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Exploring the substitution within clean energy: Evidence from China's top 14 hydropower provinces

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A R T I C L E I N F O

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A B S T R A C T

This paper quantitatively examines the substitution effects within China's clean energy sector, focusing on the hydropower and new energy generation sectors across the top 14 hydropower-producing provinces, which collectively contribute to over 80 % of the country's total hydropower output. To provide a comprehensive analysis of regions that significantly influence national trends, the study utilizes the Cross-Price Elasticity (CPE) and Morishima Elasticity of Substitution (MES). CPE measures how the quantity demanded of one energy source responds to a change in the price of another, while MES assesses the sensitivity of the ratio between two energy inputs to price changes. A Seasonal Autoregressive Integrated Moving Average (SARIMA) model is employed to forecast energy substitution dynamics, offering robust predictive accuracy. The average MES between clean energy and thermal power is 0.663, indicating a moderate substitution relationship, with the effect more pronounced in summer. Additionally, the mean MES between hydropower and new energy generation is 2.067, reflecting a strong substitution effect between these two clean energy forms. Furthermore, the SARIMA model shows a mean squared error (MSE) as low as 0.0006 in some cases, demonstrating its robust predictive accuracy in forecasting energy substitution dynamics. These results offer empirical support for policies aimed at reducing reliance on thermal power and promoting clean energy development in key provinces.

1. Introduction

The Glasgow Climate Pact calls on participating nations to strengthen their commitments to limit the global temperature increase to below 1.5 °C, as outlined in the Paris Agreement. Given that the power sector is the largest emitter of greenhouse gases, it remains a central focus for most countries(Zhao et al., 2024). The transition from fossil fuels to renewable electricity is a key solution for addressing climate change (Attílio et al., 2024). In China, achieving this target requires substantial progress in the power sector's transition to clean energy sources, as it is responsible for 39.7 % of the country's total CO_2 reductions(Zhao et al., 2021). Consequently, facilitating a clean energy transition in the power sector is critical (Chai et al., 2023). This transition not only entails replacing fossil fuel-based electricity generation with cleaner alternatives like wind, solar, and hydropower, which produce significantly lower emissions, but also optimizing waste materials and biomass utilization for energy generation. Recent advancements, such as the co-pyrolysis of de-oiled microalgal biomass and waste tires, have shown potential for enhancing bio-oil production while addressing waste management issues(Kumar et al., 2022). Furthermore, hydrothermal carbonization (HTC) of microalgae and yard waste can produce clean solid fuels with high energy density by enhancing carbon content and reducing oxygen and nitrogen levels(Kumar et al., 2024).

Guided by the Sustainable Development Goals (SDGs), many countries have advocated for a wide range of energy and environmental policies (Lee and Li, 2024). In recent years, China has played a crucial role in the global clean energy transition. To ensure the successful implementation of China's carbon neutrality strategy and energy transition goals, the Chinese government has issued a series of policy documents supporting the development of clean energy. These include the "Energy production and consumption transition strategy (2016-2030)" and the "14th Five-year plan for renewable energy development" aimed at reducing reliance on fossil fuels, increasing the proportion of new energy, and promoting a green transformation of the energy structure (Hu et al., 2024). Based on these goals and policy frameworks, China has proposed several clean energy transition initiatives, including increasing new energy installed capacity (Chai et al., 2023), investing heavily in hydropower(Wang et al., 2023), wind energy, and solar energy(Yu et al., 2021), and nuclear energy (Shang et al., 2021), and advancing technological innovation and industrial upgrading in clean energy enterprises (Du et al., 2021; Liu, F. et al., 2024). With the support of government

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Nomenclature

CPE	Cross-Price Elasticity
MES	Morishima Elasticity of Substitution
SUR	Seemingly Unrelated Regression
C-D Function	Cobb-Douglas Function
CES Function	Constant Elasticity of Substitution Function
ARIMA	Autoregressive Integrated Moving Average
SARIMA	Seasonal Autoregressive Integrated Moving Average
ADF	Augmented Dickey-Fuller test
PACF	Partial Autocorrelation Function
AR	Autoregressive
MA	Moving Average
AIC	Akaike Information Criterion
LCOE	Levelized Cost of Electricity
F	Thermal Power Generation
C	Clean Energy Generation
W	Hydropower Generation
N	New Energy Generation
CNY	Chinese Yuan
kWh	Kilowatt-hour

policies and advancements in clean energy technology, China's clean energy industry has flourished, providing strong support and valuable experience for the global clean energy transition(Zahoor et al., 2022).

The first stage of China's clean energy development was primarily driven by hydropower. As a representative of clean energy, hydropower boasts advantages such as low carbon emissions, low costs, stability, reliability, and operational flexibility, making it an effective means of combating climate change. Over the past 40 years, China has seen rapid development in hydropower, which has become a significant pillar of its early clean energy development (Sun et al., 2021). However, as suitable sites for hydropower development become limited due to geographical and environmental constraints, the focus has gradually shifted to wind, solar, and nuclear power (Guo et al., 2023). These alternative sources of energy are not only abundant and widely accessible, but also capable of providing scalable and sustainable solutions to meet the growing energy demand. The second stage of China's clean energy development primarily focuses on wind, solar, and nuclear power. With continuous advancements in new energy technologies and declining costs, wind and solar power have become the core of current clean energy development. This stage is characterized by the large-scale development and application of wind and solar power technologies(Sun et al., 2024).

This paper focuses on energy generation in the power sector, defining "clean energy" as environmentally friendly energy characterized by low pollutant emissions during production and use, with minimal environmental impact. It specifically includes hydropower, wind power, solar power, bioenergy (such as biogas), geothermal energy (including ground and water sources), and tidal energy. To provide a robust empirical analysis, this study focuses on China's top 14 hydropower-producing provinces, including Sichuan, Yunnan, Hubei, Guizhou, Guangxi, Hunan, Qinghai, Xinjiang, Gansu, Fujian, Guangdong, Chongqing, Zhejiang, and Henan. These provinces were selected due to their substantial contribution to China's hydropower generation, collectively accounting for over 80 % of the national hydropower output. This high concentration of hydropower production makes these provinces critical for understanding the broader trends and dynamics in China's clean energy transition. Additionally, these provinces encompass diverse geographical and climatic conditions, providing a comprehensive overview of the regional variations in energy substitution patterns. It is important to note that based on the theory of energy development stages, there should be a gradual substitution process within clean energy. As energy utilization technologies advance, solar and wind energy, with their price and application advantages, are expected to gradually replace traditional clean energy generation (hydropower). For example, in the early stages of clean energy development, hydropower was predominant, but as energy utilization technologies progress, there should be a transition from hydropower to solar and wind energy. This study analyzes the substitution between clean and traditional energy in China's top 14 power-generating provinces, revealing regional differences in substitution effects. Furthermore, based on the theory of energy development stages, it explores the differential substitution characteristics within clean energy, providing references for formulating more scientific and rational energy policies.

Previous studies on energy factor substitution elasticity have primarily concentrated on the substitution relationship between specific energy types. For example, Wesseh Jr et al. (2013) demonstrated that electricity is a substitute for petroleum in Liberia's industrial production. Similarly, Xie and Hawkes (2015) analyzed China's transport industry from 1980 to 2010 and found that all energy inputs are substitutes. Their study highlighted particularly high substitution between oil and natural gas and noted a significant increase in substitution elasticity between oil and electricity over time.

Additionally, there is an expanding body of research that examines the overall relationship between clean energy and traditional fossil energy, particularly in the context of China. For example, Pelli (2012), based on a Constant Elasticity of Substitution (CES) Function, used power production input data from 21 countries to estimate the average factor substitution elasticity between clean and fossil energy, finding an average elasticity of 0.51, indicating a substitution relationship. Similarly, Papageorgiou et al. (2017) used energy use data from 26 countries between 1995 and 2009 provided by the World Input-Output Database (WIOD) to estimate that the substitution elasticity between clean and non-clean energy inputs is significantly greater than 1, suggesting that the development of clean energy is highly beneficial for promoting green growth.

Focusing on China, Liu and Lin (2017) quantified inter-factor and inter-energy substitution in China's building construction industry, finding that while energy and non-energy inputs are substitutes, individual energy inputs are complementary, and that a uniform carbon tax could reduce CO_2 emissions by approximately 3 %. Moreover, Xu et al. (2021) examined the influence of policy scenarios on the levelized cost of electricity (LCOE) for various power technologies, revealing that with stringent energy policies, the economic advantages of renewable energy sources such as wind and solar photovoltaic power significantly increase over coal power. Conversely, Hou and Song (2022) analyzed the substitution relationship between thermal power and clean energy in China, finding that biased technical change is thermal power-using, which suggests that technological change is not conducive to the improvement of electricity structure from thermal power to clean energy.

Furthermore, Wang et al. (2022) examined the dynamics of substituting coal power plants with renewable energy power plants in China, concluding that renewable energy becomes the main power source at the mature stage and stressing the importance of reducing the adoption cost of energy storage and carbon capture and storage technology. Likewise, Luo and Zhang (2024) estimated the substitution elasticity between non-clean energy generation (thermal power) and clean energy generation (hydropower, nuclear power, and other energy generation) in China from 1993 to 2022, finding that the substitution elasticity between thermal power and various clean energy forms is greater than 1. Similarly, Liu, P.K. et al. (2024) explored the energy security within the dual circulation framework, demonstrating that Chinese wind power generation is a substitute for imported coal.

Despite significant efforts, existing research often focuses on the substitution between fossil fuels and clean energy, with limited studies examining the internal dynamics within clean energy itself. This gap in the literature is particularly relevant in the context of China, where early clean energy development relied heavily on hydropower, but recent advancements have shifted focus towards wind and solar power. As new energy technologies gradually develop, the increasing share of wind and solar power generation may impact the utilization of hydropower. Understanding the interactions between wind, solar, and other forms of clean energy, such as hydropower, becomes increasingly important. Unfortunately, few studies have adequately explored the complementary and substitution relationships within clean energy sources.

