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Posted Date: 1 July 2024

doi: 10.20944/preprints202407.0027.v1

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Article

Multi-Scenario Research on the Coupled and Coordinated Development of the Economic-Energy-Environmental (3E) System under the Reconstruction of the Power System - New Exploration Based on the "Dual-Triangle" Theory

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Abstract: Building a new-type power system is the key core of the green and low-carbon development of energy, the restructuring of the power system will inevitably have a linked impact on the coordinated development of the economy-energy-environment (3E) system. This paper constructs a "Dual-Triangle" theoretical framework consisting of the "Energy Trilemma" and the "Sustainable Development Triangle", by combining historical statistical analysis with scenario predictive analysis, analyzes the historical characteristics of the "Dual Triangle" and future development trends under different scenarios, and studies the coupled interaction relationship of the "Dual-Triangle" to explore the optimal transformation path of the power system that is most beneficial to the coordinated development of the 3E system. The conclusions are as follows: (1) The energy system gradually inclined towards economy and cleanliness from 2010 to 2022, the level of coordinated development of the 3E system fluctuated upwards, and the operation status of the "Dual Triangle" was stable. (2) Positive coupling relationship between "Dual Triangle" of scenario S_1 is close, which can be regarded as the preferred path for the reconstruction of the power system. Due to phased development has clear development priorities, scenario S_2 will artificially break the balance of the "Energy Trilemma", which is a development model that dynamically mitigates the challenges of the "Energy Trilemma".(3)The contradiction between economy and cleanliness is continuously weakened, and security has become the core contradiction of the "Impossible Triangle". The combination of renewable energy and energy storage is the key to resolving this contradiction. This paper conducts an integrated and innovative application of the "Dual-Triangle" theory, and the results provide a case basis for how to achieve the coupled interaction of the "Dual-Triangle", promote high-quality energy development, and support the sustainable development of the economy and society.

Keywords: coupled and coordinated development; economic-energy-environmental (3E) system; power system; "energy trilemma"; dual-triangle; scenario predictive

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1. Introduction

In the 1980s, the World Commission on Environment and Development (WCED) formally introduced the concept of "sustainable development" in its report "Our Common Future"[1] ,indicating that sustainable development is development that can meet the needs of the present generation without compromising the ability of future generations to meet their own needs. Since then, numerous international energy, economic, and environmental protection agencies have begun to focus on exploring the coordination and sustainable development issues of the economy-energy-environment system (hereinafter referred to as the 3E system), which is the "Sustainable Development Triangle" problem. In 2010, the World Energy Council (WEC) proposed the term

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energy "Impossibility Triangle" (Energy Transition Index, ETI) and constructed an "Energy Trilemma" Index to measure national energy performance. The underlying logic is that it is impossible to ensure the simultaneous development of all three indices, as they are mutually exclusive [2-3],hence a balanced choice must be made.

Research on the "Sustainable Development Triangle" issue has been conducted by scholars both domestically and internationally using various methods [4-6], from different perspectives (7-10), and across different spatial scales (such as national [11], provincial [12-13], urban agglomeration [14], and city-level [15] scales). For instance, in the construction of the 3E system evaluation index system, scholars have designed and added indices according to their areas of interest, leading to a more refined description of the 3E system [16]. In addition, scholars have also expanded their research on the 3E system by incorporating an additional subsystem, extending the 3E system to a quaternary system for study. For example, Oliveira, C. et al. [5] integrated the social subsystem into the 3E system to study the interactions between the economy, energy, and their impact on the environment; Wei Yiming et al. [17] included the population system in the research scope, constructing multi-objective planning and integrated models to reflect the balancing relationship of subsystem coordinated development. With the rapid development of technology, the impact of technological factors on the 3E system has become increasingly significant. Yu Yang [18-20], Ye Wanjun [12], and Chen Hailong [21] have incorporated technological elements into the 3E system to measure and evaluate the coordinated development of the quaternary system. The research results indicate that conforming to the characteristics of the times and adding a subsystem (or index) closely related to the characteristics of the era can make the coordinated development state of a region more realistic. Besides the 3E coupled system, some scholars have expanded their focus to include the social system, constructing a 3E1S coupled system. Bai Jiajun [22] and Wang Linyu [23] have conducted empirical research on the Chengdu-Chongqing urban agglomeration and Jiangsu Province, respectively, obtaining conclusions about the temporal and spatial heterogeneity differences between different urban agglomerations through temporal and spatial evolution.

Since the proposal of the energy "Impossibility Triangle", scholars both domestically and internationally have conducted extensive research, mainly involving three aspects: first, a qualitative explanation of the basic meaning and deep logic of the energy "Impossibility Triangle" from an interdisciplinary perspective. The "Impossible Triangle" was first proposed in the financial field, indicating that a country cannot simultaneously achieve free capital flows, independent monetary policy, and stable exchange rates in its financial policies. This theory has since been widely cited and applied in various fields. Sun Qiuye [24] and others have introduced the entropy theory as a quantitative tool into the problem of the energy system's impossible triangle, summarizing the issues of the energy system, analyzing the advantages and challenges of the ETI, and outlining potential future research directions. Second, exploration into solving the energy "Impossibility Triangle" issue. Wang Chunzhi, Chen Guang, Liu Chuanjun [25-27] and others have used the coupled coordination model to construct a comprehensive evaluation index system for energy development from the perspectives of energy security, energy cost, and energy environment, analyzing the feasibility of breaking the energy "Impossibility Triangle" ; Zhang Qingjun [28] and others have used spatial measurement methods to analyze the impact of financial openness on energy security, finding a significant negative correlation between financial openness and energy security. Masoud [29] and others have used the state transition vector autoregression model to analyze the impact of the energy impossible triangle on sustainable economic development and geopolitical risks, and pointed out that countries should formulate relevant policies to promote energy technology transformation to facilitate sustainable economic growth. The choices made by some foreign countries in the process of energy development in the face of the "Energy Trilemma" also provide relevant experience and lessons. Cosimo [30] and others have used time series analysis and machine learning to study the trilemma of carbon emissions, energy supply, and economic growth in Russia, and finally, combined with the policies initiated by Russia and the current economic background, it is proved that stabilizing or even reducing greenhouse gas emissions without harming economic growth is possible. Elsa and Neil [31] have used the Brain-Energy generation investment model to simulate the energy

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transition path trends in the UK, Germany, and Italy, and the results indicate that achieving an energy transition to break the energy "Impossibility Triangle" requires the evolution of policies and strategies of different market participants.

The aforementioned research mostly explores the development patterns of the “Sustainable Development Triangle” and the energy "Impossibility Triangle" (hereinafter referred to as the “Dual-Triangle”) by analyzing historical data. However, there is a relative lack of predictive analysis on the future development trends and influencing factors of the “Dual-Triangle,” especially research that conducts coupled and collaborative analysis of the “Dual-Triangle.” With the proposal of China’s “Dual Carbon” strategic goals and the rapid restructuring of the power system, it would be difficult to comprehensively study the impact of the energy and power industry’s development on the economy and society, and to accurately grasp the society and economy’s requirements for the energy and power industry, if the connections between the “Dual-Triangle” are not considered. This need becomes even more urgent, especially when the power industry’s goals of peaking carbon emissions and achieving carbon neutrality are increasingly related to the overall target realization.

