Coupling coordination analysis and influencing factors of regional economy growth and environmental quality——based on the perspective of energy transition

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Abstract. While energy activities are the primary driver of global CO_2 emissions, the adjustment and upgrade of energy structure is one of the key methods for countries to achieve their carbon neutrality targets while preserving the integrated growth of local economies and environmental quality. In this paper, we use the coupling coordination degree (CCD) model to estimate the regional coupling coordination degree between economy and environment of 30 provinces in China from 2006 to 2021. The results show that the coupling coordination degree between economy and environment tends to grow steadily in China with regional heterogeneity. In addition, we examine the impact of energy transition on coupling coordination degree, and we find that energy transition and factors such as industrial upgrading and environmental regulation promote regional coupling and coordination significantly.

Keywords: Energy transition, Environment and economy, Coupling and coordination

1 Introduction

The coupling and coordination of regional economy and environmental quality has always been the core issue of sustainable development. On the one hand, economic growth is founded on high-quality resources provided by the environmental system. On the other hand, sustainable economic development such as the low-carbon economy can improve the environmental quality as well. According to the World Meteorological Organization (WMO), the average annual temperature worldwide in 2023 exceeded the level prior to industrialization by 1.45±0.12°C, mainly due to increasing carbon dioxide concentrations.[1] In addition, the energy sector is a major contributor to carbon emissions, accounting for two-thirds of total

[1] Reference resource: The World Meteorological Organization. (2024) WMO confirms that 2023 smashes global temperature record.

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carbon emissions.[2] Thus, energy transition is an important option to mitigate the economic and environmental challenges associated with CO_2 emissions. Given the ongoing pace and scope of the energy transition, all nations and districts should pay more attention to the systematization and sustainability of the development between economy and environment. As the largest developing country, China emitted 1.26 billion tons of carbon dioxide in 2023. Among them, CO_2 emissions from energy combustion increased by 5.2% from 2022, higher than the global average increase of 1.1%.[3] In this context, studying China's regional economic and environmental coupling coordination degree (CCD) and its influencing factors is suggestive for other countries which want to improve their level of economic development while reducing carbon emissions.

In 1991, the environmental Kuznets hypothesis demonstrated the connection between environmental quality and economic growth,[4] emphasizing that the primary cause of the ineffectiveness of green development is the disregard for pollution control [1]. In order to quantify and evaluate how well the environment and economy are coordinated, the existing literature mainly undertook their researches through the CCD model [2], CGE model [3], Tapio decoupling model and Kuznets curve [4], Fourier quantile causality framework [5], super-efficient SBM model [6], GTFP and other methods [7]. When the CCD model is used, the spatial analysis by ESDA technique and ANP method are utilized to study the synergistic correlation between economic system and environmental system by some scholars [2][8]. Regarding the influencing factors of coupling and coordination between economy and environment, researchers found that energy saving and emission reduction [9], environmental regulation [6], consumption level [10], urbanization efficiency [11], and level of innovation [12] will significantly influence it. In addition, energy transition promotes the optimal allocation of resources across sectors, reduces carbon emissions, and has an economic expansionary effect. Thus, energy transition is important for global economic development and environmental degradation control [13]. Most papers have studied the energy transition on the supply side, but our paper is based on the energy transition on the consumption side, which provides a new perspective for studying the impact of energy transition on the CCD of economy and environment.

In this paper, we use the CCD model to estimate the regional coupling and coordination between economy and environment of 30 provinces in China from 2006 to 2021. We find that the CCD between economy and environment tends to grow steadily in China with regional heterogeneity. In addition, energy transition significantly promotes regional coupling and coordination. Our research may provide some advice for developing countries to deal with energy transition and "economy-environment" coupling coordinated development by giving some empirical evidence.

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[2] Reference resource: International Energy Agency. (2023) CO_2 Emissions in 2022.

[3] Reference resource: International Energy Agency. (2024) CO_2 Emissions in 2023.

[4] Reference resource: Grossman, G.M., Krueger, A.B. (1991) Environmental impacts of a North American free trade agreement.

