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Natural Gas–Electricity Price Linkage Analysis Method Based on Benefit–Cost and Attention–VECM Model

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Abstract: In recent years, frequent linkage events of natural gas and electricity prices have seriously affected the stability of the energy supply market. In view of the increasingly close linkage relationship between gas and electricity prices, a gas–electricity price linkage analysis method considering the benefit–cost and price transmission of gas units is proposed. Firstly, a benefit–cost model of gas units based on risk premium theory is constructed to reflect the willingness of gas units to offer prices in different market environments. Secondly, a vector error correction model (VECM)-based gas–electricity price conduction analysis method was proposed to study the long-term co-integration relationship between gas–electricity prices and the short-term fluctuation conduction process. Then, aiming at the problem of delay in price transmission, a time-delay analysis method of gas–electricity price based on the attention mechanism is proposed. Finally, the gas price index and average gas power price data of China from August 2020 to November 2022 are used to verify the validity of the proposed model; the numerical results show that the proposed method can determine the long-term stable fitting relationship between gas and electricity prices, and can also analyze and judge the conduction direction of gas and electricity price fluctuations in different time periods.

Keywords: gas–electricity price linkage; gas unit; benefit–cost model; vector error correction model; co-integration expression; attention mechanism

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1. Introduction

In the context of the increasingly serious global energy crisis and the increasing importance of energy security, natural gas, as an important energy in the process of power system transformation, is of great significance in promoting the development of the power market [1]. According to the statistics of the International Energy Agency, the global demand for natural gas in 2021 has grown rapidly, the supply of the natural gas market has increased by 134 billion cubic meters compared with 2020, the demand ratio has increased by 140 billion cubic meters, and the gap between supply and demand has reached 31 billion cubic meters. The spot price of liquefied natural gas in Northeast Asia, JKM (Japan Korea Marker, JKM), and European Dutch natural gas prices hit record highs above $40/mmBtu; in 2022, the supply and demand of the global natural gas market is still tight, with the gap widening to 36 billion cubic meters [2]. Since the outbreak of the Ukraine crisis, the global natural gas trade pattern has been reshaped, and the natural gas price has soared. The European benchmark liquefied natural gas price once rose to 100 dollars per million British thermal units. The price of JKM soared to more than $80 per million British thermal units, causing a huge shock to the energy market, especially the electricity market [3]. In addition, recent crises such as soaring electricity prices in California and Texas and soaring natural gas prices in Europe are all related to gas–electricity price transmission. The price fluctuation is transmitted through the substitution effect of electricity and natural gas [4], which intensifies the volatility and uncertainty of gas price and electricity price [5,6].

Therefore, it is of great practical significance to study the linkage relationship between gas and electricity prices (gas–electricity price for short) [7].

At present, there are few analyses on the linkage between gas price and electricity price around the globe, and the research on price transmission mainly focuses on the price of coal and electricity. Most U.S. states and Japan adjust fuel prices and end-sale electricity prices directly on a monthly or quarterly basis, so fluctuations in coal prices are transmitted to end-users, avoiding the problem of blocked transmission of coal and electricity prices. Compared with the United States and Japan, China adjusts electricity coal price, online electricity price, and sales electricity price on an annual basis, which can ensure the stability of residential electricity price, but is not conducive to the transmission of coal price fluctuations [8,9]. In our country, there are three problems, such as excessively long interaction cycle and hysteresis, blocked price transmission, and electric coal price index and unmatching benchmark online power price [10]. Existing studies on gas–electricity price linkage mainly analyze the income of natural gas units and the pricing mechanism of natural gas power generation [11,12]. The input–output price model, break-even model, and equal-calorific-value direct cost model are constructed to analyze the income of units under different market environments and calculate the prices of various natural gas users and the corresponding affordability of gas prices when the break-even point is reached, providing a theoretical basis for gas price adjustment and reform [13–15]. Among them, reference [16] focuses on the price mechanism of domestic gas consumption. Considering the upstream and downstream price block of the natural gas industry in the linkage of gas–electricity prices [17], it proposes the basic ideas and specific pricing schemes to optimize and perfect the pricing mechanism of natural gas power generation [18], and studies the equilibrium of the gas–electricity market [19]. References [20–23] mainly analyze the operating mechanism and price conduction relationship of the foreign natural gas market and electric power market, and provides a reference for our natural gas and electric power marketization reform. It can be seen from the above literature that the existing research on gas–electricity price linkage as made a relatively comprehensive analysis of the income situation of gas units and the pricing mechanism of natural gas power generation, but has not considered the pricing behavior of gas units in the market, and lacks a quantitative analysis on the time lag of gas–electricity price linkage and the consideration of the change in the strength of the correlation degree of gas–electricity prices.