In light of this, this study takes the energy system as the center, constructs a “Dual-Triangle” theoretical framework, and takes Guangzhou City, one of the four central cities in the Guangdong-Hong Kong-Macao Greater Bay Area, as an example. By combining historical statistical analysis with scenario predictive analysis, the study deeply analyzes the historical patterns and future trends of the energy system’s security, cleanliness, and economy, identifies the key factors influencing the relationship between the economy, energy, and environment, and explores the optimal combination for the collaborative development of the “Dual-Triangle.”

Case region introduction: Guangzhou City is one of the four central cities (Hong Kong, Macau, Guangzhou, Shenzhen) in the Guangdong-Hong Kong-Macao Greater Bay Area and is one of the largest super-large cities in terms of energy consumption in China. However, it is also a typical energy-importing city. Fossil energy sources such as coal, oil, and natural gas rely on imports and transfers from other regions, and the local endowment of renewable energy is poor. Except for solar energy resources, the development potential of other renewable energy sources is already close to saturation. The local power generation capacity is relatively weak. In 2022, Guangzhou City’s power consumption was 115.5 billion kilowatt-hours, with an power self-sufficiency rate of only 31.63%. It has the typical characteristics of “serious energy scarcity and extremely high power load density.” In terms of the environment, the city’s annual average PM2.5 concentration was about 22 micrograms per cubic meter in 2022, far exceeding the standard recommended by the World Health Organization (WHO) (PM2.5 < 10 micrograms per cubic meter). There is a strong desire for the restructuring of the power system and the coupled and coordinated development of the 3E system.

Figure 1. Location map of Guangzhou.

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2. Materials and Methods

2.1. The "Dual- Triangle" Theoretical Framework

The "Sustainable Development Triangle" is used to describe the interconnected relationship between energy, economy, and environment [32]. The economic subsystem is the core of the 3E system, with both energy and environment serving this core. In return, the economic system provides financial and material support for energy and the environment. The environmental subsystem is the carrier of the 3E system, providing a space for economic and energy activities. The energy subsystem is the material basis of the 3E system, providing power support for economic development and environmental protection. Any change in any subsystem of the 3E system will affect each other through their connections with other subsystems, thus impacting the coordinated development of the entire 3E system.

The energy "Impossibility Triangle" is used to describe the balance between security, cleanliness, and economy in the development of the energy system itself. These three aspects are interrelated and mutually restrictive. Pursuing higher energy security may require increased investment, thus affecting the economy of energy. Overemphasizing the cleanliness of energy may increase costs in the short term, impacting economic performance. Meanwhile, focusing too much on economy may sacrifice the security or cleanliness of energy to some extent.

There is an intrinsic link between the "Dual-Triangle" (Figure 2). Sustainable development requires a stable and clean energy supply as support, and the direction of energy system development will influence the focus choice of the energy "Impossibility Triangle" . When the development of the economic system is hindered, it is necessary to reduce energy costs to provide more space for economic growth, and the focus of energy development should lean towards economy. On the other hand, the energy economy and cleanliness in the energy "Impossibility Triangle" will affect the economic, social, and ecological activities in the "Sustainable Development Triangle". When the focus of energy development leans towards cleanliness, it may enhance the carrying capacity of the external environmental system while possibly causing energy price shocks and weakening the potential for economic development. Therefore, the energy system primarily interacts with the economic system and environmental system through changes in energy security, economy, and cleanliness.

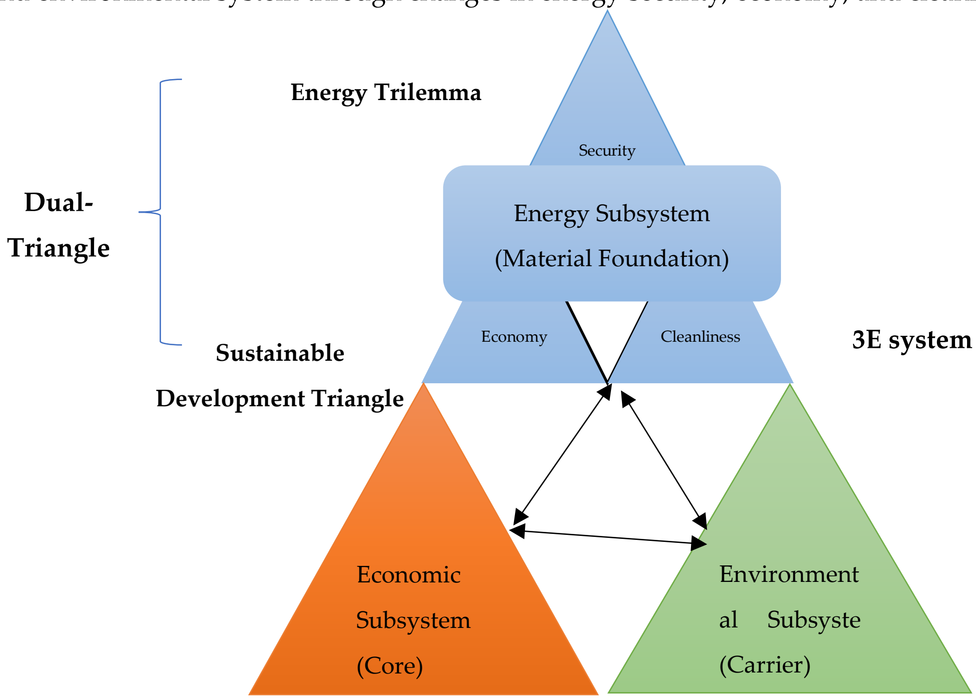

Figure 2. "Dual- Triangle" theoretical framework.

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2.2. Energy System Index Accounting

(1) Selection of measurement indicators for the energy "Impossibility Triangle"

Based on the three dimensions of the energy "Impossibility Triangle", ten measurement indicators have been selected (see Table 1 for details).

Table 1. Characteristics and measurement indicators of the new power system on the supply side.