This paper addresses the research gap by examining the substitution dynamics within clean energy in China's top 14 hydropower-producing provinces. Compared to the CES cost function, the trans-log cost function can better approximate the nonlinear characteristics of the cost function, allowing us to observe the elasticity of factor substitution and its periodic variations over time in different provinces of China. The SARIMA model is effective in forecasting time series with cyclical fluctuations. Therefore, we can not only analyze the historical changes in factor substitution elasticity across provinces but also predict future trends, which is significant for providing policy recommendations for the development of clean energy. Specifically, we analyze how the growing prominence of wind and solar power may be affecting the utilization of hydropower in these regions. This study is the first to explore the internal substitution relationship within clean energy (hydropower versus solar power and wind power) based on the theory of energy development stages. By revealing regional differences and both external and internal substitution effects of clean energy, this research contributes to the literature by providing new insights into the internal substitution dynamics within the clean energy sector itself.

This study makes three marginal contributions: First, it is the first to meticulously measure the factor substitution elasticity within clean energy, particularly between hydropower and new energy generation (solar and wind power). Using economic models and econometric methods, we quantify the substitution potential between these two forms of energy. Second, this study innovatively identifies the cost per kilowatt-hour of hydropower based on listed company data, using financial annual report data from Chinese hydropower listed companies to accurately calculate the cost per kilowatt-hour of hydropower. This cost analysis based on actual operational data provides a research framework for future assessments of the economic feasibility of hydropower in the energy market. Additionally, by comparing with non-clean energy costs, this study reveals the cost-effectiveness of hydropower, providing strong data support for promoting the economic transition of clean energy. Finally, from a regional perspective, this study establishes a prediction framework for the internal substitution elasticity of clean energy based on the Seasonal Autoregressive Integrated Moving Average (SARIMA) model. The model successfully captures the seasonal characteristics of time series data and provides accurate prediction results, which are crucial for understanding and addressing regional differences in clean energy development.

The structure of this paper is as follows: First, it introduces the importance of clean energy and its development status in China, followed by a literature review analyzing existing research on clean energy substitution. Next, the methodology section describes in detail the factor substitution theory, the trans-log cost function model, Seemingly Unrelated Regression (SUR), and the Seasonal Autoregressive Integrated Moving Average (SARIMA) model. The SUR involves a set of linear regression equations, each of which has its own dependent variable and potentially different sets of explanatory variables. The key aspect of the SUR is that, although the error terms of different equations are assumed to be uncorrelated with the explanatory variables, they may be contemporaneously correlated with each other (Zellner, 1962). These models are employed to rigorously analyze the interactions between hydropower and new energy generation across the top 14 hydropower-producing provinces, with data collected from various authoritative sources focusing on electricity generation costs and shares for thermal power, hydropower, and new energy.

Subsequently, the analysis of power costs and shares section compares the costs per kilowatt-hour of thermal power and clean energy generation, as well as hydropower and new energy generation, analyzing the cost shares of different provinces from a regional perspective. The results section presents the empirical findings, showcasing the significant substitution relationships between clean energy and thermal power, as well as within the clean energy sector itself. Using Cross-Price Elasticity (CPE) and Morishima Elasticity of Substitution (MES), we reveal how these relationships vary seasonally and regionally. The SARIMA model's predictions offer insights into future trends, emphasizing the need for targeted investments and policy interventions.

The discussion interprets these findings in the context of China's energy policies, suggesting strategic measures to enhance clean energy capacity and reliability. Finally, the paper concludes by summarizing the key results and their policy implications, advocating for tailored regional strategies, technological advancements, and improved grid management to support China's clean energy transition. The limitations of the study are acknowledged, with future research directions proposed to explore advanced grid technologies, energy storage solutions, and strategies for ensuring a consistent energy supply (Fig. 1).

2. Literature review and methodology

2.1. Data collection

To ensure data availability and statistical consistency, this study analyzes the electricity sector data of the top 14 hydropower-producing provinces in China (Sichuan, Yunnan, Hubei, Guizhou, Guangxi, Hunan, Qinghai, Xinjiang, Gansu, Fujian, Guangdong, Chongqing, Zhejiang, Henan) for the period from May 2016 to December 2022. These provinces are selected based on their substantial contribution to the national hydropower output, collectively accounting for over 80 % of the country's total hydropower generation. This selection ensures that the analysis captures the most significant trends and dynamics in the hydropower sector, which are critical for understanding broader national and potentially global energy substitution trends. Monthly data on thermal, hydropower, solar, and wind power generation were sourced from the National Bureau of Statistics[1].

The cost per kilowatt-hour (kWh) of thermal power generation is calculated by multiplying the consumption of coal, oil, and natural gas in the power sector by their respective prices and then dividing by the thermal power generation volume. This study utilizes data from the CEIC database[2] and the National Bureau of Statistics[3] for the consumption and generation volumes of coal, oil, and natural gas. Additionally, the price data for Qinhuangdao coal, Sinopec crude oil average realized prices, and pipeline gas service prices in 36 cities were sourced from the Wind database to calculate the cost per kWh for thermal power generation. The cost per kWh for hydropower generation is based on the financial reports of 15 listed hydropower companies in China, calculated as the total cost of hydropower generation divided by the hydropower generation volume. The cost per kWh for new energy generation, including wind and solar power, refers to the costs outlined in the "China New Energy Power Generation Analysis Report" from 2017 to 2023 (Fig. 2).

2.2. Cross-price and morishima elasticity of substitution

The theory of factor substitution aims to analyze the interactions between different factors in the production process, focusing primarily on how relative changes in the prices of two or more factors affect their input ratios. This theory was first proposed by Hicks (Hicks, 1932). In the context of energy production, factor substitution is evident not only in the complementary and substitutive relationships between energy, capital, and labor but also within different types of energy. A core

[1] https://www.stats.gov.cn/
[2] https://insights.ceicdata.com.cn/
[3] https://www.stats.gov.cn/

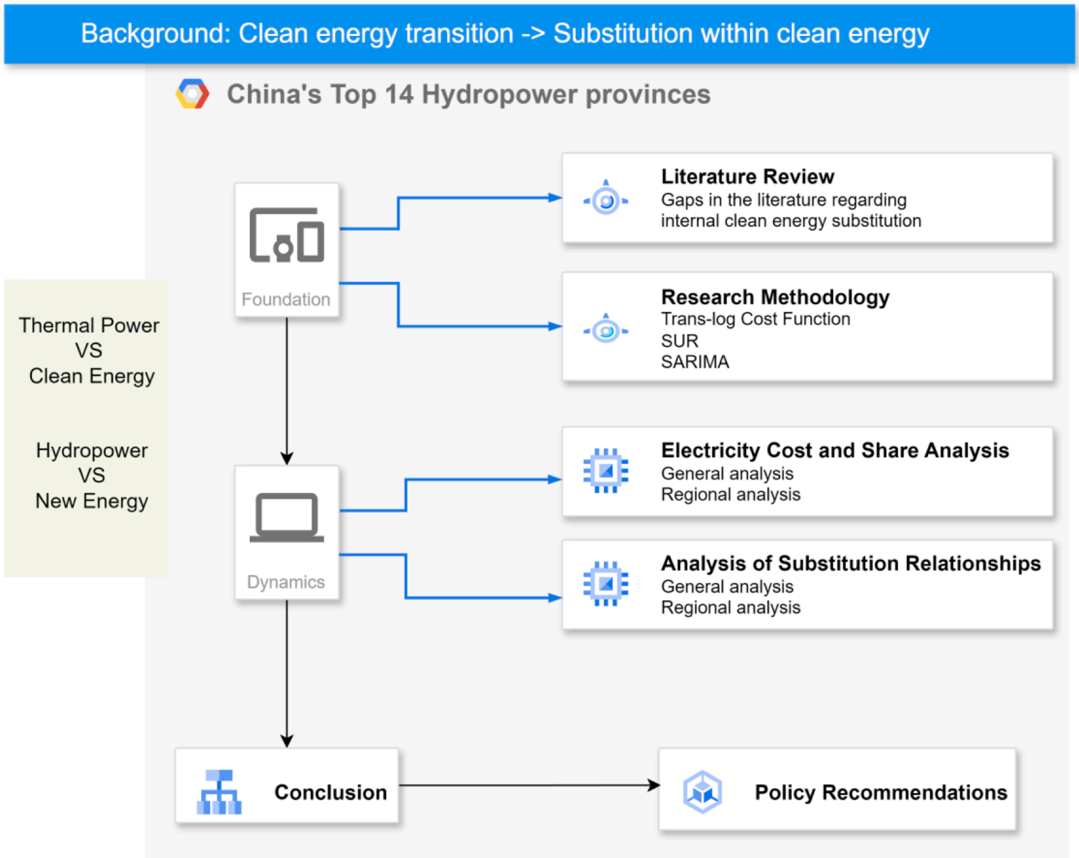

Fig. 1. Roadmap for analyzing clean energy substitution in China's top hydropower provinces.

element of substitution theory is relative price changes, whereby an increase in the price of one type of energy leads consumers or producers to switch to a lower-cost alternative. While existing studies often focus on the complementary and substitutive relationships between non-clean energy, such as fossil fuels, and clean energy, they tend to overlook the internal substitution relationships among different types of clean energy. With advancements in technology and growing environmental awareness, the costs of generating new energy, represented by wind and solar power, are gradually decreasing, making the substitution relationships among various clean energy sources more valuable for research. Therefore, this paper measures the substitution elasticity concerning both non-clean energy and clean energy, as well as the internal complementary and substitutive relationships within clean energy.