VAR and VECM models are relatively mature economic models to study the linkage relationship between prices, which are widely used in important fields such as energy, economy, transportation, and medicine [24]. Reference [25] studies how to use the VAR model to conduct a co-integration test among variables and further analysis to obtain the lag order. Reference [26] constructs the VAR model to prove that there is a long-term stable co-integration relationship between natural gas price and electricity price in the UK. Considering that most time series are not stationary, relevant scholars further proposed the VECM model based on the VAR model [27]. Reference [28] studies the short-term and long-term conduction relationships between variables based on the VECM model and machine-learning algorithm. Reference [29] constructs the VECM model to predict fuel prices, which proves that the long-term equilibrium relationship of fuel futures prices is helpful in improving the forecasting accuracy. Reference [30] adopts the co-integration test and VECM model to study the relationship between investment, international trade, and economic growth, and the causality test is further adopted. In reality, the coupling relationship between price variables is complex and the price transmission has a time lag. The VAR and VECM models can obtain the lag order, but the results are not accurate enough and cannot reflect more information about the time delay. The attention mechanism can analyze the correlation of historical price data information and establish dynamic weight parameters. The time delay of price transmission is measured according to the weight of time information between price variables [31,32].

This paper aims to quantitatively analyze the linkage relationship between natural gas price and electricity price in a certain province of China, and study the time lag of gas–

electricity price transmission. Firstly, the benefit–cost model of the gas unit is established to analyze the price changes of the natural gas market and electricity market, respectively. Secondly, based on the VECM model in econometrics, the gas–electricity price linkage relationship is studied from the static co-integration function expression and the dynamic price fluctuation response process. Then, the attention mechanism is used to calculate the delay weeks of the historical gas price to the current electricity price. Finally, the natural gas and electricity market in China is taken as an example to verify the rationality and validity of the proposed analysis method.

The paper is structured as follows: Section 2 studies the benefits and costs of natural gas units, and then it provides the basis for studying the tendency of the natural gas unit quotation. Section 3 builds the gas–electricity price linkage model and makes a comprehensive calculation and analysis of the linkage between gas and electricity prices. Section 4 calculates the delay of price conduction based on the attention mechanism. Section 5 makes an empirical analysis. Section 6 analyzes and summarizes this study.

2. Gas–Electricity Price Linkage Analysis Method Based on Benefit–Cost Model of Gas Unit

2.1. Revenue Model of Gas Unit

For the gas unit, when its own income is lower than its own comprehensive cost, the power generation willingness of the unit is low, and it may adopt a negative quotation strategy, which is embodied in the high price or even the ceiling price at the time of clearing. By constructing the benefit–cost model of the gas unit, the quotation behavior of the gas unit in different time scales can be analyzed, and the effective market information can be provided for each entity of the gas–electricity market.

The income R^i of the gas-generating unit in the electricity energy market can be divided into two parts: income R_1^i from electricity sales and income R_2^i from generation compensation.

The income R_1^i from the sale of gas unit i in the electricity market is:

$$R_1^i = \sum_{t=1}^{S} (E_{i,t} P_{i,t}) \tag{1}$$

where S is the total time period; $E_{i,t}$ is the bid-winning electric quantity of unit i in time period t; and $P_{i,t}$ is the node marginal electricity price at time period t.

The winning unit will receive additional generation compensation income in addition to electricity sales income, which can be expressed as:

$$R_2^i = \sum_{t=1}^{S} (E_{i,t} M_{i,t}) \tag{2}$$

where R_2^i represents the total compensation income obtained by unit i due to power generation; $M_{i,t}$ represents the compensation income coefficient of each kilowatt-hour corresponding to the time period t of unit i.

To sum up, the total revenue R^i of the gas unit is:

$$R^i = R_1^i + R_2^i \tag{3}$$

2.2. Cost Model of Gas Market for Gas-Generating Units

The cost C^i of the gas unit in the natural gas market can be divided into spot market electricity purchase cost C_1^i and annual bilateral negotiation contract cost C_2^i.

Suppose that the gas purchased by the unit in the spot market at the t time period is $Q_{i,t}^{sp}$, and the kilowatt-hour fuel cost is $f_{i,t}$; then, the cost C_1^i of the unit in the spot market of natural gas is:

$$C_1^i = \sum_{t=1}^{S} Q_{i,t}^{SP} f_{i,t} \tag{4}$$

The kilowatt-hour fuel cost $f_{i,t}$ of the unit at time t is expressed as:

$$f_{i,t} = \frac{P_{Gas,t}}{(1-\xi_i)b_{Gas,i}}\delta \tag{5}$$

where $P_{Gas,t}$ is the gas price of the gas unit at time period t; $b_{Gas,i}$ is the electrical generation consumption rate of unit i; ξ_i is the power consumption rate of unit i; and δ is the conversion coefficient.