Measure index	Measure index	Index selection basis
Security(2)	Self-sufficiency rate of power (+)	The self-sufficiency rate of resources is an index to measure the productivity of resources in a region, and it is also a key index to characterize the safety of resource supply. Self-sufficiency rate of power = local power generation/power consumption of the whole society, focusing on measuring the actual supply capacity from the perspective of output.
	Demand for purchased power (-)	The demand for purchased power indicates the external dependence of power, and high external dependence will seriously affect energy security.
Cleanliness(3)	Proportion of renewable energy generation (+)	The proportion of renewable energy power generation to the total power generation, and a high proportion of renewable energy power generation is the basic requirement for the construction of new power system.
	Proportion of clean energy power generation (+)	The proportion of clean energy power generation, including natural gas, to the total power generation is an important indicator to measure the cleanliness of power supply.
	Carbon emissions	Carbon emission is one of the important indicators of whether the energy system is clean and low-carbon.
Economy(5)	Initial investment cost (-)	The cost required for the construction and installation of an electricity project is one of the important factors determining the total investment cost.
	Replacement cost (-)	The expenses incurred when replacing or updating existing electricity-related equipment, facilities, or systems.
	Operational and maintenance costs (including the cost of purchased electricity, -)	The various expenses generated during the operation and maintenance of the power system.
	Fuel cost (-)	The costs of various fuels used for power generation.
	Residual value of equipment (+)	The residual value of the equipment at the end of the project lifecycle, which is better when higher.

(2) Power demand forecasting

The Long-range Energy Alternatives Planning System (LEAP) model is a bottom-up energy-environment accounting tool developed jointly by the Stockholm Environment Institute and Boston University in the United States. Energy consumption is calculated from activity levels and energy intensity.

$$E = \sum V_k \times \rho_k \quad (1)$$

Among them,

E-Power demand,

V_k-Value added of sector k, with k = 1, 2, ..., 11, denoting the 11 sub-sectors including agriculture, industry, and others.

ρ_k -The energy intensity indicator, which is primarily used in this study for power consumption forecasting. Here, the energy intensity mainly refers to the power consumption per unit of value added in sector *k*. Considering the current economic, social, and industrial structure characteristics of Guangzhou, and assuming that technological development levels and the efficiency of electrical equipment will steadily improve based on the first two years of the 13th and 14th Five-Year Plans, the government will also adopt more feasible policies and measures to guide and promote a steady increase in the electrification level of various industries.

The forecast results (Table 2) show that the power demand of Guangzhou city will increase from 115.5 billion kWh in 2022 to 156.5 billion kWh in 2030, with an average annual growth rate of 3.67%.

Table 2. Forecast results of power demand.

	2022	2023	2024	2025	2026	2027	2028	2029	2030
Power demand (10^8kWh)	1155	1210	1277	1335	1369	1420	1467	1510	1565

(3) Power supply forecast

1) Scenario setting

In this paper, four power supply scenarios are set, and the settings of different scenarios and various parameters are shown in Table 3, 4&5. Taking 2022 as the base year, the forecast period is 2023-2030.

Table 3. Description of scenario parameters.

Scenarios	Scenario description	Parameter setting
Business as Usual (BAU)	All power supply indicators remain at the level of 2022.	Installed capacity: put into production in strict accordance with Guangzhou planning[33-34]. Energy consumption for power generation: both will maintain the level of 2022. Electricity generation utilization hours: all of them maintain the level of 2022. Investment cost: all of them are maintained at the level of 2022.
Vigorously promoting renewable energy scenario(S_1)	Vigorously promote the installation of renewable energy; Improve the power generation time of gas, power and biomass units; Reduce the energy consumption of coal and gas power generation; According to the demand of economic recovery after the epidemic, the power generation time of coal power units is set to increase before 2025 and decrease year by year in 2026.	Installed capacity: According to the "Renewable Energy Capacity Statistics 2023" report released by the International Renewable Energy Agency (IRENA) [35], "to stay on track to limit global warming to 1.5 ° C, the annual increase in renewable energy installation capacity must triple by 2030". Based on Guangzhou's renewable energy potential and the current development situation, the solar photovoltaic installation capacity will be increased to 3.99 million kilowatts, and wind power will add 160MW of installation capacity in 2025, replacing coal and gas power with equal capacity. Energy consumption for power generation: The coal power unit consumption will be increased to the national benchmark and the average benchmark level in 2025 and 2030, respectively. The gas power unit consumption will decrease to 217 gce/kWh in 2025 and to 210 gce/kWh in 2030. Electricity generation utilization hours: According to the characteristics of each type of power generation and the constraints of relevant policies, a mandatory power generation time period is given for each type of power generation (see Table 4). The actual hours of power generation will be optimized through the HOMER software. Investment cost: set according to Table 5.
Security and low-carbon phased development scenario (S_2)	During the "Fourteenth Five-Year Plan" period, the primary goal is to ensure power	Installed capacity: In 2025, achieve the government's planned natural gas power installation capacity for 2028 under the baseline scenario, which is 12.7419 million kilowatts. Complete all planned natural gas power installation capacity for 2030, which is 14.15 million kilowatts, before 2027. The planned installation of

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	supply safety, while during the "Fifteenth Five-Year period, energy conservation and carbon reduction are the main considerations.	renewable energy will be postponed and concentrated for completion in the "Fifteenth Five-Year Plan", with the main new installation being photovoltaic power generation. Generation energy consumption: The same as Scenario S_1. Electricity generation utilization hours: Same as in Scenario S_1. Investment costs: The same as Scenario S_1.
Double high self-sufficiency rate scenario (S_3)	Taking thermal power as the main power supply as the development goal, the power generation duration and energy consumption of various units are the same as S2 scenario.	Installed capacity: Currently, China has very strict regulations on the approval of coal-fired power. Whether Guangzhou can newly commission coal-fired power requires thorough justification. We assume that after efforts during the Fourteenth Five-Year Plan, the additional installation capacity of coal-fired power is 10% of the current installed capacity, with the new capacity to be completed and put into operation after 2025. The remaining production capacity will be supplemented by natural gas power. Generation energy consumption: The same as Scenario S_1. Electricity generation utilization hours: The same as Scenario S_1. Investment costs: The same as Scenario S_1.

Table 4. The mandatory and optimization time periods for each type of power generation.

Power generation category	Mandatory Generation Time	System Optimization Time
Coal Power	Does not generate electricity from 11 PM to 5 AM	other time periods.
Natural Gas Power	10 AM to 9 PM	other time periods.
Biomass	9 AM to 2 PM and 3 PM to 9 PM	other time periods.
Photovoltaic	/	/
Wind Power	/	/
Hydropower	12 AM to 12 PM	/
Other	7 AM to 9 PM;	other time periods.

Table 5. Scenario parameter settings.

	2022	2023	2024	2025	2026	2027	2028	2029	2030
Coal power consumption /(g/kWh)	454	451	448	445	442	439	435	432	429
Energy consumption of gas and power (m^3/kWh)	185	182	179	176	176	175	174	174	173
Biomass energy consumption per kWh (g/kWh)	1828	1828	1828	1828	1828	1828	1828	1828	1828
Photovoltaic investment cost (yuan /kW)	4500	4410	4322	4236	4151	4068	3987	3907	3829

2) Model method

Taking the lowest net present cost (NPC) as the optimization goal, and considering the influence of fuel price, local natural resource endowment and other factors on the whole regional power system,

$$NPC = \min \sum_{i\in\Omega}\left(C_i^{cap} + C_i^{rep} + C_i^{om} + C_i^{gd} + C_i^{fp} - R_i^{gd} - R_i^{s}\right) \quad (2)$$

where *i* stands for each equipment type. Ω represents the collection of all devices in the whole system. C_i^{cap} represents the initial capital cost of the *i-th* type of equipment. C_i^{rep} represent the replacement cost of the *i-th* type of equipment. C_i^{om} represents the operation and maintenance cost of the *i-th* type of equipment. C_i^{gd} represents the cost of purchasing power from the power grid for the *i-th* type of equipment. C_i^{fp} represents the fuel purchase cost of the *i-th* type of equipment. R_i^{gd} is the income from

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selling power to the grid by the *i-th* type of equipment. R_i^S is the residual value of the *i-th* type of equipment at the end of the project's lifecycle. In terms of constraints, the main constraint is energy balance, ensuring the energy balance of the power system.