Specifically, CPE refers to the rate at which the demand for one production factor changes in response to a change in the price of another factor, holding other conditions constant. MES, also known as net elasticity of substitution, assesses the sensitivity of the ratio of two input factors to changes in prices (Morishima, 1967). Based on CPE and MES, the complementary and substitutive relationships between factors are as follows:

$$\begin{cases} MES < 0, CPE < 0, \text{Complementarity} \\ MES < 0, CPE > 0, \text{Uncertainty} \\ MES > 0, CPE < 0, \text{Uncertainty} \\ MES > 0, CPE > 0, \text{Substitutability} \end{cases} \tag{1}$$

2.3. Trans-log cost share equation

In comparison to the Cobb-Douglas (C-D) function and the Constant Elasticity of Substitution (CES) function, the trans-log cost function imposes fewer restrictions and offers a more flexible model with variable elasticity. As an application of duality theory, the trans-log cost function provides a second-order approximation for any arbitrary function of indeterminate form (Coelli et al., 2005). Utilizing the trans-log cost function allows for the examination of the elasticity of substitution between two factors over different time periods across various provinces. By approximating the cost function using the trans-log cost function, where C represents the total cost and P denotes factor prices, and F and C represent thermal and clean energy generation, respectively:

$$\ln C = \alpha_0 + \alpha_Y \ln Y + \sum_i \alpha_i \ln P_i + \frac{1}{2}\sum_i \sum_j \alpha_{ij} \ln P_i \ln P_j \tag{2}$$

Here, $i,j = F, C$. The parameter α_i is considered a distribution parameter used to measure the cost share not directly related to factor prices, while α_{ij} is used to assess the substitution relationships between factors, measuring the changes in the cost share function with factor price fluctuations. According to Shephard's lemma, the demand for a specific factor can be derived by taking the partial derivative of the cost function with respect to the price of that factor:

$$X_i = \frac{\partial C}{\partial P_i} \tag{3}$$

Where C represents the total cost, P denotes factor prices, and F and C represent thermal and clean energy generation, respectively. The cost share of a specific factor is given by:

$$S_i = \frac{X_i \cdot P_i}{C} = \frac{\partial C}{\partial P_i} \cdot \frac{P_i}{C} = \frac{\partial C}{C} \cdot \frac{P_i}{\partial P_i} = \frac{\frac{\partial C}{C}}{\frac{\partial P_i}{P_i}} = \frac{\partial \ln C}{\partial \ln P_i} \tag{4}$$

Combining Eq. (2), we get:

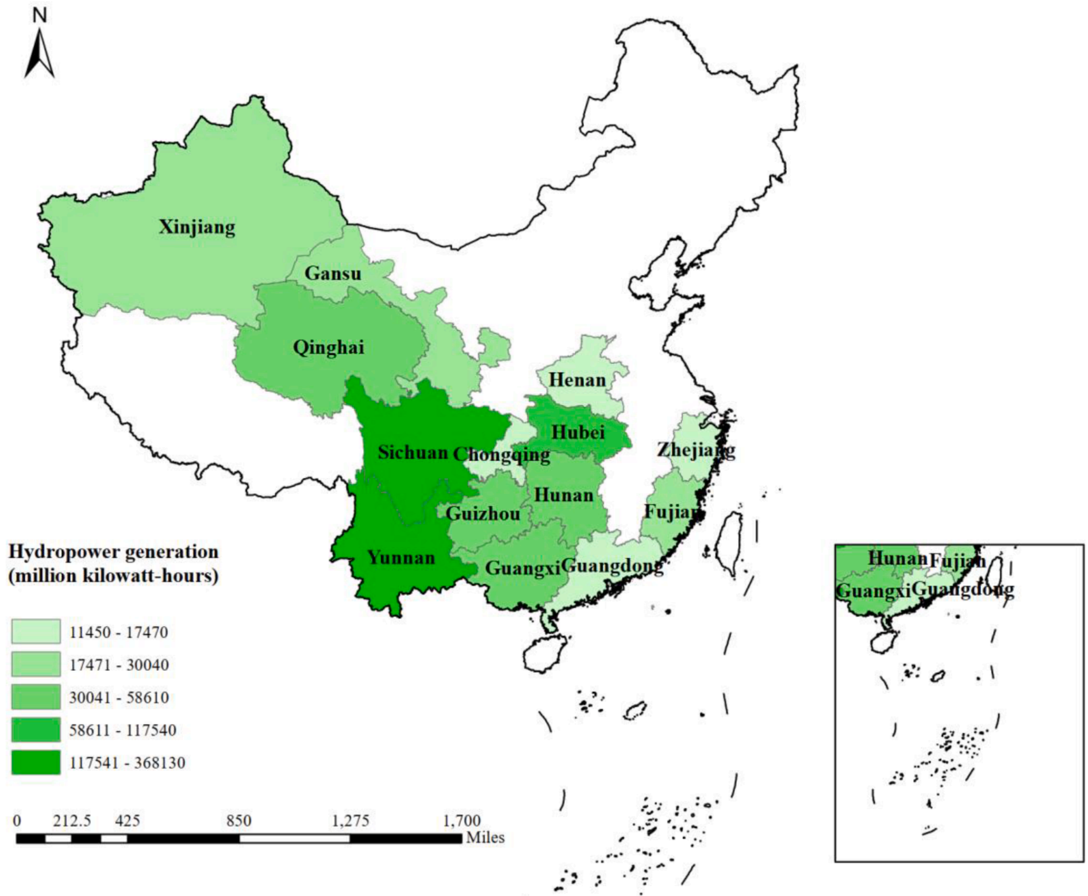

Fig. 2. Map of hydropower generation in China's top 14 hydropower-producing provinces in 2022.

$$S_i = \frac{\partial \ln C}{\partial \ln P_i} = \alpha_i + \sum_j \alpha_{ij} \ln P_j, \quad (i, j = F, C) \tag{5}$$

Therefore, the cost share for thermal and clean energy generation can be expressed as:

$$\begin{cases} S_F = \alpha_F + \alpha_{FF} \ln P_F + \alpha_{FC} \ln P_C \\ S_C = \alpha_C + \alpha_{CC} \ln P_C + \alpha_{CF} \ln P_F \end{cases} \tag{6}$$

The above cost share equations can be used to study the substitutive or complementary relationships between thermal and clean energy generation. Similarly, when i, j represent hydroelectric power W and new energy generation N, the cost share for hydroelectric and new energy generation is:

$$\begin{cases} S_W = \alpha_W + \alpha_{WW} \ln P_W + \alpha_{WN} \ln P_N \\ S_N = \alpha_N + \alpha_{NN} \ln P_N + \alpha_{NW} \ln P_W \end{cases} \tag{7}$$

This paper employs SUR model to estimate Eq. (7). First proposed by Zellner in 1962, SUR improves estimation efficiency by leveraging the correlation between the error terms across equations (Zellner, 1962). Subsequently, based on parameter estimation results, the substitution elasticity for various factors and between factors is calculated using the following elasticity formula:

$$\begin{cases} CPE_{ii} = \dfrac{\partial \ln X_i}{\partial \ln P_j} = \dfrac{\partial \ln (S_i C / P_i)}{\partial \ln P_j} = \dfrac{\beta_{ij}}{S_i} + S_j \\ MES_{ij} = \dfrac{\partial \ln X_i / X_j}{\partial \ln P_j} = \dfrac{\partial \ln X_i}{\partial \ln P_j} - \dfrac{\partial \ln X_j}{\partial \ln P_j} \end{cases} \tag{8}$$

This paper uses CPE and MES to measure and compare the elasticity relationships among factors.

2.4. Predictive model

The two most frequently utilized methods in time series forecasting are Exponential Smoothing and Autoregressive Integrated Moving Average (ARIMA) models (Brockwell and Davis, 2002). And the Seasonal Autoregressive Integrated Moving Average (SARIMA) model is a time series forecasting method that captures both regular and seasonal patterns in data. It extends the basic ARIMA model by adding terms to account for seasonality, making it well-suited for predicting trends in data that show seasonal fluctuations, such as energy production (Noor et al., 2022). By using SARIMA, we can accurately forecast how energy sources like hydropower and wind power will perform over time, especially during different seasons.

SARIMA models are widely used for forecasting time series with seasonality. For instance, Gikungu et al. (2015) utilized the SARIMA model to forecast Kenya's inflation rate using quarterly data from 1981 to 2013, demonstrating that the SARIMA model possesses high predictive accuracy. Fang and Lahdelma (2016) combined a multivariate linear model with a SARIMA model to predict heat demand for district heating systems. Additionally, Wang et al. (2013) utilized the SARIMA model to forecast precipitation trends, achieving good fit results.

Considering the seasonal patterns in hydropower generation, this study employs the SARIMA model to forecast cross-price elasticity and substitution elasticity. The general form of the SARIMA model is $SARIMA(p, d, q)(P, D, Q, s)$, where $AR(p)$ represents the autoregressive component of order p, $MA(q)$ is the moving average component of order q, $I(d)$ is the integrated component of order d, Seasonal $AR(P)$ is the seasonal autoregressive component of order P, Seasonal $MA(Q)$ is the seasonal moving average component of order Q, and Seasonal $I(D)$ is the seasonal integrated component of order D, with s representing the seasonal period. The SARIMA model can be expressed as:

$$(1-\varphi_1 B)(1-\Phi_1 B^s)(1-B)(1-B^s)y_t = (1+\theta_1 B)(1+\Theta_1 B^s)\varepsilon_t \tag{9}$$

where B is the backshift operator, φ_1 and Φ_1 are the parameters for the non-seasonal and seasonal autoregressive components, respectively, θ_1 and Θ_1 are the parameters for the non-seasonal and seasonal moving average components, respectively, y_t is the value of the series at time t, and ε_t is the white noise error term. To fit the model, the original data is first subjected to ordinary and seasonal differencing to obtain a stationary non-white noise series.