2 Analysis of coupling coordination degree

2.1 Method

2.1.1 Entropy value method

Before calculating the CCD, we need to use the entropy weight method to calculate the system synthesis value. Firstly, in order to avoid the impact of large differences in dimension and order of magnitude of data on the evaluation results, the selected indicators are standardized as equation (1), where X_{ij} is the original statistical data of the jth indicator in year i (i= 1, 2, ..., m; j= 1, 2, ..., n):

$$\mathrm{X}_{ij}^{'} = \{ \begin{matrix} (X_{ij} - \min\{X_j\}) / (\max\{X_j\} - \min\{X_j\}), \textit{positive effect} \\ (\max\{X_j\} - X_{ij}) / (\max\{X_j\} - \min\{X_j\}), \textit{negative effect} \end{matrix} \quad . \tag{1}$$

Secondly, use equation (2) to get the proportion of the ith index of the jth order parameter and equation (3) to determine the entropy value of the jth index:

$$\mathrm{S}_{ij} = \frac{\mathrm{X}_{ij}^{'}}{\sum_{\mathrm{i=1}}^{n} \mathrm{X}_{ij}^{'}} \quad . \tag{2}$$

$$\mathrm{h}_j = -\frac{1}{\ln(\mathrm{m} \times \mathrm{n})} \times \sum_{j=1}^{m} (\mathrm{S}_{ij} \times \ln \mathrm{S}_{ij}) \quad . \tag{3}$$

Thirdly, equation (4) calculates the index's redundancy, and equation (5) calculates the index's weight:

$$\mathrm{a}_j = 1 - \mathrm{h}_j \quad . \tag{4}$$

$$\mathrm{w}_j = \frac{\mathrm{a}_j}{\sum_{\mathrm{j=1}}^{n} \mathrm{a}_j} \quad . \tag{5}$$

Finally, calculate the comprehensive score of each index as equation (6):

$$U = \sum_{\mathrm{j=1}}^{n} (\mathrm{w}_j \times \mathrm{X}_{ij}^{'}) \quad . \tag{6}$$

2.1.2 Coupling coordination degree model

CCD is a thorough indicator of coordination and coupling degrees [14], frequently used to examine the interactions and equilibrium relationships between various systems [2][8]. Therefore, we use the CCD model to study the interaction between the environmental and economic systems. Firstly, the coupling degree equation (7) is built as follows:

$$C = \frac{2 \times \sqrt{U_1 \times U_2}}{U_1 + U_2} \quad . \tag{7}$$

C stands for the coupling degree, U_1 and U_2 are the comprehensive evaluation scores of regional economic system and environmental system respectively, and C ∈ (0, 1). The closer the value of C is to 1, the higher the degree of coupling among the subsystems is, which indicates a stronger correlation between the two subsystems in our study. However, there may be a deviation from the real situation where the two systems have low development levels but high coupling degrees due to specific differences in the development of the economic and environmental systems. Therefore, the coordination degree equation (8) is built as follows:

$$T = \alpha \times U_1 + \beta \times U_2 \quad . \tag{8}$$

T stands for the coordination degree, which assesses how well the system is coupled, T ∈ (0, 1). Given that we value economic subsystem and environmental system equally important, the contributions of U_1 and U_2 are denoted by α and β respectively, with a value of 0.5. Considering the strength of the interaction comprehensively and the correlation of U_1 and U_2, the CCD equation (9) is built as follows:

$$D = \sqrt{C \times T} \quad . \tag{9}$$

D stands for the coupling coordination degree, D ∈ (0, 1). D measures correlation and a sustained and harmonious development within the two systems, reflecting how closely the two systems coordinate.

2.2 Data

Considering the availability of original data, the samples are the relevant economic and environmental variables of 30 provinces (excluding Tibet, Hong Kong, Macao, and Taiwan) in China from 2006 to 2021, with 480 observations. The data comes from the National Bureau of Statistics, China Statistical Yearbook, China Industrial Statistical Yearbook, China Energy Statistical Yearbook, and statistical annual reports of provinces.

2.3 Construction of index system

We construct the index system through the system layer, factor layer, and index layer. Among them, the system layer refers to the coordination level between U_1 and U_2; the factor layer divides the systems into total elements and efficiency elements; the index layer involves representative characteristic variables in economic and environmental systems. Different from the index systems that other scholars have constructed [15][16], we skip the input variables and only select 15 variables representing economic and environmental performance. The index system and weights are shown in Table 1. The efficiency of input variables such as environmental regulation and technological innovation are examined in the following studies.