In terms of carbon emission forecasting, local power source carbon emissions are calculated based on the measured values of carbon content in various fuels from public sources and the default values in the HOMER software [36-37]. The carbon emissions from purchased electricity from 2022 to 2030 are calculated using the recommended average carbon emission factor for Guangdong Province's electricity in the "Notice by the Guangdong Provincial Development and Reform Commission on the Issuance of Methods for Accounting Carbon Dioxide Emissions in Cities Above Prefecture Level in Guangdong Province" (see Table 6).

Table 6. Average carbon emission factors for electricity in Guangdong province.

	2022	2023	2024	2025	2026	2027	2028	2029	2030
Average Carbon Emission Factor（gCO_2/kWh）	373	365	358	350	340	330	320	310	300

2.3.3. E system Index Accounting

(1) Construction of 3E system index system

To adapt to China's statistical standards and the development characteristics of the 3E (Economy-Energy-Environment) system, this paper selects several papers published by Chinese scholars in recent years as representatives [38-39], and statistically analyzes the 3E system indicator frameworks mentioned in these papers. Considering the availability of relevant data in Guangzhou, 12 indicators are optimally selected as the measurement indicators for the 3E system (Table 7), ensuring that the indicator system has a high degree of industry recognition.

Table 7. System Index of 3E System.

	3E system index
Economic subsystem (3)	Gross GDP (+) Per capita GDP (+) Proportion of tertiary industry (+)
Energy subsystem (6)	Total energy consumption (-) Power production (+) Self-sufficiency rate of power (+) Demand for purchased power(-) Proportion of clean energy power generation (+) Proportion of renewable energy power generation (+)
Environment subsystem (3)	PM2.5 (-) Carbon emissions (-) Comprehensive utilization rate of general industrial solid waste (+)

Note:"+" represent positive index；"-" represent negative index.

(2) Calculation of coupling coordinated development degree

The calculation formula of coupling coordinated development degree is as follows:

$$D=\sqrt{C(x,y,z)\cdot T(x,y,z)} \quad (3)$$

Among them,

$$C=3\times\left\{\frac{f(x)\cdot g(y)\cdot h(z)}{\left[f(x)+g(y)+h(z)\right]^3}\right\}^{1/3} \quad (4)$$

$$T=\theta\cdot f(x)+\beta\cdot g(y)+\gamma\cdot h(z) \quad (5)$$

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In the formula, D is the coupling coordinated development degree, $D\in$ [0,1]; C is the degree of coordination, reflecting the synergy level of interaction between systems; T is the development speed, reflecting the comprehensive development level of 3E system. x, y and z respectively represent economic subsystem, energy subsystem and environment subsystem; θ, β and γ are the weights to be determined for economic, energy and environmental systems respectively, $\theta+\beta+\gamma=1$. In order to maintain the robustness of the results, this paper uses the factor analysis weighting method to verify the rationality of the weights given in this paper. The weighted results of factor analysis show that the weights of economy, energy and environment subsystems are 0.3628, 0.3227 and 0.3145 respectively, which are basically consistent with the weighted results in this paper, and can ensure the robustness of the results. $f(x)$, $g(y)$ and $h(z)$ are the comprehensive scores of each subsystem to measure the development level and status of each subsystem. The calculation formula is:

$$f(x)=\sum_{i=1}^{3}w_i x_i' \quad (6)$$

$$g(y)=\sum_{j=1}^{6}w_j y_j' \quad (7)$$

$$h(z)=\sum_{k=1}^{3}w_k z_k' \quad (8)$$

x_i', y_j' and z_k' represent the values of economic, energy, and environmental system indicators, respectively, after linear proportional transformation and standardization, and are calculated using the extreme value method. w_i, w_j and w_k are the weights assigned to each indicator using the entropy method. Taking the calculation of x_i' and w_i as an example, the method is described in below[40]. The calculations of y_j', z_k', w_j, and w_k are similar to those of x_i' and w_i, where j = 1-6 and k = 1-3.

Standardization of indicators:

$$x_i'=\begin{cases}\dfrac{x_i-\lambda_{\min}}{\lambda_{\max}-\lambda_{\min}}, \lambda_{\min}\le x_i\le\lambda_{\max}, x_i \text{ is } \textit{positive}(i\text{=1-3})\\[2ex] \dfrac{\lambda_{\max}-x_i}{\lambda_{\max}-\lambda_{\min}}, \lambda_{\min}\le x_i\le\lambda_{\max}, x_i \text{ is } \textit{negative}(i\text{=1-3})\end{cases} \quad (9)$$

Determine the proportion of indicators: $X_i=\dfrac{x_i'}{\sum_{i=1}^{3}x_i'}$ (10)

Calculate the entropy value of the i-th index: where k>0 and k=$ln(i)$ $e_i=-k\sum_{i=1}^{3}X_i\ln(X_i)$ (11)

Calculate the information utility value of the i index: u_i = 1-e_i (12)

Calculate the weight of each index: $w_i=\dfrac{u_i}{\sum_{i=1}^{3}u_i}$ (13)

2.4. Data Sources and Processing

The data sources include national, Guangdong provincial, and Guangzhou municipal statistical yearbooks, government plans, and other public documents or statistical materials. Some data are sourced from first-hand research conducted by relevant government departments and enterprises in Guangzhou. The study primarily uses the LEAP model, HOMER software, and SPSSAU statistical analysis software for data processing.

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3. Results

3.1. Analysis of the Historical Patterns and Future Trends of the "Energy Trilemma"

(1) Safety characteristic analysis

From the perspective of local power generation (Figure 3), the local generation capacity of Guangzhou City showed a year-by-year decline from 2010 to 2015. However, due to the increasing power consumption, the power self-sufficiency rate showed a significant downward trend (Figure 4). From 2015 to 2019, with the addition of gas power and renewable energy installations, the local generation capacity showed an upward trend. However, due to the rapid growth in power demand, the power self-sufficiency rate still showed a downward trend. Since 2020, the self-sufficiency rate of electricity has begun to rise slowly, and the security of power supply has improved. Under the four scenarios, scenarios BAU and S_1 has been relatively low, especially in S_1, where new energy installations have replaced part of thermal power, leading to a decline in generation capacity after 2028. Scenario S_3 has the highest generation capacity, reaching 697 billion kilowatt-hours in 2030, with an highest power self-sufficiency rate of 44.51%. This is the only scenario among the four where the power self-sufficiency rate continues to rise. In the other scenarios, the power self-sufficiency rate begins to decline slowly from 2027. Due to the much faster growth rate of power demand than local power production, the demand for purchased power has shown an increasing trend since 2010 (Figure 5), with the scenario S_3 having the lowest demand for purchased power. It is evident that Scenario S_3 is the most secure option.

