^{-2} \backsim \text{Gamma}(20, 10^{-2}), (\Sigma_a)_i^{-2} \backsim \text{Gamma}(4, 10^{-4}), (\Sigma_h)_i^{-2} \backsim$

$\text{Gamma}(4, 10^{-4})$. The number of MCMC samples was set to 20,000 and the first 2000 samples were discarded to ensure the accuracy of the estimation results. According to the AIC information criterion and the SC criterion, the optimal lag order of the model is determined to be 2. **Table 2** lists the parameter estimation results of the SV-TVP-VAR model.

Table 1. ADF test.

Variable	*T*-value	*p*-value	Variable	*T*-value	*p*-value
Hbea	−1.200	0.674	dln_Hbea	−11.586	0.000
Pec	−4.175	0.001	dln_Pec	−17.490	0.000
Gpr	−3.841	0.003	dln_Gpr	−16.346	0.000
Brent	−2.328	0.163	dln_Brent	−8.748	0.000
EUA	0.546	0.986	dln_Eua	−11.108	0.000
Shibor	−5.331	0.000	dln_Shibor	−14.021	0.000

Table 2. The estimation of selected parameters in the SV-TVP-VAR model.

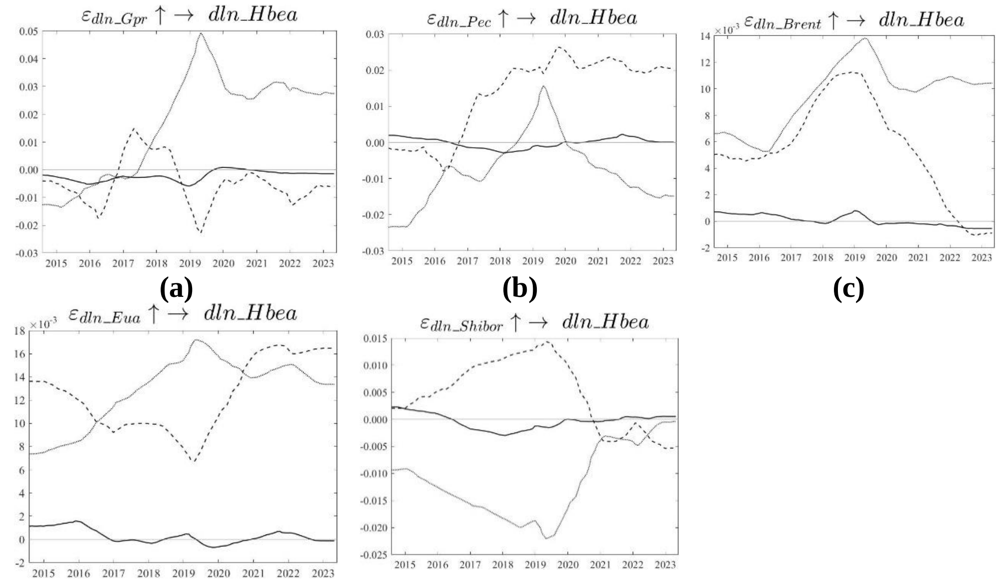
Parameter	Mean	Stdev	95% confidence interval	Geweke	Inef.
$(\Sigma_\beta)_1$	0.0227	0.0026	[0.0183, 0.0285]	0.751	5.16
$(\Sigma_\beta)_2$	0.0225	0.0026	[0.0182, 0.0281]	0.097	6.73
$(\Sigma_a)_1$	0.0054	0.0015	[0.0034, 0.0091]	0.466	26.05
$(\Sigma_a)_2$	0.0056	0.0017	[0.0033, 0.0098]	0.011	38.58
$(\Sigma_h)_1$	0.0056	0.0017	[0.0034, 0.0098]	0.631	27.05
$(\Sigma_h)_2$	0.0055	0.0016	[0.0034, 0.0095]	0.350	32.53

Note: Mean and Stdev denote posterior means and standard deviations; Geweke is Geweke convergence diagnostics statistics; Inef. is an inefficiency factor.