The augmented Dickey-Fuller (ADF) test is used to check for stationarity. Once stationarity and non-white noise are confirmed, the autocorrelation function (ACF) and partial autocorrelation function (PACF) plots of the differenced series are examined to preliminarily determine the values of p, d, and q for model fitting. By examining the ACF and PACF plots, the appropriate orders of the autoregressive (AR) and moving average (MA) components are identified, leading to the determination of the optimal $SARIMA(p, d, q)(P, D, Q, s)$ model based on the Akaike Information Criterion (AIC). By following these steps, the SARIMA model effectively captures the seasonal characteristics of hydropower generation, enabling accurate forecasts of cross-price elasticity and substitution elasticity.

We utilized data from May 2016 to December 2021 as our training set and data from the entire year of 2022 as our test set. Our objective was to predict the CES and MES for 2022 and 2023. We conducted elasticity measurements and predictions for CES and MES from 2016 to 2023 at both the national and provincial levels. The SARIMA parameters of the national CES and MES average prediction models are detailed in Table 1, and the results can be seen at Figs. 8 and 9. These model specifications are designed to capture the seasonal dynamics in the data, thereby providing robust forecasts for the elasticity measures under consideration.

3. Electricity cost and share analysis

3.1. General analysis

Considering the stability of energy supply, thermal power generation has remained a crucial component of China's energy system. Despite its relatively high cost per kilowatt-hour and vulnerability to fuel price fluctuations, it maintains a significant position. The primary costs of thermal power generation include fuel costs, operational and maintenance costs, and environmental management costs. Among these, fuel costs dominate, especially when coal prices are high, leading to increased electricity costs. Additionally, driven by policy and environmental requirements, environmental management costs for thermal power generation have been rising yearly, requiring companies to allocate more resources to pollutant treatment and emission control.

In 2021, the significant increase in coal prices was likely due to a combination of factors: limited coal production capacity, demand growth spurred by economic recovery, decreased transportation efficiency, environmental policy impacts, and market expectations of future supply-demand tensions. The interaction of these factors exacerbated market supply-demand conflicts, driving up coal prices.

Table 1
SARIMA model parameters.

	p	d	q	P	D	Q	s
CPE_{NW}	1	0	2	1	1	0	12
CPE_{WN}	1	0	0	0	1	0	12
MES_{WN}	1	1	0	1	1	0	12
CPE_{CF}	0	1	0	0	0	1	12
CPE_{FC}	0	1	1	1	1	0	12
MES_{FC}	2	0	0	1	0	0	12

Note: p and seasonal P indicate number of autoregressive terms (lags of the stationarized series); d and seasonal D indicate differencing that must be done to stationarize series; q and seasonal Q indicate number of moving average terms (lags of the forecast errors); s indicates seasonal length in the data.

In contrast, clean energy generation, such as hydropower, though initially expensive to invest in, offers relatively stable and lower electricity costs. The main costs of hydropower are concentrated in initial construction investment and subsequent operation and maintenance. Since hydropower utilizes natural resources, its fuel cost is nearly zero, giving it a clear advantage in electricity cost. Furthermore, with technological advancements and economies of scale, the cost per kilowatt-hour of clean energy generation is trending downward (Fig. 3).

As shown in Fig. 4, the cost per kilowatt-hour of hydropower has remained relatively stable throughout the period, averaging approximately 0.0887 CNY/kWh. This indicates that hydropower is a relatively economical method of power generation in China, offering significant cost advantages. In contrast, the initial cost per kilowatt-hour of new energy generation was higher, around 0.5283 CNY/kWh, but it has shown a gradual downward trend. This decline reflects the impact of technological advancements and economies of scale, bringing the cost of new energy generation closer to, and potentially below, that of traditional hydropower.

Overall, the cost per kilowatt-hour for hydropower is significantly lower than that for new energy generation. However, the rapid decrease in the cost of new energy generation over time is narrowing the gap. With continued policy support and technological progress, the cost of new energy generation is expected to keep declining, further enhancing its market competitiveness.

Our analysis of the cost per kilowatt-hour reveals that hydropower currently retains a clear cost advantage. Nevertheless, with the advancements in new energy technologies and the benefits of economies of scale, the cost of new energy generation is decreasing rapidly. In the future, new energy generation may match or even surpass hydropower in cost-effectiveness, providing strong support for the transformation of China's energy structure.

Fig. 5 shows that from 2016 to 2022, the share of thermal power generation in China generally increased, while the share of clean energy generation declined. In 2021, the share of thermal power generation peaked at approximately 77 %, while the share of clean energy generation dropped to its lowest point at about 23 %. This highlights the heavy reliance of the power industry on thermal power. Additionally, the cost shares exhibited clear seasonal fluctuations during this period, with thermal power shares higher in winter and clean energy shares lower. This can be attributed to increased heat demand during cold seasons and reduced hydropower output. Hydropower typically reaches its nadir in winter, further increasing dependence on thermal power. Conversely, clean energy generation plays a crucial role during the summer and rainy seasons, particularly from April to August, when the cost share of hydropower generally rises.

Fig. 6 indicates a fluctuating decline in the share of hydropower from 2016 to 2022, while the share of new energy generation rose from about 35 % in 2016 to nearly 70 % in 2022. This trend signifies the growing proportion of new energy generation in China's energy mix, reflecting rapid development and policy support in the new energy sector. Seasonal analysis reveals that hydropower shares are typically higher in summer (June to August) due to the seasonality of water resources, with increased rainfall favoring hydropower generation. In contrast, new energy generation, particularly wind and solar power, may see a drop in winter due to shorter daylight hours and less favorable wind conditions. However, the overall growth trend of new energy generation shares appears unaffected by seasonal factors, indicating that advancements in new energy technology and grid management are gradually overcoming these limitations. With continued technological progress and policy support, the share of new energy generation is expected to keep increasing. Meanwhile, hydropower will need to optimize its scheduling strategies to better adapt to the evolving energy structure.

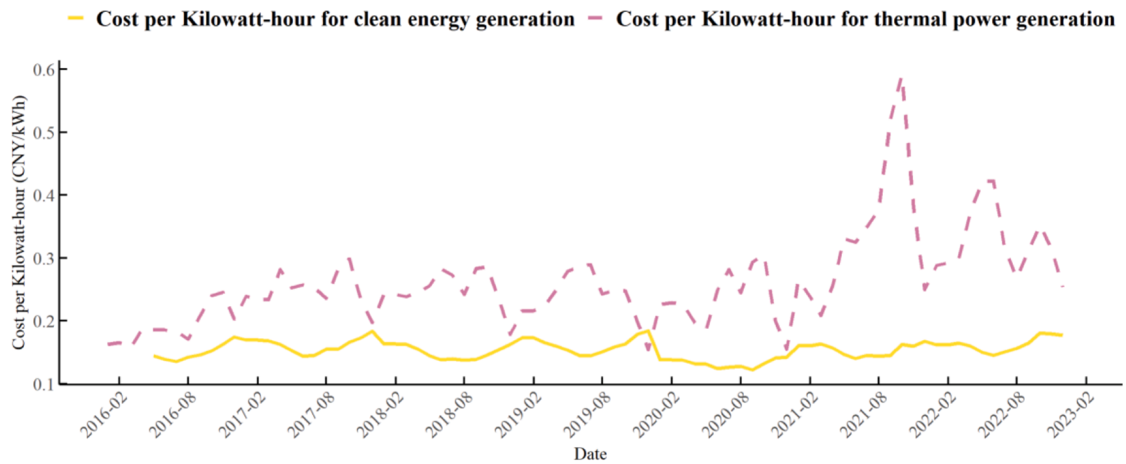

Fig. 3. Mean cost per Kilowatt-hour for clean energy generation and thermal power generation across all provinces.

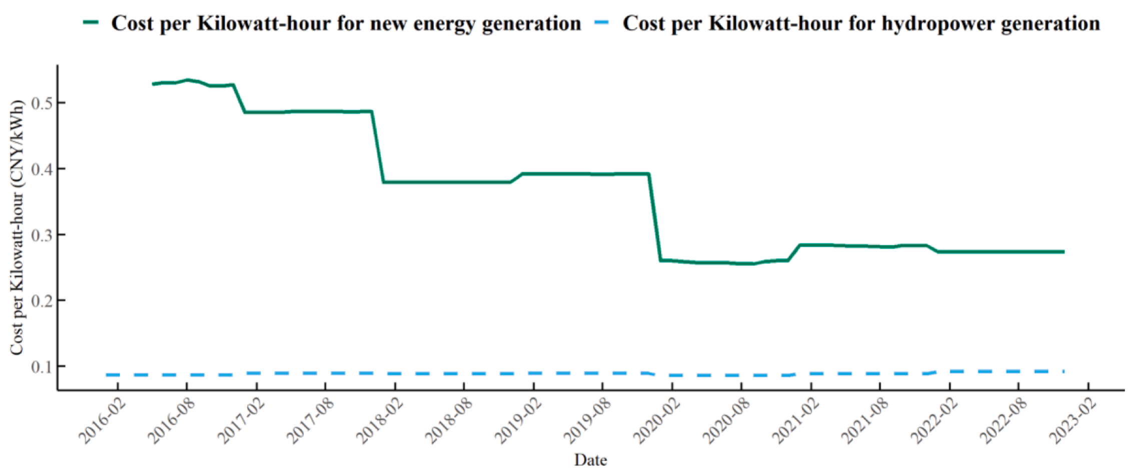

Fig. 4. Mean cost per kilowatt-hour for new energy generation and hydropower generation across all provinces.