Table 1. Evaluation index system.

Level1	Level2	Level3	Attribute	weight
U_1	Total	GDP (billion yuan)	+	0.1392

	Elements	Total retail sales of consumer goods (billion yuan)	+	0.1466
		Fixed assets investment (billion yuan)	+	0.1394
		Total export-import volume (thousand dollars)	+	0.3326
		Local fiscal budget expenditure (billion yuan)	+	0.0962
	Efficiency Elements	GDP growth rate (%)	+	0.0101
		GDP per capita (yuan)	+	0.0850
		GDP per area (billion yuan/km^2)	+	0.0509
U_2	Total elements	Emissions of CO_2 (million tons)	-	0.0870
		Emissions of SO_2 (10,000 tons)	-	0.2766
	Efficiency elements	Carbon intensity (ton/million yuan)	-	0.1597
		Emissions of CO_2 per capita (ton)	-	0.0884
		SO_2 intensity (kg/k·Wh)	-	0.0518
		Emissions of SO_2 per capita (ton)	-	0.2095
		Energy consumption per GDP (tce/10,000 yuan)	-	0.1270

2.4 Analysis

After calculating the CCD, we analyze the regional coupling and coordination from the time and space perspectives in this section. The CCD is often divided into extreme disorder ((0.0, 0.1)), serious disorder ([0.1, 0.2)), moderate disorder ([0.2, 0.3)), light disorder ([0.3, 0.4)), near disorder ([0.4. 0.5)), reluctance coordination ([0.5, 0.6)), primary coordination ([0.6, 0.7)), middle coordination ([0.7, 0.8)), well coordination ([0.8, 0.9)), and high coordination ([0.9, 1.0)) [15].

Table 2. Classification of provincial coupling coordination degree.

Levels	East	Central	Northeast	West
		2006		
Moderate disorder				Ningxia
Light disorder	Hainan	Shanxi	Jilin	Guizhou, Qinghai, Gansu, Inner Mongolia, Guangxi, Xinjiang, Chongqing, Shaanxi
Near disorder	Hebei, Tianjin, Fujian	Jiangxi, Anhui, Hunan, Hubei, Henan	Heilongjiang, Liaoning	Yunnan, Sichuan
Reluctance coordination	Shandong, Zhejiang, Beijing, Jiangsu, Shanghai			
Primary coordination	Guangdong			
		2021		

Near disorder				Ningxia, Qinghai
Reluctance coordination	Hainan	Gansu Shanxi	Heilongjiang, Jilin	Xinjiang, Inner Mongolia
Primary coordination	Tianjin	Jiangxi	Liaoning	Guizhou, Shaanxi, Guangxi, Yunnan
Middle coordination	Hebei, Fujian, Beijing	Hunan, Anhui, Hubei, Henan		Chongqing, Sichuan
Well coordination	Shanghai, Shandong, Zhejiang			
High coordination	Jiangsu, Guangdong			

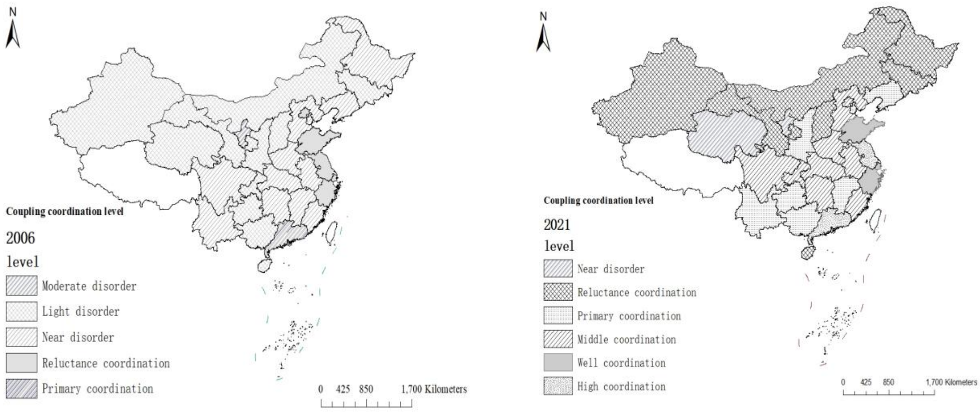

Figure 1. Space variation of coupling coordination degree.