Table 2 shows the parameter estimation results. The standard deviation of each parameter is small, and the posterior means are all within the 95% confidence interval. From the point of view of convergence, at the 5% significance level, the diagnostic value of convergence does not exceed the critical value of 1.96, indicating that the null hypothesis of "parameters converge to the posterior distribution" cannot be rejected. The maximum value of the invalid factor is about 39, which means that in the case of continuous sampling 20,000 times, we can get at least 518 (20,000/38.58) unrelated samples, which can meet the needs of the model posterior inference.

5.3. Time-varying stochastic fluctuation analysis

The impulse responses with different lags are chosen to be period 1, period 2, and period 6, respectively. **Figure 4** shows the pulse response diagram of carbon price after one standard deviation positive impact of each influencing factor in different periods, revealing the time-varying characteristics of carbon price for the random volatility of different driving factors. Among them, the horizontal axis represents the time node, and the vertical axis represents the impulse response strength.



(a) (b) (c) (d) (e)

Figure 4. Impulse response results for different lag phases.

Note: Dotted, dashed, and solid lines indicate lags of one, two, and six periods, respectively. **(a)** Carbon price response to public concern about shocks; **(b)** Carbon price response to government carbon regulation about shocks; **(c)** Carbon price response to crude oil price about shocks; **(d)** Carbon price response to European carbon price about shocks; **(e)** Carbon price response to interest rates about shocks.

It can be seen that the three shock curves all show obvious time-varying characteristics and structural abrupt changes. In particular, the short-term shock effects are more significant and volatile compared to the medium and long term. Specifically, public concern, the degree of carbon regulation, crude oil futures price, EUA futures price and interest rate on carbon price are more significant in lag one and lag two. However, when the lag period is six, the impact is approximately 0. The peak of impulse response of carbon price to all variables is mostly in 2019. Before 2019, the impact of various factors on carbon price continued to rise, but after that, the impact of various factors showed an obvious turning point. This suggests that in recent years, carbon price have been less influenced by external factors. From the peak of impulse response, public concern and the degree of carbon regulation have the biggest impact on carbon price, followed by EUA futures price, interest rate and crude oil futures price. To be specific:

Figure 4a shows the response of carbon price to public concern is positive at the first lag and fluctuates around the value of zero at the second lag. Overall, an increase in public concern may lead to a higher carbon price. From the impulse response of the first lag, the response of carbon price to public concern has remained stable at a high level since the introduction of the carbon peak and neutrality targets, indicating that public concern has had a stable and large impact on the fluctuation of carbon price in recent years. The impulse response of the second lag fluctuates around the value of zero, indicating that this effect gradually disappears in both periods. This could be attributed to the fact that internet public opinion has a more pronounced impact on the financial market in the short term (Zhang et al., 2015).

Figure 4b shows the response of carbon price to carbon regulation is negative at lag one and positive at lag two, and the effect of lag two is higher than the impulse response at lag one in terms of the intensity of the impulse response. That's consistent with the view of Wen et al. (2022), where the impact of significant events like market performance and the formulation of relevant regulations affects carbon price. During the initial stage of the Hubei carbon market, due to the immaturity of the regulations related to the setting of the total amount of carbon quotas, the inclusion of industries in the scope, the approval of CCER projects and the proportion of offsetting emission reductions, to a certain extent, the volume of carbon emissions trading was not high and the trading price was low. With the introduction of carbon market related management measures and increased media coverage of related policies, a more transparent and scientific market mechanism has led to a certain increase in carbon price. This finding has important policy implications.

Figure 4c shows the response of carbon price to oil price is positive, peaking in 2019, and decreasing as the number of lags increases. The response of carbon price to oil price shocks decreases significantly after 2019, especially the response intensity of the lag 2 period decreases steeply and the response value approximates to 0 in 2022. The impact of crude oil prices on carbon price is obviously time-varying, and the short-term impact of crude oil price on carbon price is higher than the long-term impact (Li et al., 2023). The decrease in the response of carbon price to crude oil price may be associated with clean energy. With the extensive development and application of new energy in China, enterprises have reduced their investment in highly polluting factors of production, and the ratio of new energy use and clean energy technology has increased.