Given the sharp volatility of electricity and natural gas prices, gas units hope to realize hedging strategies through medium- and long-term contracts. At present, there are two theories about the relationship between spot price and futures price: the warehousing theory and risk premium theory. The former considers the cost and convenience of goods holding inventory, while the latter deduces the relationship between short-term and long-term prices based on the spillover effect of price fluctuations and other methods. Combined with the actual situation of the natural gas commodity and market, this paper analyzes the corresponding relationship between futures price and spot price according to the risk premium theory, and its expression is as follows:

$$P^F_{t-T,t} = E_{t-T}(P^S_t)e^{(r_T - i_T)} = E_{t-T}(P^S_t)e^{-p_T} \tag{6}$$

where T is the time difference between the signing of the natural gas futures contract and the actual delivery; $P^F_{t-T,t}$ is the delivery price of natural gas futures signed under time period $t-T$ at time period t; $E_{t-T}(P^S_t)$ is the expected value of natural gas spot price P^S_t at time period $t-T$; i_T is the appropriate discount rate for investors to invest in futures contracts; and r_T is the risk-free rate.

If too many producers in the futures market want to avoid risks and hedge their products, the futures price may be lower than the expected future spot price, that is, $p > 0$. When the demand side is unwilling to take risks, the opposite situation will occur, that is, $p < 0$.

The futures cost of the unit needs to consider time value, interest, risk, and other factors; thus, it can be expressed as:

$$C^i_2 = \sum_{t=1}^{S} Q^{FP}_{i,t} E_{t-T}(P^S_t) \tag{7}$$

where $Q^{FP}_{i,t}$ is the gas consumption of futures contract at time period t.

To sum up, the total cost C^i of the gas unit is:

$$C^i = C^i_1 + C^i_2 + C^i_3 \tag{8}$$

where C^i_3 is the reduced fixed cost of the unit. For unit i, if the income it can obtain in the total time period S is lower than its own comprehensive cost ($R_i - C_i < 0$), the willingness of unit i to generate electricity decreases, and the probability of the market behavior of offering a high price or even the top price increases.

3. VECM-Model-Based Gas–Electricity Price Linkage Analysis

The VAR model is an econometric model that uses the vector autoregressive method to analyze a system composed of various interrelated factors. It has been widely used in important fields such as economy, transportation, medicine, and the chemical industry [24]. The specific expression of the VAR model in the analysis of gas–electricity price linkage is as follows:

$$\begin{bmatrix} Y_t \\ X_t \end{bmatrix} = \varepsilon_t + \phi_0 + \sum_{i=1}^{p} \phi_i \begin{bmatrix} Y_{t-i} \\ X_{t-i} \end{bmatrix} \tag{9}$$

where Y_t is the time series of electricity price; X_t is the gas price time series; ε_t is the perturbation column vector of the model; ϕ_0 is the column vector composed of constant terms in the regression equation; p is the lag order of the gas–electricity price VAR model; ϕ_i is the coefficient matrix between gas price and electricity price and lag term data; and $t = 1, 2, \ldots, T$, where T is the total number of days for collecting price data.

The premise of using the VAR model is that the time series is stationary. Most time series in reality do not meet the requirement of stationarity, so the VECM model is usually used in the study of price transmission. The VECM model is a VAR model with co-integration constraints, which is mostly used for non-stationary time-series models with co-integration relations. The expression of the VECM model is as follows:

$$\begin{bmatrix} \Delta Y_t \\ \Delta X_t \end{bmatrix} = \varepsilon_t + \theta_0 + \sum_{i=1}^{p-1} \theta_i \begin{bmatrix} \Delta Y_{t-i} \\ \Delta X_{t-i} \end{bmatrix} + \Gamma \begin{bmatrix} Y_{t-1} \\ X_{t-1} \end{bmatrix} \tag{10}$$

where ΔY_t is the first-order difference term of the electricity price time series; ΔX_t is the first-order difference term of the gas price time series; θ_0 is a column vector of order 2; θ_i is a 2×2 matrix; and Γ is compression matrix.

VECM is essentially a constrained VAR model with a co-integration constraint in explanatory variables. When a large range of short-term fluctuations occurs, VECM will make endogenous variables converge to their long-term co-integration relationship [33]. Compared with other methods, the VECM model treats both gas price and electricity price as endogenous variables, thus reducing the uncertainty of simultaneous equations caused by subjective judgment errors. In addition, the expression of a static and stable co-integration relationship between gas and electricity prices and the transmission mechanism of dynamic price fluctuations can be obtained through the VECM model. The specific research methods can be divided into the stationarity test, co-integration test, Granger causality test, and dynamic characteristic analysis.

When constructing the VECM model and conducting research, it is necessary to conduct the stationarity test first to ensure that there will not be two invalid results of a negative model coefficient and pseudo regression in the research.

Most of the time series actually obtained cannot meet the requirements of stationarity in a strict sense. Therefore, the co-integration test should be conducted again after the stationarity test to ensure the existence of a stable co-integration relationship between gas price and electricity price, which meets the requirements of further research. In addition, in order to make the model more accurate, it is necessary to carry out the unit root test on the residual sequence in the co-integration test.