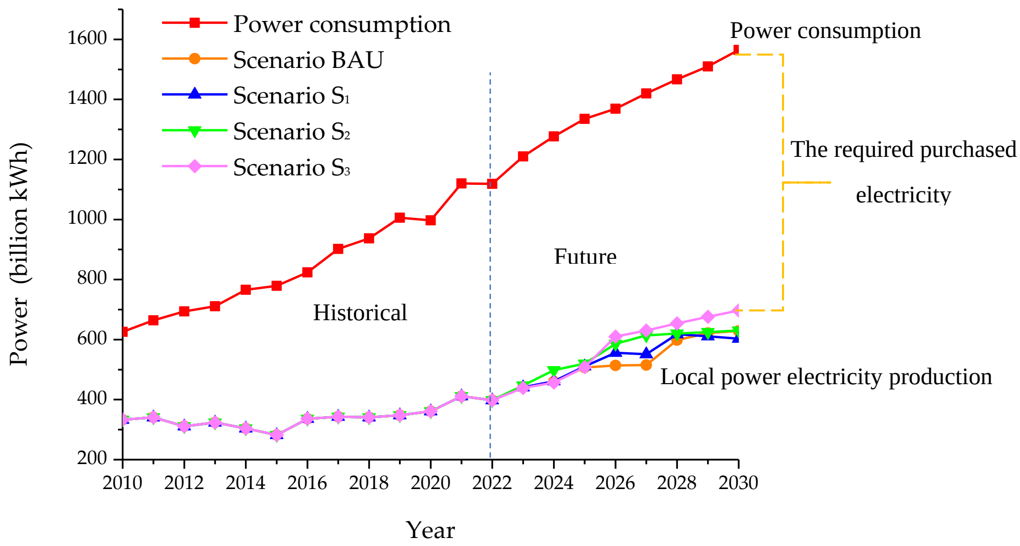

Figure 3. Trend of local power production under different scenarios.

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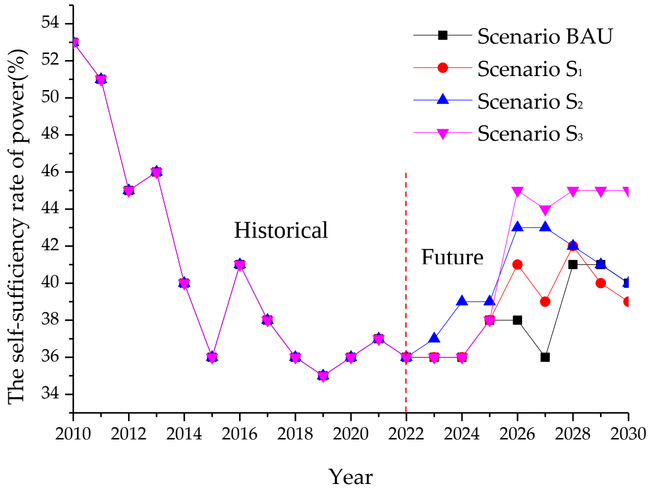

Figure 4. Variation trend of power self-sufficiency rate under different scenarioscharacteristics analysis.

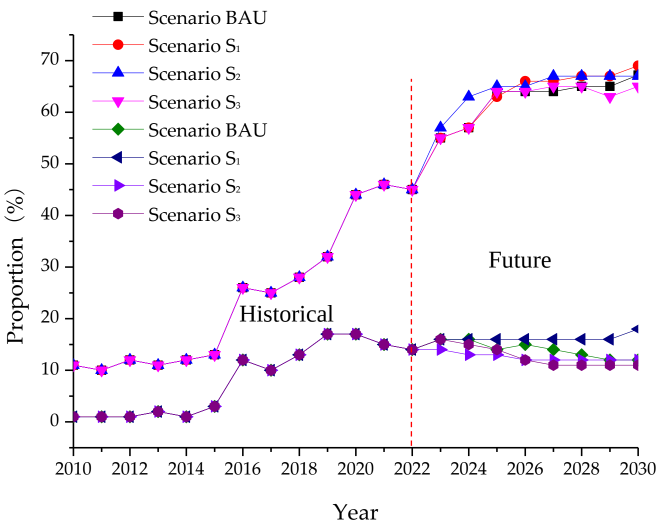

Figure 5. Proportion of clean energy and renewable energy power generation.

(2) Cleanliness characteristic analysis

Looking at the proportion of local clean and renewable energy generation, the proportion of clean energy generation in Guangzhou's total local power generation increased year by year from 2010 to 2028 (Figure 5). In 2028, under Scenario S_2, this proportion reached its highest at 68.34%, indicating a continuous improvement in the cleanliness of Guangzhou's power generation structure. From 2028 to 2030, the proportion of clean energy remained largely stable. In terms of local renewable energy supply, the proportion of renewable energy generation increased year by year from 2010 to 2020. However, after 2020, except for a slight increase in the proportion of renewable energy supply under Scenario S_2, the proportions in other scenarios showed a slow downward trend, hovering around 10%.

In terms of carbon emissions, since the study optimizes for the lowest cost, none of the four scenarios show a significant peak in carbon emissions. From 2010 to 2022, carbon emissions increased year by year. From 2023 to 2030, the carbon emissions in the BAU, S_2, and S_3 scenarios show a rising

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trend year by year, with no signs of peaking. The S_1 scenario has the lowest carbon emissions and reaches a peak in 2025, but then experiences a rebound (Figure 6). Under this scenario, it is necessary to introduce end-of-pipe measures such as carbon capture, storage, and utilization (CCS or CCUS) and ultra-low emissions for coal and gas power to ensure that Guangzhou can achieve a carbon peak by 2030. Looking at the average carbon emissions per kilowatt-hour (Figure 6), the carbon emissions per kilowatt-hour in all four scenarios decrease year by year, with the S1 scenario showing the fastest decline, indicating that the local power generation structure in the scenario S_1 is the cleanest.