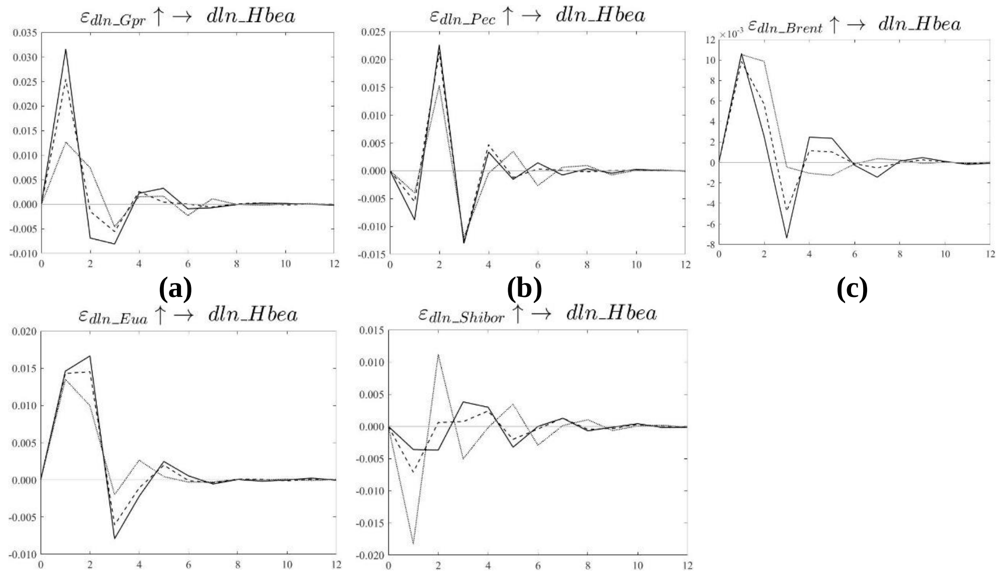
Figure 4d shows the response of Chinese carbon price to European carbon price is positive in the long run and relatively stable in general. The impulse response values of the European carbon price to the Chinese carbon price lagged by one phase and lagged by two phases are relatively similar, but the response value of lagged by two phases is slightly larger than that of lagged by one phase since 2020.

Figure 4e shows the impact of interest rate on carbon price is negative in lag one and positive in lag two, and the degree of response in lag one is greater than that in lag two, that is, interest rate has a negative impact on carbon price in general. In Yang et al.'s (2023) study, a contrasting trend in the response outcomes of lag one and lag two periods is observed, which is consistent with the findings presented here. After 2020, the response of carbon price to interest rate impact in different lag periods are all suddenly weakened.

5.4. Time-point impulse response analysis

The graphs of the impulse response results with different lags show a more obvious time-varying characteristic of the influence relationship between the variables. To further analyze the changes of public concern, degree of carbon regulation, crude oil futures price, EUA futures price, and interest rate on the carbon price in different time point models. Considering the gradual public concern to low carbon and environmental protection as well as the gradual maturity of carbon market operation, the first point in time was the promulgation of the National Carbon

Emissions Trading Market Construction Plan (Power Generation Industry) (December 2017), which marked the official launch of the construction of China's unified carbon emissions trading market system and the gradual development of China's carbon market towards standardization; the second point in time is the introduction of the carbon peak and neutrality targets (September 2020), when the public has a better understanding of carbon peaking and carbon neutrality; the third time point is the official launch of the national unified carbon market (July 2021), the carbon price is subject to a positive shock of one standard deviation for each variable, yielding the time-point impulse response results in **Figure 5**.



(a) **(b)** **(c)** **(d)** **(e)**

Figure 5. Results of the time-point impulse response.

Note: Dotted, dashed, and solid lines indicate that the shocks occur in December 2017, September 2020, and July 2021, respectively. **(a)** Carbon price response to public concern about shocks; **(b)** Carbon price response to government carbon regulation about shocks; **(c)** Carbon price response to crude oil price about shocks; **(d)** Carbon price response to European carbon price about shocks; **(e)** Carbon price response to interest rates about shocks.