As shown in Table 2 and Figure 1, comparing through longitudinal analysis, the level of CCD in all province show a trend of leap from 2006 to 2021. For example, Jiangsu province jumped from reluctance coordination to high coordination; Hubei province jumped from near disorder to middle coordination; Liaoning province jumped from near disorder to primary coordination; and Chongqing jumped from light disorder to middle coordination. By 2021, the CCD level of Ningxia province and Qinghai province were the lowest, while that of Jiangsu province and Guangdong province were the highest. From the regional perspective, the level of CCD in the four regions shows an increasing trend. Comparing with other regions, the level of CCD in the eastern region has a larger jump. Meanwhile, the intra-regional differences are larger in the eastern region, and they are getting larger during our sample period.

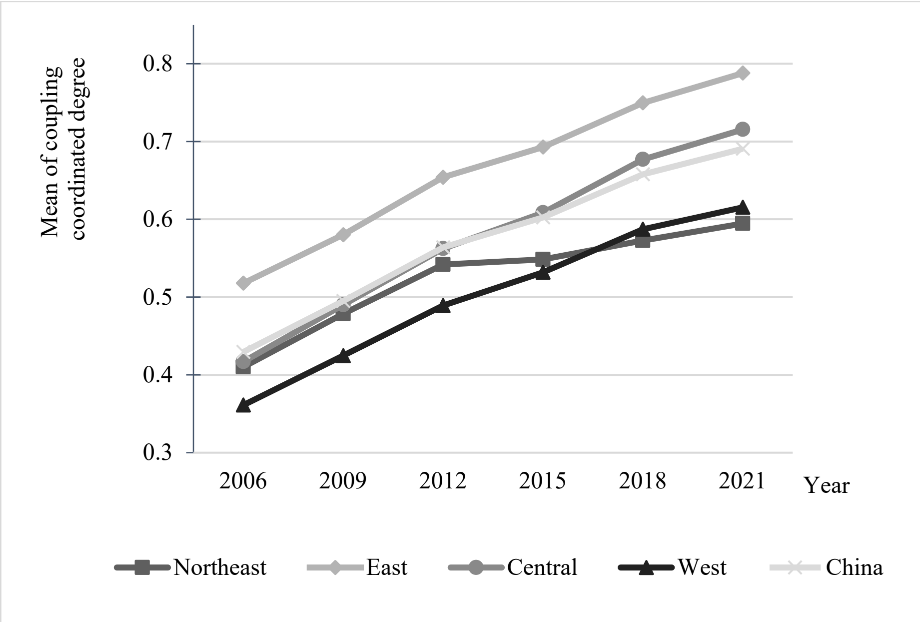

Figure 2. Time variation of coupling coordination degree.

Regarding temporal evolution shown in Figure 2, the overall CCD in China is in an upward trend from regional level. It indicates that China has achieved a favorable equilibrium between its economy and the environment in the past few years. The level of the coupling and coordination in regions are differentiated, with the overall pattern of "East > Central > Northeast > West" but the CCD in the Northeast is slightly lower than that in the West since 2016.

3 Empirical analyses of influencing factors

3.1 Data and method

By measuring the CCD between economy and environment, we find that the degrees vary greatly between regions and different years. In this section, we try to find the causes of such variances from the perspective of energy transition. We use the CCD calculated before as the dependent variable. As for energy transition, the existing literature usually uses the proportion of clean power generation to measure it [17], but we measure it through another aspect. As for proxy variable, we employ the proportion of electricity consumption to terminal energy consumption, since the energy consumption structure may also influence the CCD between economy and environment. In addition, we choose industrial structure, environmental regulation, technology innovation, urbanization, infrastructure, foreign direct investment and population density as control variables referring to the relative literature [18][19][20]. The specific variables are shown in Table 3.

Table 3. Variables for assessing the influencing factors.