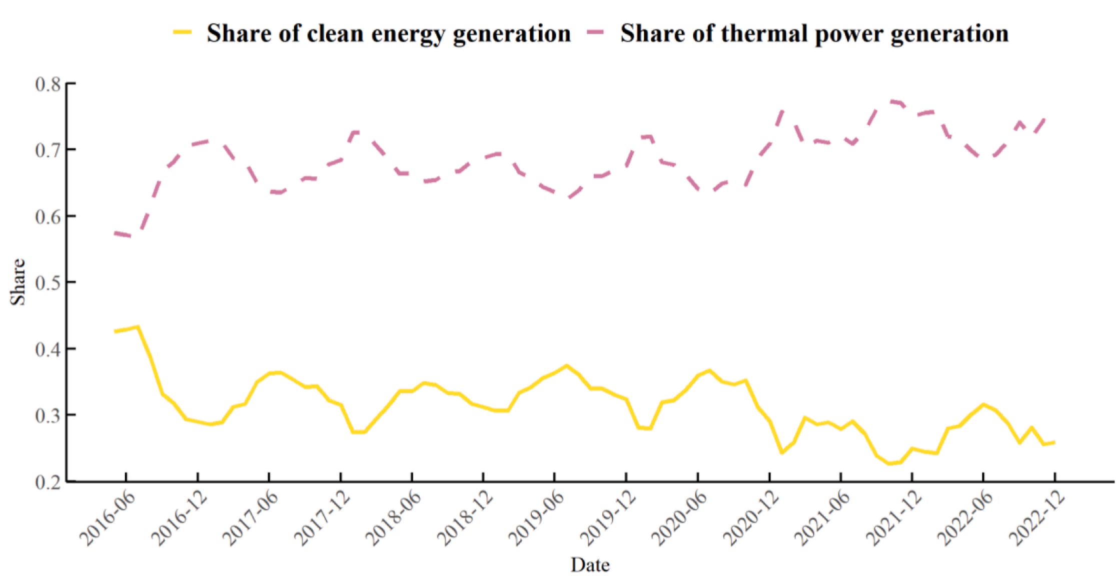

Fig. 5. Mean cost share of clean energy generation and thermal power generation across all provinces.

3.2. *Reginal analysis*

Fig. 7 and Table 2 show that Yunnan, Sichuan, and Qinghai have the highest proportions of clean energy generation, at 75 %, 74 %, and 73 %, respectively. These provinces, located in western China, are rich in water resources, and their terrain and climate conditions are also

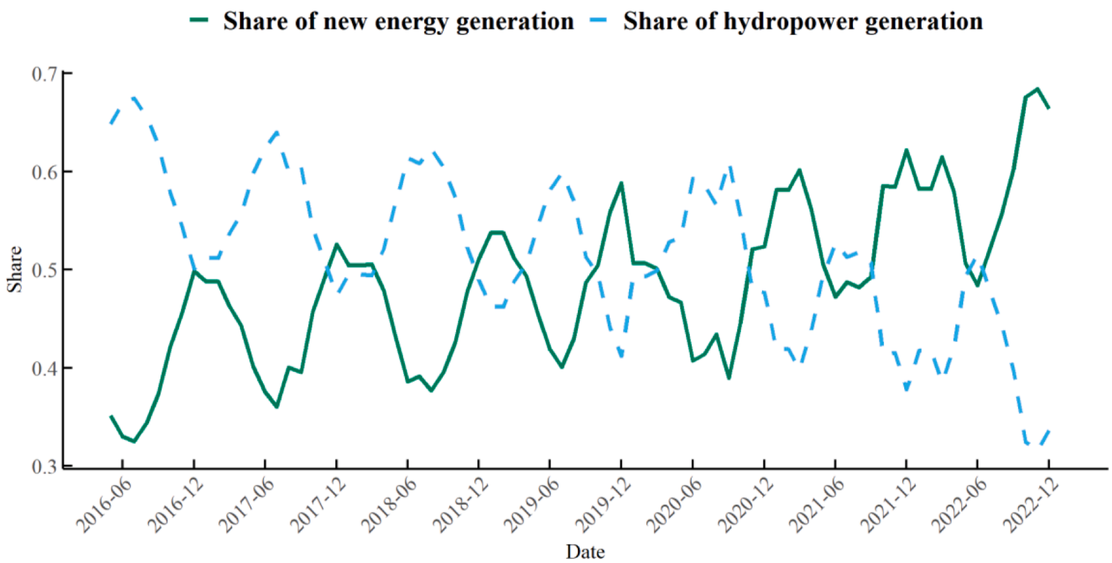

Fig. 6. Mean cost share of new energy generation and hydropower generation across all provinces.

favorable for the development of wind and photovoltaic power. In contrast, provinces like Gansu, Hubei, Hunan, and Guangxi have clean energy generation shares between 27 % and 38 %. While these regions have a foundation in clean energy, thermal power still dominates. Seasonal and cyclical variations are more pronounced in these provinces. For instance, Gansu has abundant wind resources in winter, while Hubei and Hunan's hydropower is significantly affected by seasonal rainfall.

Zhejiang and Guangdong have relatively low shares of clean energy generation, at only 6 % and 7 %, respectively. These economically developed and highly industrialized provinces have substantial power demands, leading to a heavy reliance on thermal power. Although they are actively promoting clean energy projects, progress has been slow due to infrastructure and policy support limitations.

In the global efforts to combat climate change and promote sustainable development, China is actively transitioning its energy structure towards clean energy. Hydropower, as a mature clean energy technology, holds a central position in many provinces. Additionally, the rapid growth of new energy sources such as wind and solar power is driving the transformation of the energy structure.

Data analysis from Fig. 7 and Table 2 highlights that provinces like Sichuan, Chongqing, and Hubei are national leaders in hydropower generation, demonstrating their proficiency in utilizing water resources. Sichuan, renowned for its abundant hydropower resources, dominates its power structure thanks to its mountainous terrain and ample rainfall. Chongqing and Hubei also perform well, with hydropower not only meeting local energy needs but also supplying electricity to other provinces.

While hydropower plays a significant role, the development of new energy sources like wind and solar power is accelerating. Although the share of wind and solar power may not be as high as hydropower, these sources are crucial for diversifying the energy structure and reducing carbon emissions. Regions like Xinjiang and Gansu, with their unique geographical and climatic conditions, have become hotspots for wind and solar energy development.

However, promoting and utilizing clean energy, including hydropower, is not without challenges. Seasonal and regional differences significantly impact hydropower capacity, potentially leading to unstable power supplies. Additionally, the intermittent and unstable nature of wind and solar power necessitates advancements in energy storage technologies and smart grids.

To achieve sustainable development and reduce environmental impact, China must continue to optimize its energy structure, increase the share of new energy and hydropower, and develop related technologies to address fluctuations in energy demand. Furthermore, policy support and international cooperation are vital for advancing clean energy development.

4. Analysis of substitution relationships

4.1. General analysis

Following the methodology outlined earlier, this study calculates the CPE and MES for clean energy and thermal power, as well as hydropower and new energy generation for all provinces. The average elasticity values for all provinces are displayed in Figs. 8 and 9.

Additionally, we utilized the SARIMA model to analyze elasticity. The period from May 2016 to December 2021 served as the training set, while the period from January 2022 to December 2022 was used as the test set. The predictive performance of the SARIMA model, as shown in Table 3, demonstrates high accuracy on the test set, indicating robust forecasting capability.

According to the results in Fig. 8, there is a clear substitution relationship between thermal power generation and clean energy generation. The mean MES_{FC} is 0.663, the mean CPE_{FC} is 0.240, and the mean CPE_{CF} is 0.423. This indicates that while thermal power and clean energy generation substitute each other, the degree of substitution is limited. Seasonal variations play a crucial role in this relationship, with the substitution effect being more pronounced in summer than in winter.

During the summer, longer and more intense daylight increases the output of solar and wind energy, effectively meeting peak electricity demand driven by air conditioning and cooling needs, thereby reducing reliance on thermal power. Additionally, the rainy season provides abundant water resources, significantly boosting hydropower generation and decreasing the demand for thermal power. The high output of clean energy can also lower wholesale electricity market prices, making it more economically competitive and further substituting thermal power generation.

According to the results shown in Fig. 9, the average MES_{WN} is 2.067, the average CPE_{WN} is 0.974, and the average CPE_{NW} is 1.093. This indicates a substitution relationship between hydropower and new energy generation. In the hot summer months, the value of CPE_{NW} is higher. During the rainy season, abundant water resources significantly boost hydropower generation, leading to a decrease in electricity prices and, consequently, a reduced demand for new energy. In contrast, during the cold winter months, the value of CPE_{WN} is higher due to scarce water resources, increasing the use of solar and wind energy to compensate for