It can be seen that the impulse responses of public concern, degree of carbon regulation, crude oil futures price, and EUA futures price on carbon price are roughly the same in December 2017, September 2020, and July 2021, and the impulse response values of public concern, degree of carbon regulation, and EUA futures price increase accordingly with time, and the carbon price is more vulnerable to the impact of these three. In contrast, the impulse response of crude oil futures price decreases slightly but does not change much at the three time points. There is a substantial contraction in the response of carbon price to interest rates. The peak impulse responses of carbon price to all five variables occur at lag one and lag two, again demonstrating that shocks to carbon price are more pronounced in the short run. To be specific:

Figure 5a shows the response of carbon price to public concern shock is generally positive and reaches its maximum at lag one, the impulse response in December 2017 is still positive at lag two, while the impulse response turns from positive to negative in September 2020 and July 2021, reaches a negative peak at lag three, and the response turns positive at lag four and approximates zero from lag six onwards. The similar trend in the impulse response of carbon price to public concern over time but with a substantial increase in the degree of response can also prove that public concern has increased in recent years and does produce stable and large fluctuations in the impact on the carbon price. A comparison between the two pulse curves from September 2020, when China's carbon peak and neutrality targets were proposed, to July 2021, when the national unified carbon market was officially launched, reveals that the response of carbon price to public concern has been further improved by the improvement of carbon market trading management methods and the enrichment of trading methods.

Figure 5b shows the response of carbon price to carbon regulation shocks is generally positive. The response is negative at lag one, peaks at lag two, and reaches a negative peak at lag three. The response turns positive after lag four and is essentially zero after lag five. Compared with December 2017, the impulse response of carbon price to the degree of carbon regulation is greater in July 2021. That is, with the successive introduction of carbon market-related management measures and the increasing maturity of regulations related to carbon emission accounting, financing constraints, and carbon emission allowance allocation for emission-controlled enterprises, the carbon price signals in the carbon market are more sensitive to market information. The results are similar to Zhou and Li (2019). China's carbon trading market system is still incomplete, and there are deficiencies in information disclosure, market supervision, and punishment violations. These problems have caused some of the information to be easily distorted and the information transmission was lagging behind.

Figure 5c shows the response of carbon price to crude oil price shocks is generally positive, peaking positively at lag one, decreasing at lag two, and peaking negatively at lag three. From the three different time points, the impact of crude oil price on China's carbon price has weakened, indicating to some extent that the energy dependence of China's enterprises has eased after making low-carbon transition. Similar conclusions were drawn in the study by Li et al. (2023), suggesting to some extent that Chinese enterprises have alleviated their dependence on foreign energy sources in recent years.

Figure 5d shows the response of carbon price to EUA futures price shocks is generally positive, peaking positively at two time points in December 2017 and September 2020 at lag one, at lag two in July 2021, and reaching a negative peak at lag three, turning positive at lag four and converging to zero from lag six onwards.

Figure 5e shows the overall response of carbon price to interest rate level shocks is negative, peaking in the first two lags, but compared to December 2017, the impulse response peaks in September 2020 and July 2021 have dropped significantly, fluctuating around 0 and decaying to 0 after three lags. The role of interest rate instruments in the carbon market has diminished.

5.5. Results discussion

In our comprehensive exploration of the Hubei carbon trading pilot market, we delved into the intricate interplay of factors such as public concern and carbon regulatory policies on carbon prices. While existing research has made strides in dissecting the influence of structured elements like energy and financial markets on carbon prices, our study ventures into uncharted territory, shedding light on nuanced dynamics that demand further consideration.