	Variables	Symbol	Description
Dependent variable	coupling coordination degree	Coup	results of the CCD model calculations
Core explanatory variable	energy transition	Elec	electric energy (tce)/terminal energy consumption (tce)
Control variables	industrial structure	Indu	added value of the secondary and tertiary industries (billion yuan)/GDP (billion yuan)
	environmental regulation	Regu	investment in industrial pollution treatment (hundred yuan)/industrial added value (billion yuan)
	technology innovation	Tech	logarithm of domestic invention patent applications authorized(item)
	urbanization	Urba	urban population /total population
	infrastructure	Infr	logarithm of total freight volume (ten thousand tons)
	foreign direct investment	Fdi	foreign direct investment (ten thousand yuan)/ GDP (ten thousand yuan)
	population density	Popu	population (thousands)/area (square kilometers)

The descriptive statistics are shown in Table 4.

Table 4. Descriptive statistics.

Variables	Coup	Elec	Indu	Regu	Tech	Urba	Infr	Fdi	Popu
Max	0.9593	0.2631	0.9978	0.2451	11.5410	0.8960	12.9815	0.1210	3.9259
Min	0.2615	0.0118	0.6975	0.0004	3.1355	0.2746	8.8917	0.0001	0.0076
Mean	0.5768	0.1084	0.8953	0.0321	7.6894	0.5637	11.4516	0.0223	0.4590
SD	0.1316	0.0438	0.0560	0.0295	1.6571	0.1370	0.8584	0.0200	0.6763
N	480	480	480	480	480	480	480	480	480

The VIF tests are shown in Table 5. It shows VIF<5, which means that the variables do not exhibit multicollinearity.

Table 5. VIF tests.

Variables	VIF	1/VIF
Elec	1.29	0.772587
Indu	2.08	0.479643
Regu	1.11	0.897538
Tech	4.3	0.232724
Urba	4.01	0.249249
Infr	2.49	0.400845
Fdi	1.35	0.739349
Popu	1.9	0.526231
Mean VIF	2.32	

In this paper, a two-way fixed effects (TWFE) model is adopted to analyze the factors influencing the CCD calculated before, controlling for province and time-fixed effects in the analysis. We set up the structure of model (10) as follows:

$$Coup_{it} = \alpha + \beta_1 Elec_{it} + \sum_j \beta_j Controls_{it} + \varphi_i + \gamma_t + \varepsilon_{it} \quad . \qquad (10)$$

where the *Coup* is the CCD, which is the dependent variable; and *Elec* is the core explanatory variable, reflecting energy transition. *Controls* is a group of control variables that could have an impact on the CCD. Among them, *Indu* stands for industrial structure, *Regu* for environmental regulation, *Tech* for technology innovation, *Urba* for urbanization, *Infr* for infrastructure, *Fdi* for foreign direct investment, *Popu* for population density. In addition, α is a constant term, i denotes province and t denotes time, φ_i denotes time effect, γ_t denotes area effect, and ε_{it} denotes the random perturbation term.

3.2 Empirical results

From the baseline regression results in Table 6, the regression coefficient of the core explanatory variable (*Elec*) is 0.373, and the regression coefficient of *Elec* with control variable added is 0.241. Both pass the test of significance level of 1%, which indicates that the energy transition does promote the CCD between economy and environment significantly, and increasing the level of electrification can promote both economic and environmental benefits.

The regression results of the control variables show as followed: All control variables maintain significant positive effects on CCD, contributing to regional green development. The positive coefficient of industrial structure (*Indu*) indicates that developing secondary and tertiary industries would inject power into the sustainable development of economy. The positive coefficient of environmental regulation (*Regu*) means that the more regional investment in industrial pollution control, the better the quality of environment and economy. Moreover, The positive coefficient of technological innovation (*Tech*) shows that the quality of environment and economy would be improved by green production caused by patented inventions. The positive coefficient of urbanization (*Urba*) denotes that urban residential agglomeration would lead to industrial agglomeration and ecological restoration, which in turn enhance the development of urban green economy. The positive coefficient of infrastructure (*Infr*) suggests that the level of transport infrastructure plays a positive role in the balanced development of economy and environment as well. The positive coefficient of foreign direct investment (*Fdi*) means that foreign trade would also promote the development of green economy. The positive coefficient of population density (*Popu*) shows that moderate population density can promote economies of scale while achieving intensive environmental management.