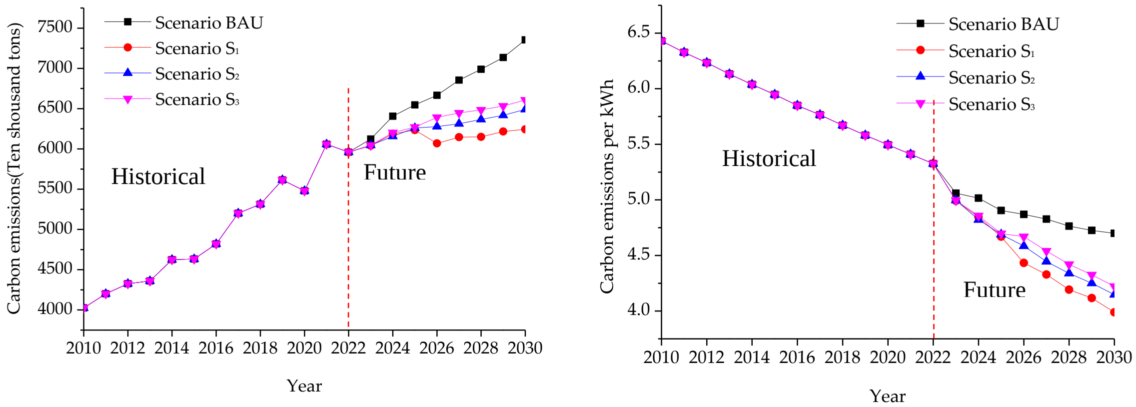

Figure 6. Changing trend of carbon emissions and carbon emission per kWh.

(3) Economic characteristics analysis

The total cost of power generation investment under the four scenarios is increasing year by year (Figure 7a), among which BAU scenario has the highest investment cost and S_1 scenario has the lowest economic advantage. Especially in the "Fifteenth Five-year plan" period, the economic advantage of S_1 scenario is more obvious, and the gap with BAU cost is increasing year by year. The main reason for the gap is that high proportion of photovoltaic installed capacity replaces the operation of other types of generator sets, which reduces the overall fuel cost (Figure 7b, 7c). With the continuous progress of renewable energy development technology, the power generation cost of renewable energy with zero fuel cost represented by solar energy is decreasing year by year, and the gap with fossil fuel power generation cost is getting smaller and smaller. Renewable energy power generation has become the default economic option to increase power capacity. Thus, S_1 scenario is not only the cleanest scenario, but also the most economical scenario. In the future, renewable energy generation will significantly weaken the competitiveness of fossil fuels, which is exactly the development trend we most hope to see in the process of building a new power system.

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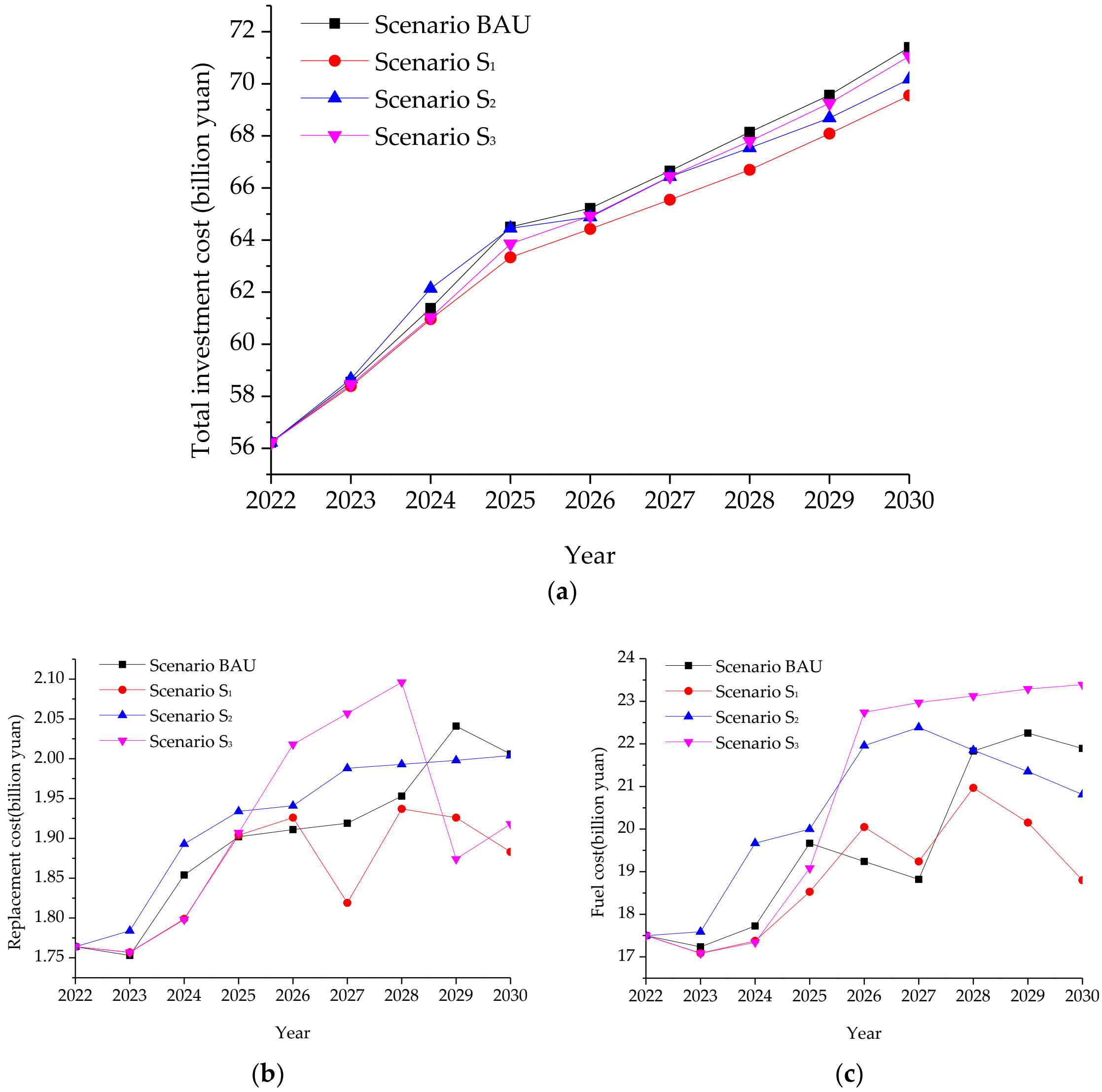

Figure 7. Trend of investment cost changes.