One noteworthy revelation from our historical trend analysis, conducted by synthesizing quantified data on monthly public concern and carbon prices, unveils a previously unexplored directional consistency in their recent trends. This novel finding challenges the prevailing literature, which has yet to address this intriguing alignment. Moreover, our scrutiny of non-structured factors, such as public awareness and carbon regulatory policies, in comparison to their structured counterparts like energy and financial factors, revealed compelling disparities in the outcomes. Over time, the impact of public concern and carbon regulatory policies on carbon prices has emerged as a more potent force than the traditional influences of energy and financial markets. Aligning with the pioneering works of Li et al. (2023), Zhang et al. (2015), Wen et al. (2022), and Zhou and Li (2019), our research consistently contributes to the evolving landscape of carbon influencing factors. Employing the state-of-the-art SV-TVP-VAR method, our study, attuned to the time-varying characteristics of the phenomena under scrutiny, produces conclusions that likely better mirror the actual unfolding scenario. Notably, our findings diverge from Deeney et al. (2016), as we posit a positive impact of carbon regulatory policies on carbon prices. This incongruity may be attributed to the intricate web of time-varying relationships and distinctions in our research parameters. Our discerning approach prompts a reconsideration of established notions, paving the way for a more nuanced understanding of the multifaceted realm of carbon pricing dynamics.

Moreover, it is essential to underscore the discernible variations in how carbon prices respond to shocks from diverse factors at different junctures. This phenomenon is intricately tied to the phased evolution of the Chinese carbon market, a facet that has not been adequately addressed in the existing literature. The construction of this market unfolded in two pivotal stages, each bearing distinct objectives and outcomes. The inaugural stage was predominantly geared towards establishing the foundational institutional framework of the national carbon market. This encompassed the completion of crucial tasks such as formulating national carbon market management measures, quota allocation schemes, and a comprehensive array of regulations and technical specifications crucial for the smooth operation of the carbon market. Transitioning into the second stage, the focus of the Chinese carbon market's development shifted towards the power generation industry, with the overarching goal of realizing the operationalization of a national-level carbon market. This strategic approach has positioned the Chinese carbon market as the preeminent global carbon market, attaining the status of the world's largest (Weng and Xu, 2018). In contrast to the existing literature, exemplified by Li et al. (2023), which acknowledged the potential influence of time-varying factors on carbon price fluctuations but predominantly concentrated on events such as volatile crude oil prices and the global COVID-19 pandemic, our research delves into uncharted territory. Specifically, we illuminate the nuanced discussion surrounding the phased development of the Chinese carbon market, filling a conspicuous gap in the current body of knowledge. Drawing on the findings of our study, the maturation of the Chinese carbon trading market system in crucial areas such as information disclosure, market regulation, and penalty enforcement plays a pivotal role in mitigating issues related to distorted carbon price signals and delayed information transmission (Zhou and Li, 2019). This progress not only addresses structural deficiencies but also, to a significant extent, amplifies the impact of public awareness on carbon prices. Consequently, it engenders a more authentic and responsive behavior of carbon prices to public concerns, underscoring the intricate interplay between market development and societal awareness in shaping the dynamics of carbon pricing.

To sum up, our theoretical contribution lies in the innovative methodologies employed to gauge the degree of carbon regulation and public concern. By integrating policies, news reports, Baidu search index, and microblog texts, we not only quantified the impact of regulatory measures but also delved into the emotional dimensions of public sentiments. This holistic approach offers a richer understanding of the multifaceted influences on carbon prices, surpassing conventional models. This temporal analysis, combined with the examination of short-term shock effects, adds a layer of sophistication to our understanding of the intricate dynamics of carbon prices. Furthermore, our study emphasizes the temporal evolution of factors, moving beyond static analyses that overlook the dynamic nature of the carbon market. The identification of precursors in the form of unprecedented surges in public concern and the promulgation of carbon regulatory policies provides a blueprint for understanding future fluctuations in carbon prices. This temporal sensitivity adds depth to the theoretical frameworks governing carbon price dynamics.

On a practical level, our research offers actionable insights for a diverse range of stakeholders. First, investors stand to benefit from recognizing the significant time variability in the impact of various factors on carbon prices. The integration of fluctuation information can empower investors to anticipate carbon price shifts, enabling them to establish more rational investment portfolios and mitigate extreme risks. High-energy-consuming enterprises, in particular, can leverage these insights to optimize energy structures and reduce production costs effectively. Second, the government intervention emerges as a critical aspect, with a focus on low-carbon production and enterprise development through the introduction of restraint and incentive policies. The effective implementation of these policies hinges on stringent supervision and regulatory systems. Governments play an active role in shaping carbon prices through measures such as setting total carbon quotas, penalty systems for exceeding emissions, and the provision of certifiable emission reductions.