The co-integration test can obtain the long-term stable functional relationship between electricity price and gas price, while the Granger causality test can further judge the sequential relationship between gas price and electricity price in time. It should be noted that the result obtained by the Granger causality test is not a causal relationship of practical significance.

Each research method is described in detail below.

3.1. Gas–Electricity Price Stability Test

The analysis of the linkage relationship between gas and electricity prices requires the stationarity test of the data to ensure that the data meet the requirements of the VAR model test. Considering that there may be collinearity and heteroscedasticity in the gas–electricity price time series, it is necessary to clean the original data first, and let the processed natural gas and electricity price time series be X_t and Y_t, respectively.

Taking the stationarity test of power price time series Y_t as an example, the given regression equation of electricity price is:

$$Y_t = kY_{t-1} + \varepsilon_t \tag{11}$$

where k is the regression coefficient and ε_t is the error term.

The electricity price at time t can be expressed by historical data:

$$Y_t = k^n Y_{t-n} + \sum_{i=0}^{n-1} \varepsilon_{t-i} k^i \tag{12}$$

If $k = 1$, the variance of the electricity price time series in (11) will continue to increase, and the influence of residual ε_{t-i} cannot be eliminated, which will lead to the instability of the series. Therefore, $k = 1$ is called the unit root of the electricity price time series. The augmented Dickey–Fuller (ADF) test method can be used to determine whether there is a unit root in (11), so as to determine whether the time series of electricity price is stable.

Similarly, the same stationarity test should be conducted for gas price time series X_t.

3.2. Gas–Electricity Price Co-Integration Test

After the stationarity test, the linkage relationship of the gas–electricity price time series can be further analyzed. When there is a stable internal mechanism between gas price and electricity price, the gas price or electricity price can still maintain a stable equilibrium state even if there are short-term fluctuations. In order to directly reflect this equilibrium state, the co-integration test of the gas–electricity price can be carried out to reflect the linkage relationship of gas–electricity price in the form of a co-integration expression. The co-integration test mainly involves the following two steps:

First, the ordinary least squares (OLS) method is used to estimate the gas–electricity price fitting equation and calculate the corresponding residual value:

$$Y_t^* = a^* X_t + b^* \tag{13}$$

$$e_t = Y_t - Y_t^* \tag{14}$$

where a^* and b^* are the optimal parameters obtained by fitting; Y_t^* is the estimated electricity price; and e_t is the residual difference between the real value and the predicted value of electricity price.

Second, the stationarity of e_t is tested. If e_t is a stationary series, it is considered that there is a co-integration relationship between gas price and electricity price. In this case, there is no pseudo-regression problem in the equation obtained by regression.

3.3. Granger Causality Test of Gas–Electricity Price Based on VECM Model

In the VAR model, the Granger causality test is typically used to assess the temporal relationship between gas price and electricity price after performing a co-integration test. However, Granger causality tests require stable time series data, and direct testing of unstable data can lead to false regressions. The processed variables in the VECM model have stable characteristics and meet the necessary conditions for Granger causality tests, ensuring the accuracy of the results. Therefore, a VECM-model-based Granger causality test can be used to analyze variables $\Delta \ln Y_t$ and $\Delta \ln X_t$. It should be noted that the results obtained from the Granger causality test do not necessarily establish causality in a practical sense, but they can provide valuable insights for further causal analysis. For instance, considering the test of the first-order lag model "whether gas price $\Delta \ln X_t$ causes changes in electricity price $\Delta \ln Y_t$", the initial assumption is that "gas price $\Delta \ln X_t$ does not cause changes in electricity price $\Delta \ln Y_t$", and the specific steps are as follows:

(1) Estimate the unconstrained regression model (u) and the constrained regression model (r) of electricity price Y_t, respectively:

$$u:\ \Delta \ln Y_t = \phi_{11}(1) \Delta \ln Y_{t-1} + \phi_{12}(1) \Delta \ln X_{t-1} + \varepsilon_{1t} \tag{15}$$

$$r:\ \Delta \ln Y_t = k \Delta \ln Y_{t-1} + \varepsilon_{1t} \tag{16}$$

The estimation coefficients $\hat{\phi_{11}}(1)$, $\hat{\phi_{12}}(1)$, and $\hat{k}$ of Equations (14) and (15) are calculated, respectively. Then, the residual sum of squares of the model is obtained according to Equations (16) and (17) and the F statistic is constructed:

$$RSS_u = \sum_{i=1}^{T} \left(\Delta \ln Y_t - \hat{\phi_{11}}(1)\Delta \ln Y_{t-1} - \hat{\phi_{12}}(1) \ln X_{t-1} - \varepsilon_{1t}\right)^2 \tag{17}$$

$$RSS_r = \sum_{i=1}^{T} \left(\Delta \ln Y_t - \hat{k}\Delta \ln Y_{t-1} - \varepsilon_{1t}\right)^2 \tag{18}$$

$$F = \frac{(RSS_r - RSS_u)/p}{RSS_u/(n-k)} \sim F(p, n-k) \tag{19}$$

where $k = 2p$. In this paper, the lag order is order 1, so $p = 1$ and $k = 2$.