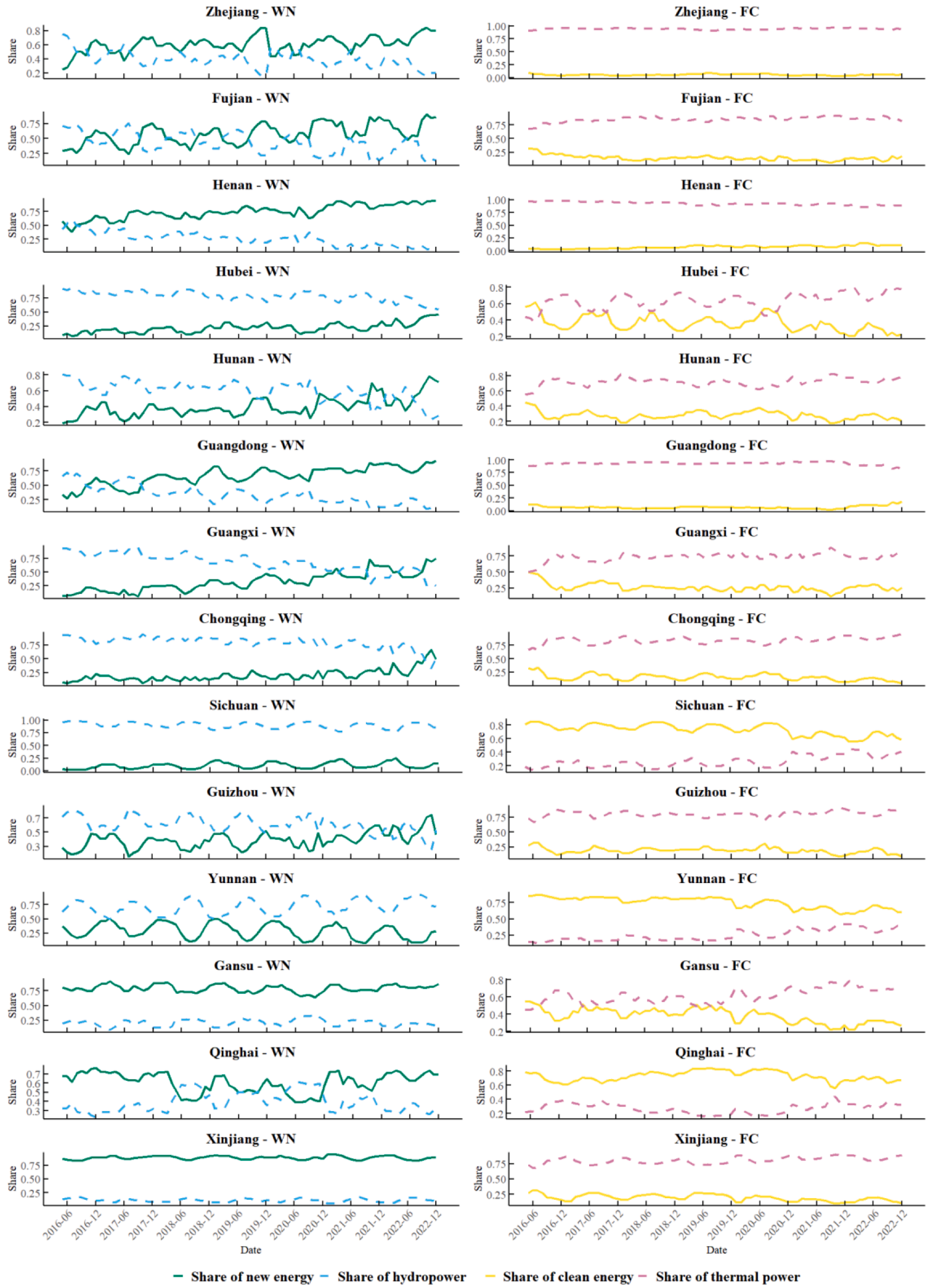

Fig. 7. Cost share of new energy, hydropower, clean energy, and thermal power by province.

the shortfall in hydropower.

Policymakers need to ensure that energy supply can adapt to seasonal demand fluctuations. For instance, electricity demand typically rises in summer and winter due to increased use of air conditioning and heating equipment. Policies should incentivize energy companies to boost production during peak demand periods or develop demand response programs to alleviate pressure during these times.

Combining the predictive results, all elasticities are expected to maintain current trends, with thermal power and clean energy generation, as well as hydropower and new energy generation, continuing their substitution relationships. The predictive accuracy of the model is higher when periodicity is more pronounced; actual elasticities during the test period mostly fall within the 95 % confidence interval of the model predictions.

Overall, the substitution elasticity between thermal power and clean energy generation shows less pronounced periodicity and remains

Table 2
Ranking of mean cost shares by province.

Province	Clean energy	Thermal power	Province	New energy	Hydropower
Yunnan	0.75	0.25	Xinjiang	0.89	0.11
Sichuan	0.74	0.26	Gansu	0.79	0.21
Qinghai	0.73	0.27	Henan	0.75	0.25
Gansu	0.38	0.62	Guangdong	0.66	0.34
Hubei	0.36	0.64	Qinghai	0.61	0.39
Hunan	0.28	0,72	Zhejiang	0.60	0.40
Guangxi	0.27	0.73	Fujian	0.58	0.42
Xinjiang	0.19	0.81	Hunan	0.40	0.60
Guizhou	0.19	0.81	Guizhou	0.39	0.61
Chongqing	0.16	0.84	Guangxi	0.33	0.67
Fujian	0.15	0.85	Yunnan	0.29	0.71
Henan	0.08	0.92	Hubei	0.22	0.78
Guangdong	0.07	0.93	Chongqing	0.20	0.80
Zhejiang	0.06	0.94	Sichuan	0.10	0.90

relatively stable in magnitude. The substitution elasticity between new energy generation and hydropower demonstrates more distinct periodicity, with CPE_{NW} and CPE_{WN} generally exhibiting cyclic decreases and increases, respectively, while MES_{WN} shows relatively stable cyclical changes.

Table 3
Modelling sufficiency evaluation of all the models (all the statistics are based on the tested months).

	MSE	RMSE	MAE	MAPE [%]
CPE_{CF}	0.0027	0.0523	0.0492	11.53
CPE_{FC}	0.0006	0.0243	0.0233	12.18
MES_{FC}	0.0046	0.0679	0.0615	9.81
CPE_{NW}	0.0147	0.1214	0.0891	9.42
CPE_{WN}	0.0317	0.1781	0.1570	11.97
MES_{WN}	0.0081	0.0902	0.0725	3.50

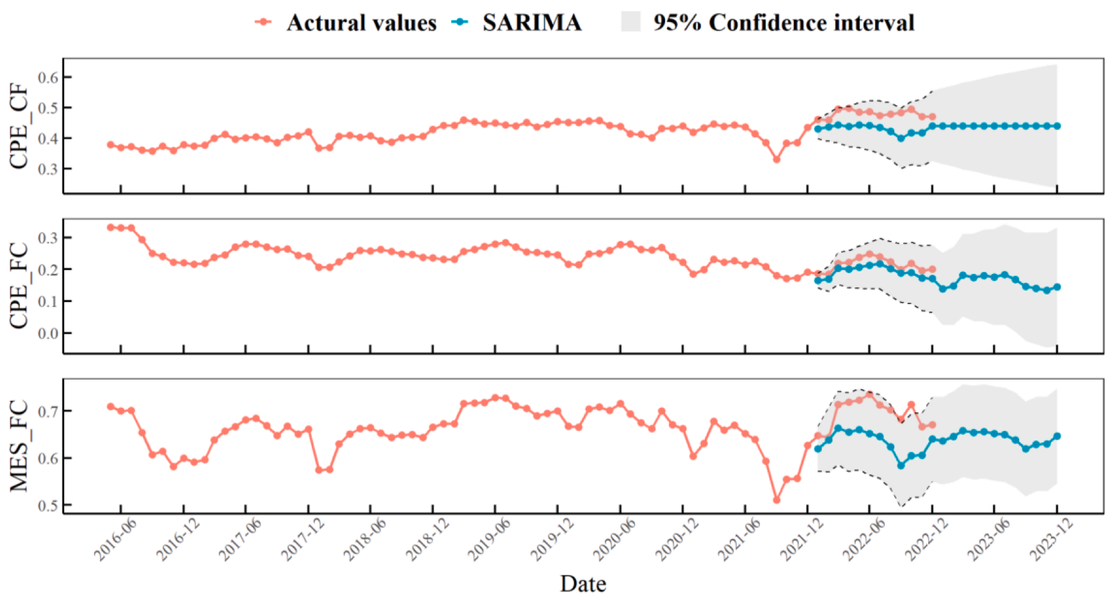

Fig. 8. Elasticity of substitution between thermal power generation and clean energy generation.

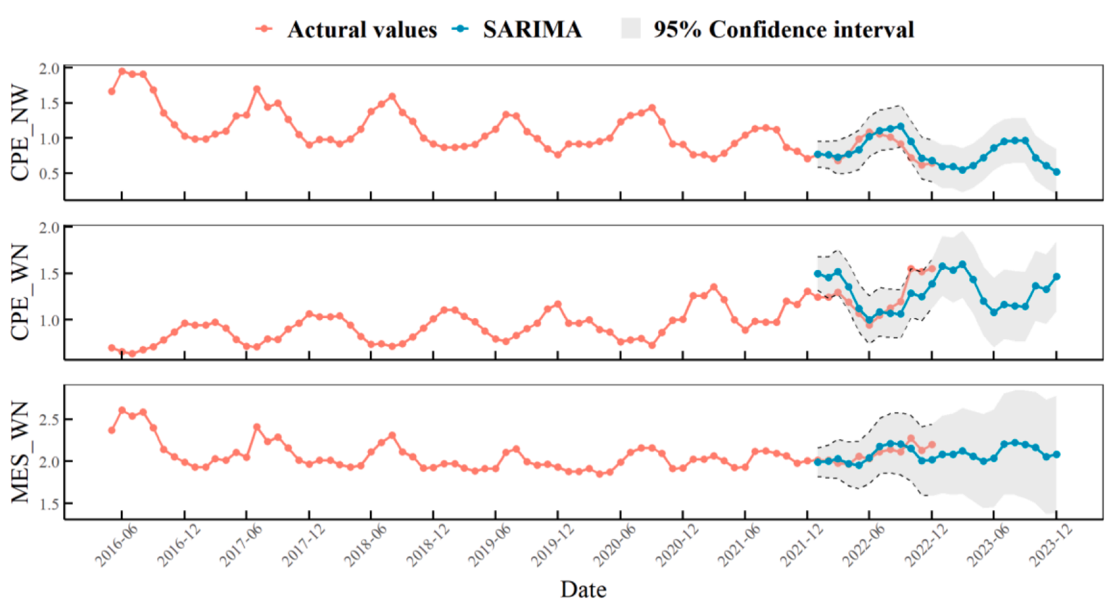

Fig. 9. Elasticity of substitution between hydropower generation and new energy generation.