Third, the proliferation of internet use as a platform for expressing dissatisfaction with environmental pollution underscores the need for emission-controlling enterprises to align with public sentiment. The correlation between public concern and carbon prices, especially under government-led low-carbon advocacy, emphasizes the importance of staying attuned to both policy directions and public demands for environmental responsibility.

Fourth, our findings shed light on the persistent challenge of centralized trading in China’s carbon market. As the future sees a tightening of carbon allowance allocations, emission control enterprises must proactively manage carbon allowances to mitigate risks associated with price fluctuations. This entails reducing dependence on carbon allowances, making informed corporate decisions, and enhancing the effectiveness of emission reduction strategies.

5.6. Robustness checking

We review our main conclusions again and discuss the robustness check to test the robustness of our main results for the replacement efficiency measure.

Specifically, we determined that the optimal lag order of the model is 2nd order, and the number of MCMC sampling times is 20,000. We selected lags of two, four, and eight periods to construct equal-spaced impulse responses. We changed the data frequency and used quarterly data instead. Monthly data are used for robustness testing. The results are shown in **Figure 6**. The convergence diagnostic value of the parameter estimation results cannot reject the null hypothesis of convergence of the estimation results at the 5% significance level. All invalid factors are at low levels, indicating that the parameter estimation results are reliable. From the second lag period, we can find that public attention and government carbon regulations still have a significant positive impact on carbon prices, and their impulse response shows an increasing trend, while the fourth and eighth lag periods The impulse response of the period has gradually converged in recent years. Compared with the baseline model, the robustness test results of the impact of public attention and government carbon regulations on carbon prices are more time-varying. The results of TVP-SV-VAR estimation are shown in **Figure 6**. The trends in response trajectories for efficiency and liquidity are similar to those in the main empirical studies (absolute averages). These results are consistent with our main conclusions drawn above and confirm that our results are reliable.

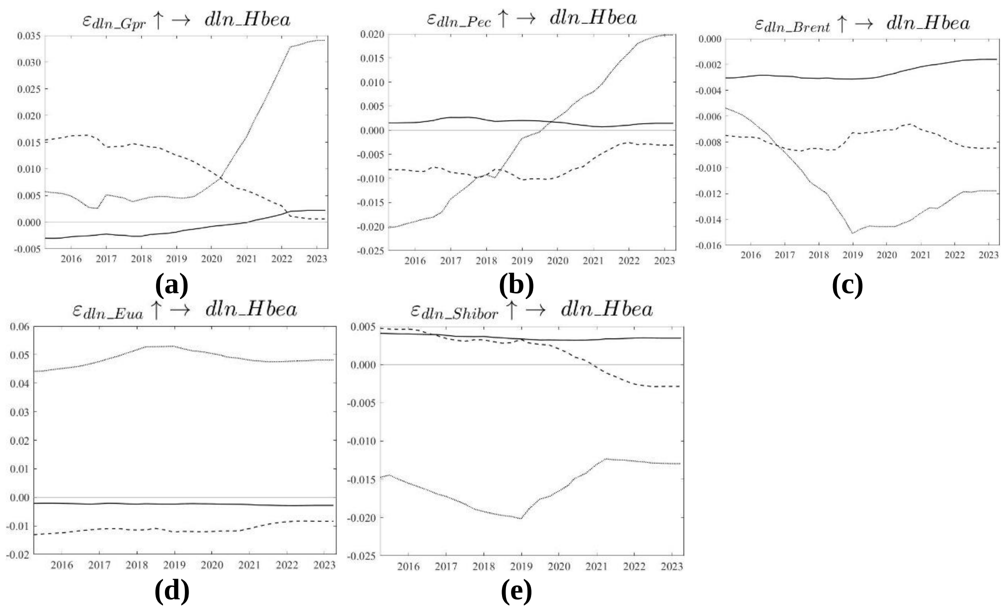


Figure 6. Robustness test of TVP-SV-VAR model.