According to the statistical results, the original hypothesis "gas price $\Delta \ln X_t$ is not the reason for the change of electricity price $\Delta \ln Y_t$" can be judged. If $F < F_\alpha(p, n-k)$, it is believed that "gas price $\Delta \ln X_t$ is not the reason for the change of electricity price $\Delta \ln Y_t$" on the premise that the significance level is α; otherwise, reject the null hypothesis.

(2) Change the sequence of causality between gas price and electricity price, and use the same method in (1) to test.
(3) If the test results both reject "gas price is not the reason for the change of electricity price" and accept "electricity price is not the reason for the change of gas price", it can be concluded that "gas price is the Granger cause of electricity price".

The results of the Granger causality test can be compared with the actual supply and demand of the gas and electricity market to verify the accuracy of the results.

4. Time-Lag Analysis of Gas–Electricity Price Based on Soft Attention Mechanism

The linkage between gas and electricity prices is complex, so electricity price reflects gas price fluctuations with a time lag, and the attention mechanism can assign a weight value of influence on current electricity price according to each historical gas price, namely, attention weight value. The delay time of gas price conduction to electricity price can be judged according to the value of the attention weight. Attention mechanisms can be divided into hard attention and soft attention [34]. The hard attention mechanism assigns a weight value of 0 or 1 to the historical gas price, while the soft attention mechanism assigns a weight value of [0, 1], which is more flexible and more in line with the actual situation. Therefore, the soft attention mechanism is used in this paper to calculate the influence weight value of the historical gas price on current electricity price.

The attention mechanism can calculate the attention weight value of the gas price at each time node to current electricity price y_t according to electricity price Y_t and gas price X_t; the specific expression is:

$$\alpha_i = \frac{e^{-x_i}}{\sum\limits_{i=t-k+1}^{i=t} e^{-x_i}} \tag{20}$$

where α_i is the weight value of the attention of gas price x_i to current electricity price y_i, and $\sum\limits_{i=t-k+1}^{i=t} e^{-x_i} = 1$; considering that the gas price with a relatively long time has a small influence on the current electricity price, and this paper determines the transmission delay of gas–electricity price through the relative size of the attention weight value, it is necessary to estimate and determine an appropriate time period k and analyze some historical data.

a_i obtained from the analysis of Equation (21) is the weight value of the gas price in one day, and the weight value of weekly scale A_j can be further obtained through summation:

$$A_j = \sum_{m=t-7\times(j-1)}^{t-7j+1} a_m \tag{21}$$

where A_j is the weight value of the week j, and the delay time of gas–electricity price conduction can be judged according to the weight value.

5. Case Studies

This paper focuses on the linkage relationship between gas and electricity prices in China. Empirical data are derived from the Northeast Asia JKM natural gas price index of some months from August 2020 to November 2022 and the average price data of gas power generation in the spot market published by Power Trading Center (the spot market of electricity is not open in some months).

5.1. Analysis of Benefit–Cost Model of Gas Unit

As shown in Figure 1, from March to July 2022, when the spot market of electricity is open, the JKM price index affects the declaration of gas engine price by linking it with gas price, and the fluctuation trend of gas price and electricity price is the same. Since September, cities in northern China have been gradually taking heating measures. In order to ensure the supply of natural gas to the north, the supply of natural gas engines has been strained. Therefore, the JKM price index and the unit price fluctuate in an inconsistent trend, and the correlation is weakened.

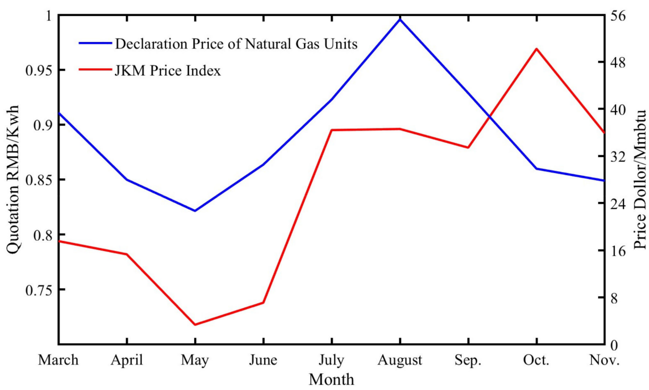

Figure 1. JKM price index with gas unit quotes.