Table 6. Baseline regression results.

Variables	(a)	(b)
Elec	0.373***	0.241***
	(0.0964)	(0.0762)
Indu		0.116**
		(0.0561)
Regu		0.097**
		(0.0407)
Tech		0.022***
		(0.0037)
Urba		0.360***
		(0.0526)
Infr		0.023***

		(0.0054)
Fdi		0.292***
		(0.0649)
Popu		0.115***
		(0.0255)
Constant	0.536***	-0.250***
	(0.0106)	(0.0670)
Province FE	YES	YES
Year FE	YES	YES
Adjusted R-squared	0.974	0.984
Observations	480	480

Notes: standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1

3.3 Robustness Tests

In order to further assess the validity of the outcomes of the regression, we thoroughly examine the robustness of the primary regression results by changing the control variables and lagging explanatory variables by one period, respectively. References to existing literature [19][20][21], we use the proportion of the added value of the secondary industry in GDP (*Indu2*) to measure the industrial structure, logarithm of completed investment in sewage treatment projects (*Regu2*) to measure environmental regulation, logarithm of domestic invention patent applications accepted (*Tech2*) to measure technology innovation, logarithm of urban area (*Urba2*) to measure urbanization, urban road area per capita (*Infr2*) to measure infrastructure, logarithm of foreign direct investment (*Fdi2*) to measure foreign direct investment, logarithm of resident population (*Popu2*) to measure population density.

Table 7. Robustness regression results.

Variables	(a)	(b)	Variables	(c)	Variables	(d)
L.Elec	0.257***	0.140**	L.Elec	0.150*	Elec	0.272***
	(0.0977)	(0.0706)		(0.078		(0.0619)
Indu		0.298***	L.Indu	0.107*	Indu2	0.097***
		(0.0762)		(0.0550)		(0.0289)
Regu		0.104**	L.Regu	0.088**	Regu2	0.002**
		(0.0444)		(0.0390)		(0.0008)
Tech		0.017***	L.Tech	0.024***	Tech2	0.007***
		(0.0037)		(0.0037)		(0.0017)
Urba		0.412***	L.Urba	0.385***	Urba2	0.010***
		(0.0573)		(0.0571)		(0.0037)
Infr		0.025***	L.Infr	0.022***	Infr2	0.001**
		(0.0066)		(0.0058)		(0.0005)
Fdi		0.285***	L.Fdi	0.306***	Fdi2	0.012***
		(0.0686)		(0.0686)		(0.0015)
Popu		0.162***	L.Popu	0.113***	Popu2	0.004***
		(0.0349)		(0.0259)		(0.0004)
Constant	0.559***	-0.438***		0.229***		0.024
	(0.0106)	(0.0992)		(0.0692)		(0.0414)
Province FE	YES	YES		YES		YES
Year FE	YES	YES		YES		YES
Adjusted R-squared	0.973	0.984		0.984		0.984
Observations	450	450		450		480

Notes: standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1

The robustness tests are shown in Table 7. Columns (a) and (c) show the results of lagging each explanatory variable by one period, in which column (a) does not control other variables, and column (c) includes other control variables. Column (b) shows the results with one-period lag of the core explanatory variables, including the control variables without lags. Column (d) shows the results of replacing variables. We find that every column's energy transition coefficient is significantly positive, passing the robustness test.

4 Conclusions

In this paper, we find that the overall CCD of regional economy and environment in China shows a growing trend through the CCD model, but there is still some regional heterogeneity. In addition, we study how the energy transition affects the CCD between the environment and the economy, and we find that the energy transition can support the environmentally friendly growth of the regional economy. Accordingly, we put forward the policy recommendations as below. Firstly, energy transition, economic development, and environmental protection should be integrated into a unified policy setting framework with a more reasonable top-level design. Secondly, governments should strengthen the transition of energy consumption structure by promoting electrification in industrial and other sectors. Thirdly, other methods such as technology innovation, environmental regulations, industrial structure, infrastructure construction, foreign trade, urbanization and moderate population density could be reinforced at the same time. However, we must acknowledge that the lack of data accessibility has limited our research; still, city-level research can be done in the future, or policy evaluations could be done when the policy has been carried out more deeply.

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