3.2. Analysis of the History and Future Trend of the Coordinated Development of 3E Systems

From 2010 to 2030, the comprehensive score f(x) of Guangzhou's economic subsystem continued to rise(see from Figure 8), indicating that the economic development of Guangzhou has been steadily improving. On the whole, the comprehensive score g(y) of energy subsystem shows a trend of first decreasing and then increasing, while the comprehensive score h(z) of environmental subsystem shows a trend of first increasing and then decreasing. The trend lines of the comprehensive development level of the three subsystems meet, forming two significant stages:

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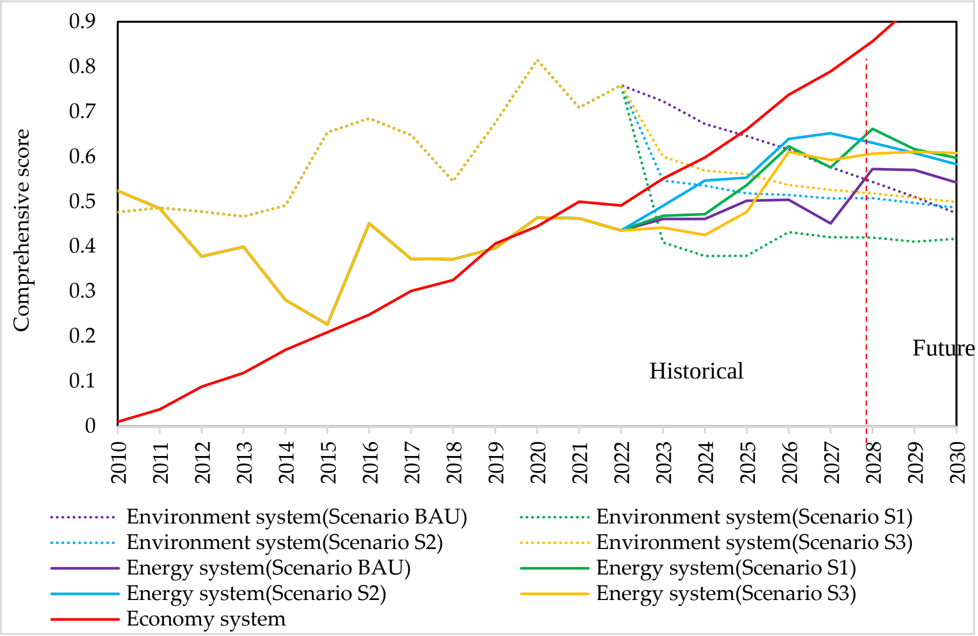

Figure 8. Comprehensive score of each subsystem of 3E system.

Stage 1:Continuous improvement stage of environmental system (2010-2020)

From 2010 to 2020, the comprehensive development level of environmental subsystems fluctuated and rose, with h(z) >g(y) > f(x) at this stage. Among them, from 2010 to 2015, Guangzhou's economy developed rapidly, the industrial structure was optimized and upgraded, the proportion of the secondary industry decreased, the proportion of the tertiary industry increased, and the comprehensive development level of economic subsystems continued to rise. At this stage, the energy demand is also rising steadily. However, due to the slow progress of renewable energy development and insufficient energy production capacity in Guangzhou, the local power generation continues to decrease, and the self-sufficiency rate of power decreases, and the comprehensive development level of energy subsystems decreases accordingly. From 2015 to 2020, with the improvement of energy utilization efficiency and local power production capacity, the comprehensive development level of energy subsystems has been significantly improved.

Stage 2: The stage of environmental system decline (2021-2030)

Since 2021, the comprehensive development level of environmental subsystem began to decline, especially after 2022, due to the economic recovery after the epidemic and the surge in demand for energy, the comprehensive development level of economic and energy subsystems continued to rise in four scenarios, while the comprehensive development level of environmental subsystems declined to varying degrees. Among them, in S_1 scenario, the decline speed of environmental subsystem is the slowest, and the comprehensive development level of economic and energy subsystem exceeds that of environmental subsystem in 2026 and 2028 respectively. In S_2 scenario, the comprehensive development level of environmental subsystem decreases the fastest, and the comprehensive development level of economic and energy subsystems will surpass that of environmental subsystem in 2023.

From the perspective of the development of 3E system coupling and coordination (see Figure 9), the development degree of 3E system coupling and coordination is on the rise from 2010 to 2020, which shows that the development state of Guangzhou coupling and coordination is constantly improving. In 2020-2022, affected by the epidemic situation in COVID-19, the economic development was severely limited, and the degree of coupled and coordinated development of 3E system decreased significantly. Since 2023, the degree of coupled and coordinated development in Scenario S_1 has shown a continuous upward trend after reaching its lowest point in 2024. By 2030, the coupling coordination development degree of this scenario has risen to 0.724, reaching the intermediate

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coordination level. The development degree of coupling and coordination of other scenarios is declining continuously. By 2030, the development degree of coupling and coordination of BAU, S_2 and S_3 scenarios will drop to 0.55, 0.60 and 0.46, respectively, which are in a state of reluctant coordination, primary coordination and on the verge of imbalance. Therefore, the S_1 scenario is the most consistent with the "high quality" development of China.

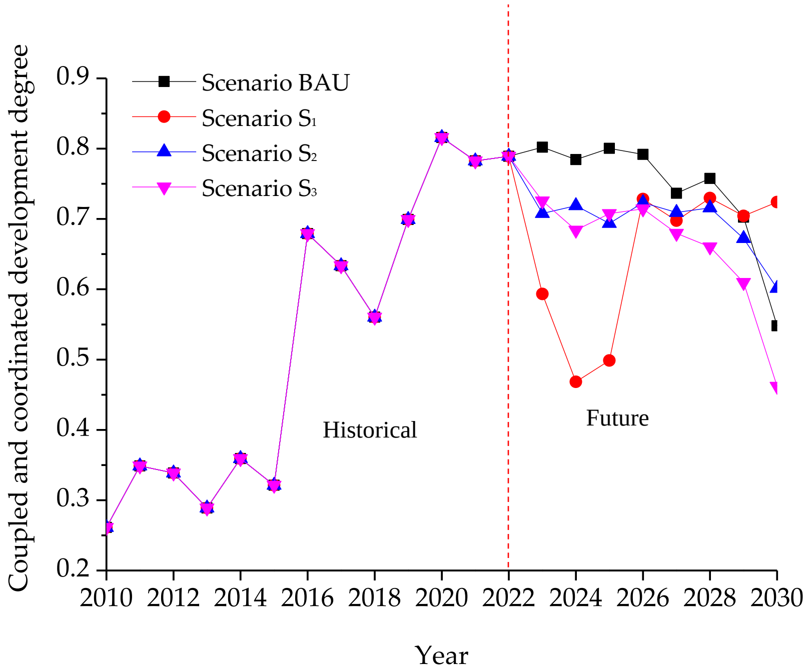

Figure 9. Trend of coupled and coordinated development degree of 3E system.

4. Discussion

From 2022 to 2030, under the BAU and S_3 scenarios, the coordination and coupled development degrees between the security, cleanliness, and economy of the power system show a fluctuating downward trend (see Figure 10). This indicates that the balance of the "Impossible Triangle" of the power system is gradually deteriorating under these scenarios. As a result, the coupled and coordinated development level of the 3E system under both scenarios also shows a downward trend (see Figure 9). The decline in the comprehensive development level of the environmental system is the main driving force behind the decrease in the coupled and coordinated development level of the 3E system (Figure 8). At this point, although the interlinkage between the "Dual-Triangle" is relatively close, it is not what we hope to see, and we refer to it as "malignant coupling."