4.2. Reginal analysis

Fig. 10 reveals the dynamic relationship between thermal power generation and clean energy generation across various Chinese provinces during the observation period. In provinces such as Yunnan, Sichuan, Guangxi, Xinjiang, Hubei, Hunan, Gansu, Fujian, Guizhou, Chongqing, and Qinghai, there is a consistent substitution relationship between thermal power and clean energy generation. This suggests that as the price of thermal power increases, the demand for clean energy generation correspondingly rises, indicating market sensitivity to energy price changes and a preference for clean energy.

In contrast, the situation in Guangdong, Zhejiang, and Henan is more complex. During most months of the observation period, these provinces exhibit a substitution relationship between thermal and clean energy generation, but there are months when this relationship becomes uncertain. This fluctuation may be due to various factors, including

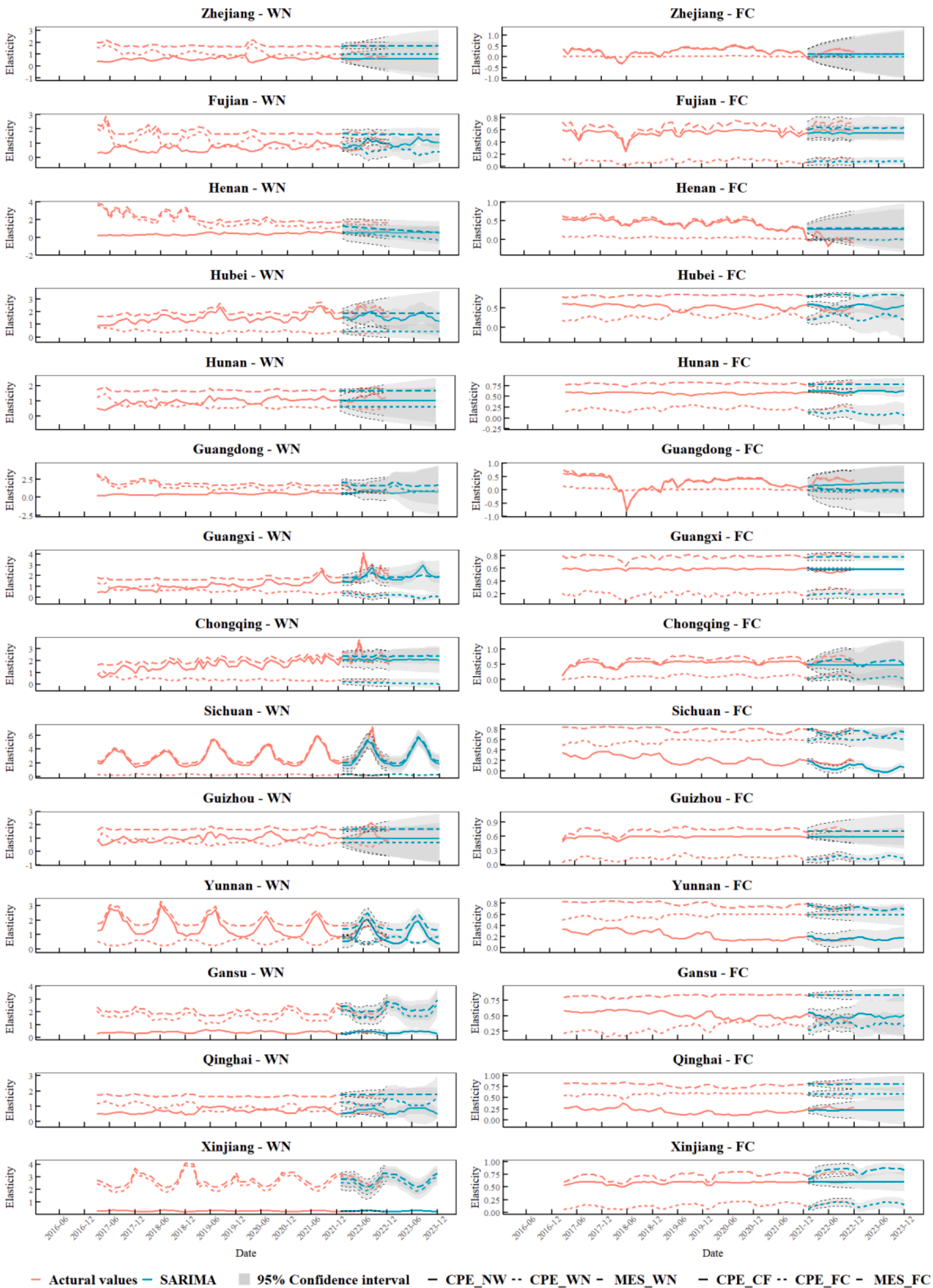

Fig. 10. Elasticity of substitution by province.

seasonal demand changes, policy adjustments, market supply and demand conditions, and the external economic environment. For instance, the increased demand for air conditioning in summer and heating in winter may drive up the demand for thermal power, creating a ripple effect on the demand for clean energy generation.

Within the clean energy sector, hydropower and new energy generation generally exhibit a substitution relationship in 14 provinces. Sichuan, for example, is a significant base for hydropower due to its abundant water resources, making hydropower a crucial component of the province's energy structure. High MES values indicate that as new energy generation grows, hydropower's role in meeting energy demand is enhanced, particularly when new energy supply is insufficient. Similarly, Xinjiang, with its rich wind and solar resources, shows rapid growth in new energy generation, leading to high MES values. This reflects the significant potential of new energy to replace non-clean energy sources, including hydropower. This substitution relationship demonstrates not only the market's adaptability to energy type shifts but also the crucial role of energy policies and technological advancements in driving the transformation of the energy structure.

From the predictive results, except for certain elasticity values in Henan, Zhejiang, and Guangdong that are less than zero, other provinces maintain a trend of cyclical fluctuations in elasticity values, all greater than zero, indicating a substitution relationship. The more pronounced the cyclical changes in elasticity, the better the model's predictive performance.

5. Conclusion

This study provides a detailed quantitative analysis of the substitution effects within China's clean energy sector, focusing on the dynamics between hydropower and new energy sources such as wind and solar power across the top 14 hydropower-producing provinces. The findings are based on the estimation of cross-price elasticity (CPE) and Morishima elasticity of substitution (MES), revealing significant substitution relationships that have substantial implications for energy policy and strategic planning.

1. Substitution Dynamics Between Clean Energy and Thermal Power Generation.

   Our analysis indicates a moderate substitution effect between clean energy and thermal power generation, with the mean MES being 0.663. This substitution effect is more pronounced during peak seasons, particularly in summer, when the demand for air conditioning drives up electricity consumption. The seasonal variations highlight the critical role of enhancing the capacity and reliability of clean energy sources to mitigate peak electricity demand. Policymakers should consider prioritizing investments in solar and wind power infrastructure, especially in regions with high seasonal energy demands. Enhancing grid integration and storage solutions will further stabilize the energy supply, reducing reliance on thermal power during peak periods and aligning with China's carbon neutrality goals.
2. Strong Substitution Relationship Within Clean Energy Sector.

   The study reveals a strong substitution relationship within the clean energy sector, particularly between hydropower and new energy sources, with the mean MES reaching 2.067. This indicates that as the costs of wind and solar power decrease, these new energy sources increasingly replace hydropower, especially during periods of water scarcity. Policies that support technological advancements and cost reductions in wind and solar power are crucial. Incentives for research and development, as well as subsidies or tax incentives for deploying these technologies, will be essential. Additionally, enhancing grid flexibility and storage capacity will maximize the benefits of these renewable sources.
3. Regional Disparities in Substitution Dynamics.

   The study highlights significant regional differences in substitution dynamics. Provinces like Yunnan, Sichuan, and Qinghai, with abundant hydropower resources, should focus on optimizing hydropower generation while gradually increasing the share of wind and solar power. In contrast, economically developed provinces with higher energy demands and less favorable conditions for hydropower, such as Zhejiang and Guangdong, should prioritize the development of wind and solar power infrastructure and improve energy efficiency measures. Tailored policies that consider local resource endowments and economic contexts will ensure a more balanced and sustainable energy transition across the country.
4. Predictive Analysis Using SARIMA Model.

   The application of the Seasonal Autoregressive Integrated Moving Average (SARIMA) model in this study provides a valuable tool for policymakers. The model's high accuracy in forecasting elasticity values enables the anticipation of future substitution dynamics, allowing for proactive policy adjustments. Policymakers can use these predictions to plan for seasonal and cyclical variations in energy supply and demand, ensuring a more stable and reliable energy system. For instance, during anticipated periods of high demand, policies can be implemented to encourage energy conservation or to ramp up clean energy production.

6. Limitations and future work

There are several limitations to this study that should be acknowledged, and areas for future research that could enhance our findings.

1. Temporal Scope of the Data: The data used in this study spans from May 2016 to December 2022. While this provides a solid foundation for understanding recent trends and dynamics, extending the data to include 2023 and beyond would offer a more current and potentially richer perspective on the substitution effects within China's clean energy sector. Future research should aim to incorporate the most recent data to capture ongoing developments and policy impacts more accurately.
2. Advanced Grid Management: Integrating variable renewable energy sources such as wind and solar into the grid presents significant challenges related to stability and reliability. Our current discussion does not fully address these complexities. Future research should investigate advanced grid management technologies and strategies. This includes smart grids, real-time monitoring systems, and advanced distribution management systems that can handle the variability and intermittency of renewable energy sources more effectively.
3. Energy Storage Solutions: The intermittency of wind and solar power necessitates effective energy storage solutions to ensure a stable energy supply. Future work should analyze the role of various energy storage technologies, including battery storage, pumped hydro storage, and other innovative solutions. These technologies are crucial for balancing supply and demand and for mitigating the effects of renewable energy variability.

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CRediT authorship contribution statement

Yubao Wang: Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Huiyuan Pan:** Writing – review & editing, Writing – original draft, Software, Data curation. **Junjie Zhen:** Writing – review & editing, Methodology, Conceptualization. **Boyang Xu:** Writing – review & editing, Software, Methodology.

Declaration of competing interest

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

Data availability

Data will be made available on request.