Figure 2 shows the variation of kilowatt-hour cost with the JKM price index and the average kilowatt-hour revenue of gas units in 3 months according to the benefit–cost model of gas units from March to May 2022. On the whole, the kilowatt-hour cost fluctuates with the increase of the JKM price index. According to the JKM price index of three months in Figure 1, the average kilowatt-hour cost in March was 0.794 yuan/kWh, significantly higher than the average kilowatt-hour income of 0.706 yuan/kWh. The average kilowatt-hour cost in April is 0.772 yuan/ kWh, which is slightly different from the average kilowatt-hour income of 0.759 yuan/ kWh. The average kilowatt-hour cost in May is 0.712 yuan/kWh, lower than the average kilowatt-hour income of 0.727 yuan/kWh, so the proportion of high capacity of gas units in March should be significantly higher than that in April and May. Figure 3 shows the actual quoted capacity of gas units from January to May 2022. It can be seen that the average daily high price capacity of gas units accounted for 42% in March, 26% in April, and 28% in May, which is in line with the expected results.

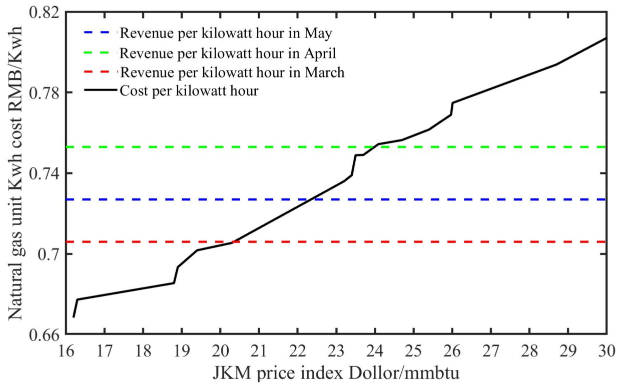

Figure 2. The relationship between average kilowatt-hour income and kilowatt-hour cost with JKM price index in March, April, and May 2022.

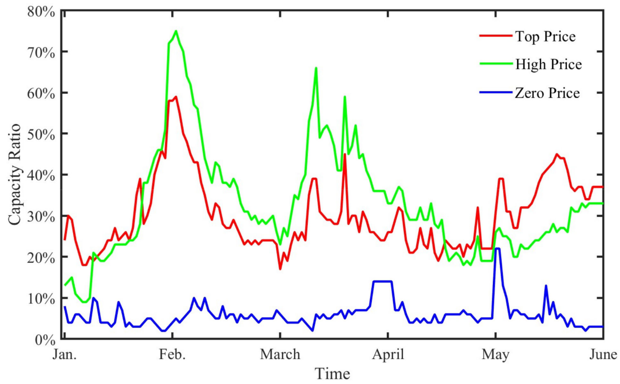

Figure 3. The quoted capacity ratio of gas units from January to May 2022.

5.2. Analysis of VECM Model of Gas–Electricity Price

As shown in Figure 1, gas–electricity prices from March to July 2022 have a strong correlation, so the VAR model focuses on analyzing the gas–electricity price linkage in the above time periods. It should be noted that the gas price X and electricity price Y studied are the data obtained from the original data after cleaning, normalization, logarithm, and other preprocessing.

First, gas price $\ln X_t$ and electricity price $\ln Y_t$ and their difference sequences are tested for stationarity, and the results are shown in Table 1. It can be seen from Table 1 that both the statistical probabilities of the original time series $\ln X_t$ and $\ln Y_t$ of gas price and electricity price at the significance level of 5% are greater than 0.05, indicating that the time series is not stable, and it is necessary to determine whether the VECM model can be analyzed according to the stationariness test results of the first-order difference series. The first-order difference sequences $d \ln X_t$ and $d \ln Y_t$ are tested as stationary sequences, so they can be further studied.

Table 1. Gas–electricity price time series stability test results.

Sequence of Variables	ADF Test Value	Statistical Probability at the Significance Level of 5%	Inspection Result
$\ln X_t$	0.686	0.8626	Unstable
$\ln Y_t$	−2.519	0.3185	Unstable
$d \ln X_t$	−10.489	0.0000	Stable
$d \ln Y_t$	−12.815	0.0000	Stable

Furthermore, the results of the co-integration test can be obtained, as shown in Equation (22) and Table 2.

$$\ln Y_t = 0.9404 \ln X_t + 2.3983 + ecm \tag{22}$$

Table 2. Test results of gas–electricity price time series co-integration test.

Equation Coefficient	Optimal Parameter Value	*t*-Test Value	Statistical Probability
a	0.9404	17.2245	0.0000
b	2.3983	43.1492	0.0000

According to the numerical results, the co-integration relationship between gas prices and electricity prices can be expressed as: the unit root test shows that the error term ecm satisfies the stationarity assumption, implying a stable co-integration relationship. The goodness of fit $R^2 = 0.7036$ of the co-integration expression indicates a strong correlation between the two variables, and the fitted values are of practical significance. Moreover, the statistical significance level of the residual errors is less than 0.05, suggesting that the series is stable and there exists a stable equilibrium relationship between gas price and electricity price. Specifically, a 1% increase or decrease in gas price will lead to a 0.9404% increase or decrease in electricity price.