Note: The dotted line, dotted line, and solid line represent lags of two, four, and eight periods respectively. **(a)** Carbon price response to public concern about shocks; **(b)** Carbon price response to government carbon regulation about shocks; **(c)** Carbon price response to crude oil price about shocks; **(d)** Carbon price response to European carbon price about shocks; **(e)** Carbon price response to interest rates about shocks.

6. Conclusion

In our research, the comprehensive exploration of the intricate dynamics influencing carbon prices provides a nuanced understanding of the evolving landscape in China's carbon market. The multifaceted factors, including public concern, carbon market policy design, energy price changes, financial market situations, and macroeconomic trends, collectively shape the complex correlations between variables. The endeavor to measure the degree of carbon regulation through policies, news reports, and innovative methods involving the Baidu search index and microblog texts has allowed us to construct robust indicators reflecting public sentiments toward low carbon advocacy, environmental regulation, and pollution prevention. Our study unveils a temporal consistency with the actual operation of carbon prices in Hubei, China, offering a comprehensive depiction of carbon market volatility. The construction of an SV-TVP-VAR model, encompassing six key variables, facilitates an in-depth examination of the time-varying effects of each factor on carbon prices.

The results exhibit clear time-dependent characteristics, emphasizing the significance of short-term shock effects compared to the medium and long term. The impact analysis reveals a noteworthy shift in the factors influencing carbon prices. Prior to 2019, carbon regulation policies and European carbon prices held sway, indicating imperfections in China's carbon market management during that period. The subsequent years, however, witnessed a transformation with public concern and the degree of carbon regulation emerging as primary influencers, followed by European carbon prices, interest rates, and the Shanghai Interbank Offered Rate. Carrying out project cooperation through the CDM, as well as learning advanced management experience and models from the European carbon market, and supplementing and improving the trading mechanism of China's carbon market can alleviate the problems of inactive trading behaviours and low trading prices that exist in China's carbon market.

The sustained high impact of public concern on carbon prices post the introduction of carbon peak and neutrality targets underscores the pivotal role of public awareness in environmental protection, low carbon advocacy, and the advancement of carbon market management mechanisms. Notably, the evolving energy market in China, marked by reduced dependence on external oil due to the development and application of new energy sources, adds a layer of complexity to the analysis. Despite this, interest rates emerge as the sole factor exerting a negative impact on carbon prices, a trend further accentuated during the COVID-19 pandemic. Despite repeated stimulus signals from the market in the form of interest rate and interest rate cuts, companies are likely to remain cautious about making additional investments. Overall, among the many factors influencing the carbon price, non-structural influences like public concern and government carbon regulation are trending upwards, while the influence of non-structural factors is levelling off or declining.

Acknowledging the practical limitations inherent in our study, including the constrained number of variables in the SV-TVP-VAR approach, limitations on the dimensions of the influencing factors assessed, insufficient discussion of the dynamic process of interaction between carbon prices and influencing factors, and the challenge of finely distinguishing between public concern and the extent of carbon regulation—especially within the scope of our current research efforts—we employ a relatively "broad" expression. It is noteworthy that despite these challenges, the empirical results obtained thus far are indeed gratifying, affirming the reliability of our research outcomes and paving the way for future investigations. To delve deeper into the intricate dynamics of carbon price fluctuations, further empirical research is essential. This could involve a nuanced examination of how specific public concerns and carbon regulations impact carbon trading prices. This might be achieved by dissecting carbon regulations and dissecting issues of public concern, or by employing advanced research methods, mechanisms, and risk mitigation strategies. Furthermore, as the Russo-Ukrainian war and the Palestinian-Israeli conflict continue to evolve, the lasting impact of factors like energy shocks and commodity trade on the macroeconomy remains a subject deserving of continued attention. The study advocates for ongoing exploration of indicators such as natural gas prices, yuan exchange rates, and weather conditions to enrich our understanding of the evolving dynamics within China's carbon market.

Author contributions: Conceptualization, FH and YL; methodology, YL; software, XW; validation, FH, YL, XW and DLC; formal analysis, YL; investigation, FH; resources, FH; data curation, YL; writing—original draft preparation, YL; writing—review and editing, FH; visualization, YL; supervision, FH; project administration, DLC; funding acquisition, FH. All authors have read and agreed to the published version of the manuscript.

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