References

Attílio, L.A., Faria, J.R., Silva, E.C.D., 2024. Countervailing impacts of fossil fuel production and exports of electrical goods on energy transitions and climate change. J. Cleaner Prod. 464, 142797. https://doi.org/10.1016/j.jclepro.2024.142797.

Brockwell, P.J., Davis, R.A., 2002. Introduction to time series and forecasting. Springer. https://doi.org/10.2307/2965440.

Chai, S., Liu, Q., Yang, J., 2023. Renewable power generation policies in China: policy instrument choices and influencing factors from the central and local government perspectives. Renew. Sustain. Energy Rev. 174, 113126. https://doi.org/10.1016/j.rser.2022.113126.

Coelli, T.J., Rao, D.S.P., O'donnell, C.J., Battese, G.E., 2005. An introduction to efficiency and productivity analysis. springer science & business media.

Du, K., Cheng, Y., Yao, X., 2021. Environmental regulation, green technology innovation, and industrial structure upgrading: the road to the green transformation of Chinese cities. Energy Econ. 98, 105247. https://doi.org/10.1016/j.eneco.2021.105247.

Fang, T., Lahdelma, R., 2016. Evaluation of a multiple linear regression model and SARIMA model in forecasting heat demand for district heating system. Appl. Energy 179, 544–552. https://doi.org/10.1016/j.apenergy.2016.06.133.

Gikungu, S.W., Waititu, A.G., Kihoro, J.M., 2015. Forecasting inflation rate in Kenya using SARIMA model. Am. J. Theoretical Appl. Stat. 12 (3), 15–18. https://doi.org/10.11648/j.ajtas.20150401.13.

Guo, Y., Ming, B., Huang, Q., Yang, Z., Kong, Y., Wang, X., 2023. Variation-based complementarity assessment between wind and solar resources in China. Energy Convers. Manage. 278, 116726. https://doi.org/10.1016/j.enconman.2023.116726.

Hicks, J.R., 1932. The theory of wages. Am. J. Sociol. 32 (125). https://doi.org/10.2307/2552450.

Hou, G.S., Song, H.Y., 2022. Whether the directed technical change promotes the improvement of the energy structure in China. Front. Environ. Sci. 10. https://doi.org/10.3389/fenvs.2022.928239.

Hu, Y.-J., Zhang, R., Wang, H., Li, C., Tang, B.-J., 2024. Synergizing policies for carbon reduction, energy transition and pollution control: Evidence from Chinese power generation industry. J. Cleaner Prod. 436, 140460. https://doi.org/10.1016/j.jclepro.2023.140460.

Kumar, A., Jamro, I.A., Rong, H., Kumari, L., Laghari, A.A., Cui, B., Aborisade, M.A., Oba, B.T., Nkinahamira, F., Ndagijimana, P., Sajnani, S., Bhagat, W.A., Guo, D., 2024. Assessing bioenergy prospects of algal biomass and yard waste using an integrated hydrothermal carbonization and pyrolysis (HTC–PY): A detailed emission–to–ash characterization via diverse hyphenated analytical techniques and modelling strategies. Chem. Eng. J. 492, 152335. https://doi.org/10.1016/j.cej.2024.152335.

Kumar, A., Yan, B., Tao, J., Li, J., Kumari, L., Tafa Oba, B., Akintayo Aborisade, M., Ali Jamro, I., Chen, G., 2022. Co-pyrolysis of de-oiled microalgal biomass residue and waste tires: deeper insights from thermal kinetics, behaviors, drivers, bio-oils, bio-chars, and in-situ evolved gases analyses. Chem. Eng. J. 446, 137160. https://doi.org/10.1016/j.cej.2022.137160.

Lee, C.-C., Li, Y.-Y., 2024. Does environmental policy matter for renewable energy production and economic activity? evidence from granger causality in quantiles. Econ. Anal. Policy 81, 225–237. https://doi.org/10.1016/j.eap.2023.11.024.

Liu, F., Xia, Z., Lee, C.-C., 2024. Does green credit benefit the clean energy technological innovation and how? The policy catering behavior of enterprises. J. Cleaner Prod. 444, 141256. https://doi.org/10.1016/j.jclepro.2024.141256.

Liu, H.X., Lin, B.Q., 2017. Energy substitution, efficiency, and the effects of carbon taxation: evidence from China's building construction industry. J. Cleaner Prod. 141, 1134–1144. https://doi.org/10.1016/j.jclepro.2016.09.119.

Liu, P.K., Guo, K.L., Wu, J.H., 2024. Research on alternative relationship between Chinese renewable energy and imported coal for China. Sustainability 16 (8). https://doi.org/10.3390/su16083446.

Luo, C., Zhang, K., 2024. Elasticity of substitution between clean energy and non-clean energy: Evidence from the Chinese electricity industry. Clean. Energy Syst. 8, 100117. https://doi.org/10.1016/j.cles.2024.100117.

Morishima, M., 1967. A few suggestions on the theory of elasticity. Keizai Hyoron (Economic Review) 16 (1), 144–150.

Noor, T.H., Almars, A.M., Alwateer, M., Almaliki, M., Gad, I., Atlam, E.-S., 2022. SARIMA: a seasonal autoregressive integrated moving average model for crime analysis in Saudi Arabia. Electronics 11 (23), 3986. https://doi.org/10.3390/electronics11233986.

Papageorgiou, C., Saam, M., Schulte, P., 2017. Substitution between clean and dirty energy inputs: a macroeconomic perspective. Rev. Econ. Stat. 99 (2), 281–290. https://doi.org/10.1162/REST_a_00592.

Pelli, M., 2012. The elasticity of substitution between clean and dirty inputs in the production of electricity. In: Proceedings of the Conference on Sustainable Resource Use and Economic Dynamics (SURED 2012). Ascona, Switzerland, pp. 1–40.

Shang, D., Geissler, B., Mew, M., Satalkina, L., Zenk, L., Tulsidas, H., Barker, L., El-Yahyaoui, A., Hussein, A., Taha, M., Zheng, Y., Wang, M., Yao, Y., Liu, X., Deng, H., Zhong, J., Li, Z., Steiner, G., Bertau, M., Haneklaus, N., 2021. Unconventional uranium in China's phosphate rock: review and outlook. Renew. Sustain. Energy Rev. 140, 110740. https://doi.org/10.1016/j.rser.2021.110740.

Sun, J., Wang, Y., He, Y., Cui, W., Chao, Q., Shan, B., Wang, Z., Yang, X., 2024. The energy security risk assessment of inefficient wind and solar resources under carbon neutrality in China. Appl. Energy 360, 122889. https://doi.org/10.1016/j.apenergy.2024.122889.

Sun, L., Niu, D., Wang, K., Xu, X., 2021. Sustainable development pathways of hydropower in China: interdisciplinary qualitative analysis and scenario-based system dynamics quantitative modeling. J. Cleaner Prod. 287, 125528. https://doi.org/10.1016/j.jclepro.2020.125528.

Wang, C., Raza, S.A., Adebayo, T.S., Yi, S., Shah, M.I., 2023. The roles of hydro, nuclear and biomass energy towards carbon neutrality target in China: A policy-based analysis. Energy 262, 125303. https://doi.org/10.1016/j.energy.2022.125303.

Wang, Y., Chang, X., Gao, M., Hou, X., 2013. Seasonal autoregressive integrated moving average model for precipitation time series. J. Math. Stat. 8 (4), 500–505. https://doi.org/10.3844/jmssp.2012.500.505.

Wang, Y.D., Mao, J.Q., Chen, F., Wang, D.L., 2022. Uncovering the dynamics and uncertainties of substituting coal power with renewable energy resources. Renew. Energy 193, 669–686. https://doi.org/10.1016/j.renene.2022.04.164.

Wesseh Jr., P.K., Lin, B., Appiah, M.O., 2013. Delving into Liberia's energy economy: technical change, inter-factor and inter-fuel substitution. Renew. Sustain. Energy Rev. 24, 122–130. https://doi.org/10.1016/j.rser.2013.03.061.

Xie, C., Hawkes, A.D., 2015. Estimation of inter-fuel substitution possibilities in China's transport industry using ridge regression. Energy 88, 260–267. https://doi.org/10.1016/j.energy.2015.05.034.

Xu, Y., Yang, Z.J., Yuan, J.H., 2021. The economics of renewable energy power in China. Clean Technol. Environ. Policy 23 (4), 1341–1351. https://doi.org/10.1007/s10098-021-02031-0.

Yu, S., Lu, T., Hu, X., Liu, L., Wei, Y.-M., 2021. Determinants of overcapacity in China's renewable energy industry: evidence from wind, photovoltaic, and biomass energy enterprises. Energy Econ. 97, 105056. https://doi.org/10.1016/j.eneco.2020.105056.

Zahoor, Z., Khan, I., Hou, F., 2022. Clean energy investment and financial development as determinants of environment and sustainable economic growth: evidence from China. Environ. Sci. Poll. Res. 29 (11), 16006–16016. https://doi.org/10.1007/s11356-021-16832-9.

Zellner, 1962. An Efficient Method of Estimating Seemingly unrelated regressions and tests for aggregation bias. J. Am. Statist. Assoc. 57 (298), 348–368. https://doi.org/10.1080/01621459.1962.10480664.

Zhao, G.P., Yu, B.Y., An, R.Y., Wu, Y., Zhao, Z.H., 2021. Energy system transformations and carbon emission mitigation for China to achieve global 2°C climate target. J. Environ. Manage. 292. https://doi.org/10.1016/j.jenvman.2021.112721.

Zhao, L.J., Wang, K., Yi, H.R., Cheng, Y.F., Zhen, J.T., Hu, H.S., 2024. Carbon emission drivers of China's power sector and its transformation for global decarbonization contribution. Appl. Energy 376. https://doi.org/10.1016/j.apenergy.2024.124258.