Once the co-integration relationship between variables is determined, a vector error correction model can be developed to verify their mutual adjustment rate and short-term interaction effects, and examine the causal relationship between them. The error correction term Coint Equation (1) represented in Table 3 reflects the short-term adjustment to long-term equilibrium. The outcomes demonstrate that Coint Equation (1) is negative, indicating that there is an error correction mechanism between gas and electricity prices, which stabilizes the short-term fluctuations and ultimately maintains the equilibrium relationship. It can be seen from the first column of Table 3 that the price of natural gas has a significant positive impact on the electricity price in the short term because the energy price directly impacts the spot market of electricity. Consequently, the rise in the price of natural gas leads to an increase in the power generation cost of gas-burning units, resulting in a corresponding increase in the electricity price. From the second column of Table 3, it is evident that the electricity price has a positive impact on the gas price at the 10% confidence level. This is because the increase of electricity price will increase the price of energy commodities to some extent. Despite the presence of a long-term stable co-integration relationship between gas and electricity prices, short-term price fluctuations still affect their respective markets. Therefore, market players need to pay close attention to the linkage between gas and electricity prices.

Table 3. Vector error correction model estimate results.

Error Correction Term	$d\ln Y_t$	$d\ln X_t$
Coint Equation (1)	−0.4218 (0.1941)	−0.1082 (0.1136)
$d\ln Y_{t-1}$	−0.0782 (0.2151)	1.3195 (0.0835)
$d\ln X_{t-1}$	2.1982 (0.0029)	−0.5194 (0.1837)

The co-integration expression and VECM model can reflect the specific linkage relationship between gas and electricity prices. However, they do not provide information on the direction of price transmission at the time level. Therefore, it is necessary to conduct a Granger causality test. Considering the differences in gas–electricity market environments across different months, the causality of gas–electricity prices in different time periods is analyzed, and the results are shown in Table 4.

Table 4. Causal test analysis of gas and electricity prices.

Time	Actual Situation of Gas and Electricity Market	Null Hypothesis	Statistical Probability	Conclusion
August 2020	Gas is cheap, and electricity supply environment is easy	Gas price $d\ln X_t$ is not the cause of electricity price $d\ln Y_t$ changes	0.79	Electricity price causes gas price change
		Electricity price $d\ln Y_t$ is not the cause of gas price $d\ln X_t$ changes	0.08	
May 2021	Gas price is high, and electricity supply environment is tight	Gas price $d\ln X_t$ is not the cause of electricity price $d\ln Y_t$ changes	0.09	There is a two-way causal relationship between gas price and electricity price
		Electricity price $d\ln Y_t$ is not the cause of gas price $d\ln X_t$ changes	0.06	
From March to July 2022	Gas price is high, and electricity supply environment is tight	Gas price $d\ln X_t$ is not the cause of electricity price $d\ln Y_t$ changes	0.08	Gas price causes electricity price change
		Electricity price $d\ln Y_t$ is not the cause of gas price $d\ln X_t$ changes	0.98	
From August to November 2022	Gas price is high, and electricity supply environment is easy	Gas price $d\ln X_t$ is not the cause of electricity price $d\ln Y_t$ changes	0.85	There is no obvious causal relationship between gas price and electricity price
		Electricity price $d\ln Y_t$ is not the cause of gas price $d\ln X_t$ changes	0.39	

When there is a co-integration relationship between the time series, it can be determined that there is a long-term equilibrium relationship between variables. Therefore, the VECM model can be further used to study the short-term nature of the time series. When there is no co-integration relationship in the time series, the Granger causality test can be used to establish the causal relationship between variables. In this paper, the Granger causality test is carried out on the processed time variables after the co-integration relation test. The processed gas price $d\ln X_t$ and electricity price $d\ln Y_t$ meet the stationarity requirements of the causality test, and the validity of the test results is guaranteed. Therefore, the Granger causality test based on the vector error correction model can be used to test the short-term relationship between gas and electricity prices [35,36]. The actual supply and demand of the gas and electricity market in different periods in Table 4 provides a reference for the results of the Granger causality test.

As can be seen from Table 4, the actual operation situation of the gas–electricity market is that the gas price is cheap and the electricity supply is loose in August 2020, and the electricity price mainly affects the change of the gas price. The gas price in May 2021 is expensive and electricity supply is tight, so the gas price interacts with electricity price during this period. From March to July 2022, the gas price continues to rise, becoming an important factor affecting electricity price. Although the gas price remained high from August to November, the correlation between gas and electricity price was low and there was no obvious causal relationship due to the policy of guaranteeing the supply of gas for winter in northern China. The result of Granger's causality test is in good agreement with the supply and demand situation reflected in the actual gas and electricity market.