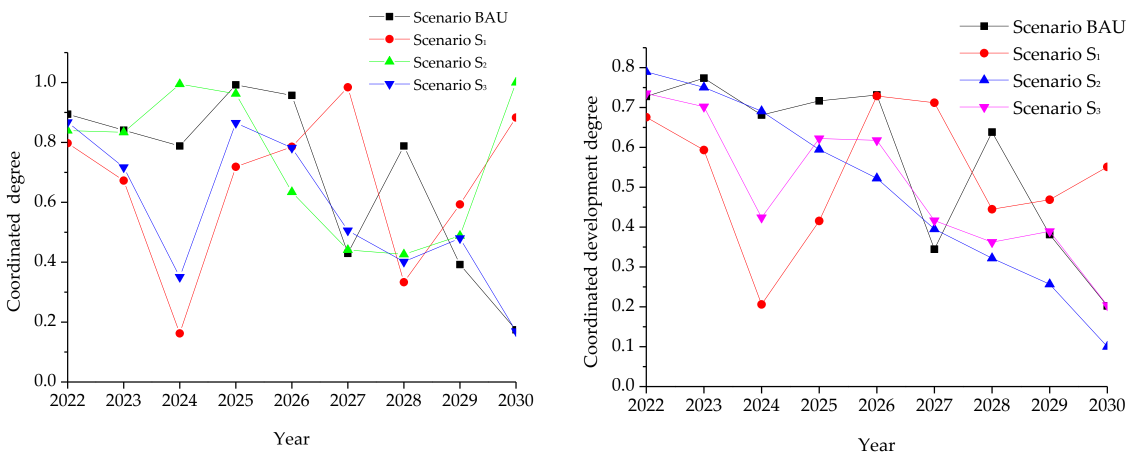

Figure 10. Coordination relationship diagram of the "Impossible Triangle".

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Under the S_1 scenario, the installed capacity of electric power is compared with the latest report "Statistical Report on Installed Capacity of Renewable Energy in 2023" issued by IRENA. "If we want to keep the global warming at 1.5°C, by 2030, the annual installed capacity of renewable energy must be tripled." According to the endowment potential of renewable energy in Guangzhou and the current development situation, Guangzhou still has great installed potential in solar energy. Therefore, in this scenario, the installed capacity of solar photovoltaic will be tripled on the basis of 2022, that is, it needs to reach 4 million kilowatts in 2030. Because renewable energy replaces fossil energy, clean energy accounts for a relatively high proportion, which makes the total power generation smaller. At the same time, the massive access of renewable energy also brings great challenges to the security and stability of the power grid. Therefore, the security of the energy system in this scenario is significantly lower than that in other scenarios. However, with the progress of renewable energy power generation technology and the improvement of efficiency, renewable energy power generation has broken through the cost bottleneck and has more and more economic advantages. Therefore, in this scenario, the economy and cleanliness of the whole energy system are high, and the relationship with economic system and environmental system is getting closer and closer, and the coupling and coordinated development degree of 3E system is gradually improved. The coupling and coordination relationship between the "Dual Triangle" is the closest, representing "benign coupling" that aligns with China's high-quality development requirements. The power transition path under this scenario can be considered the optimal choice for the reconstruction of the energy system.

In Scenario S_2, considering the economic recovery needs after the end of the COVID-19 pandemic, as well as the characteristics of Guangzhou's power development and the constraints of the carbon peak target, the government adopts a phased development approach, with different focuses at each stage. From 2022 to 2025, the economic recovery increases the demand for energy, shifting the focus of energy system development towards safety. During this phase, the increase in power installation and generation capacity is mainly driven by clean natural gas power, ensuring the cleanliness of the energy and power system. The balance between the safety, cleanliness, and economy of the energy system is relatively stable, and although the coupled and coordinated development level of the 3E system shows a slow downward trend, the overall impact is minimal. After 2026, the development in the energy sector focuses primarily on carbon peak and carbon reduction targets, with no new coal or natural gas power installations. The incremental generation is mainly from renewable sources, which reduces overall fuel costs and enhances the economic viability of the power system. However, this also significantly lowers the system's safety. At this stage, the balance between high cleanliness, high economy, and low safety is disrupted, leading to a significant decrease in the coupled and coordinated development level of the 3E system. This demonstrates that phased development with clear focuses can exacerbate the breaking of the balance in the energy "Impossible Triangle."

5. Conclusions

Addressing the question of how the restructuring of the energy and power system affects the coupled and coordinated development of the 3E system, this study constructs a "Dual Triangle" theoretical framework. It analyzes the historical characteristics and future trends of the "Dual Triangle," and studies the coupled interaction relationship between them to explore the optimal transformation path of the power system that is most conducive to the coupled and coordinated development of the 3E system. The conclusions are as follows:

(1) From the perspective of historical development patterns, from 2010 to 2022, the local electricity production in Guangzhou initially decreased and then increased. With the rapid development of the economy, the demand for electricity increased rapidly, leading to a year-by-year decrease in the self-sufficiency rate of electricity and an increase in the dependence on purchased electricity, which endangers energy security. However, with the proposal of targets for climate change response and energy conservation and emission reduction, the proportion of clean energy power generation increased year by year, the growth rate of power carbon emissions slowed down,

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and progress was made towards the goal of carbon peak. The level of coordinated development of the 3E system fluctuated upwards, and the operation status of the "Dual Triangle" was stable.

(2) Looking at future development trends, from 2023 to 2030, under the BAU and S_3 scenarios, the development levels of the "Dual Triangle" show a downward trend. Although the coupling relationship between the "Dual Triangle" is relatively close, it is not what we hope to see, which is considered "malignant coupling." Under Scenario S_1, the development levels of the "Dual Triangle" show an upward trend, and the positive coupling relationship between them is close, which is considered "benign coupling". Although the contradiction of the impossible trinity has always existed, the comprehensive development level of the sustainable development trinity in Guangzhou has been continuously improving since 2010. If this coordinated relationship is to be maintained in the future, the power transformation will need to develop along the path of Scenario S_1.Under Scenario S_2, due to the clear focus of phased development, it is the closest to the historical development characteristics of our country. Although this development model may exacerbate the breaking of the balance of the"Energy Trilemma" it is an effective development model for dynamically mitigating the challenges of the energy " Energy Trilemma ".

(3) In summary, the "Dual Triangle" is interrelated and mutually influential. A benign coupling between them can jointly promote society towards a more sustainable and balanced direction. Due to the progress of power generation technology and the reduction in the cost of clean energy generation brought about by economies of scale, the contradiction between economy and cleanliness is continuously weakened, and security has become the core contradiction of the "Energy Trilemma". Vigorously developing renewable energy and equipping it with energy storage is the key to resolving this contradiction. This can promote the "Dual Triangle" to achieve coordination at a higher level, thereby achieving high-quality development in energy and supporting the high-quality development of the economy.

Author Contributions: H.C.and W.W.contributed equally to this work. H.C.:data curation, methodology. W.W.: conceptualization, writing-original draft, visualization, validation. L.C.:data curation. W.H.:methodology. Z. G.:validation. J.L.:data curation. G.C. validation.All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by Guangdong Power Grid Co., Ltd power science and technology project (GZHKJXM20210044（080005KK52210024））

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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