5.3. Gas–Electricity Price Time Delay Analysis Results

Table 4 shows that, from March to July 2022, there exists a one-way Granger causality relationship affecting gas price and electricity price. Therefore, the time-lag relationship of the influence of gas price fluctuation on electricity price during this period can be analyzed. Table 5 shows the top five period gas prices with the greatest influence according to the weight value A_j, among which the influence weight in the second period is the highest, reaching 0.24. The influence weights of period 1 and period 3 are 0.21 and 0.19, respectively, while the weights of the remaining periods are relatively small. The sum of cumulative influence weights in the first three periods reaches 0.64, indicating that the time delay of gas–electricity price conduction is mainly in the first three periods. However, A_2 does not play an absolute role in the results of the example, which shows from the side that the price interaction between gas and electricity is weak, and the key problem lies in the high gas price and high volatility.

Table 5. The weight of the influence of weekly-scale gas price on the current electricity price.

Number of Cycles j	Cycle Scale Weight Value A_j	Cumulative Influence Weight
2	0.24	0.24
1	0.21	0.45
3	0.19	0.64
4	0.14	0.78
6	0.08	0.86

Table 6 shows the lag order determined according to the VECM model. The AIC of lag period 2 is the smallest, so the lag time of gas and electricity price is two periods. Although both methods can determine the optimal delay time, the proposed method can also reflect the weight relationship between different delay periods. Price transmission is an extremely complex process. The time delay of gas and electricity price transmission is affected by many factors, such as market supply and demand, and market price fluctuation. Therefore, the weight of the lag period can provide more price transmission information for market decision makers. Although the standardized coefficient method can analyze the relative importance of price variables, it lacks the ability to analyze the contribution degree in specific time periods. The variance decomposition method can disintegrate and analyze the total variance of the electricity price time series, so it can reflect the contribution trend of electricity price and gas price more accurately.

Table 6. Determination of the lag order of VAR model.

Order of Lag	AIC
1	−2.41
2 *	−5.13
3	−4.88
4	−4.64
5	−3.08
6	−3.32

* represents the optimal lag order determined according to AIC criterion.

6. Conclusions

The coupling degree of the natural gas market and electricity market is deepening, leading to a stronger linkage relationship between gas and electricity prices. In this context, it is crucial to accurately analyze the linkage mechanism between gas and electricity prices to enhance the ability of market participants to manage price risk events and gain a better understanding of the market environment. Therefore, this paper proposes a gas–electricity price linkage analysis method based on the benefit–cost and Attention–VECM models. An empirical analysis of natural gas and electricity markets in China confirms the effectiveness of this method in accurately capturing the linkage mechanism between gas and electricity prices.

(1) The gas unit benefit–cost model proposed in this paper captures the quotation behavior of gas units in the market by assessing the profitability of the units. This model provides valuable gas and electricity price information for the co-ordinated operation of the gas and electricity market, thereby helping market participants to manage market risks, such as an insufficient natural gas supply.
(2) Calculation reveals the co-integration relationship of long-term gas and electricity price stability. The results demonstrate a goodness of fit value greater than 0.7, indicating a strong correlation between the two. Additionally, this paper employs the VECM model to study the short-term volatility of gas and electricity prices. The results reveal the existence of an error correction mechanism, suggesting that short-term volatility will eventually tend to balance. This finding further confirms the presence of a long-term equilibrium relationship between gas and electricity prices. To analyze the causality relationship between prices in different periods, the processed gas and electricity price time series are subjected to a Granger causality test. The comparison of the results with actual market conditions reveals that the supply and demand situation in the gas and electricity market is continually changing.
(3) In this paper, an attention mechanism is used to quantitatively describe the conduction delay time of gas–electricity price fluctuations. Compared with determining the lag order by the VAR model, the proposed method comprehensively reflects the influence weight of the delay in each time period, and the results are more consistent with the actual price transmission process. An analysis of the weight value of each cycle and the cumulative influence weight reveals that the time delay is mainly within the first three weeks, and there is no time delay accounting for absolute proportion in the results. Therefore, it can be qualitatively concluded that the existing gas–electricity price linkage is not strong.

The proposed natural gas–electricity price linkage analysis method has practicability in the following aspects. Firstly, the benefit–cost model can reflect the quotation tendency of gas units in the market and the supply situation of the natural gas market. Secondly, the VECM model and the co-integration relationship of gas and electricity prices provide a reference for evaluating the long-term trend and short-term fluctuation range of prices. Thirdly, the Granger causality test results directly reflect the coupling relationship and supply and demand of the gas and electricity market. Lastly, the results of price conduction delay calculated by the attention mechanism can help market players develop reasonable trading strategies for natural gas and electricity.

In practice, the linkage between gas price and electricity price will also be affected by other energy resource prices, the upstream and downstream transmission relationship of the industrial chain, and the impact of macro policies. Therefore, the research method proposed in this paper is not applicable to the electricity market environment where the proportion of natural gas generation is relatively low. Moreover, price fluctuations themselves have relatively strong uncertain factors that were not considered in this study. In the future, the linkage relationship between gas price and electricity price could be further investigated through alternative methods.

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