ISSN: 2688-9323

Study on the Coupled and Coordinated Development of Energy, Economy and Environment in Sichuan Province

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Abstract

The coordinated development of energy economy and environment plays a pivotal role in the development of a region. Taking Sichuan Province as an example, the entropy TOPSIS method and the modified coupling model were used to analyse the level of coordinated development of the energy economy and environment in Sichuan Province from 2011 to 2020.The results show that although the level of coordinated development of the energy-economic-environment system in Sichuan Province has been improving, it is only at an intermediate level of coordination until 2020.Finally, from the perspective of energy, economy and environment, we propose the following suggestions for coordinated development:(1)optimise the energy consumption structure and vigorously develop clean energy; (2)adjust the industrial structure and transform the economic development mode; (3)strengthen environmental protection, energy conservation and emission reduction.

Keywords

Energy; Economy; Environment; Entropy TOPSIS Method; Coupled Coordination.

1. Introduction

The energy-economy-environment system, referred to as the 3E system, is in an interdependent and mutually constraining unity [1]. Specifically, economic development is based on energy and has a strong dependence on energy [2], the exploitation of energy is an important factor causing environmental changes, and as energy resources decrease, the deterioration of the ecological environment will also have a negative impact on economic development. The harmonious development of the energy-economy-environment triad has become a hot issue in China's social development today. In order to improve the severe situation between energy-economy-environment, we should focus on the coordinated development between the three, so that we can achieve a win-win, multi-win and win-win situation and achieve sustainable development.

Studies on the coordinated development between energy, economy and environment have been studied earlier by foreign scholars. Song Jae Ho described the energy-economy-environment system by constructing a system dynamics model of the changes in the national energy-economy-environment (3E) system under the introduction of carbon tax and predicted the changes caused by the imposition of carbon tax[3].Oliveira developed an energy-economy-environment model to prospectively analyse changes in the economic structure and energy system and assess the corresponding environmental impacts to provide decision support for policy making. Domestic scholars, on the other hand, have conducted studies on the coordinated development of energy, economy and environment in the context of China's economic development situation[4].Song Yuchen took the five cities of Hubao-Egyin-Yu as an example and studied the level of coordinated development among the three systems in these five cities with the help of entropy value method and coupled coordination degree evaluation

ISSN: 2688-9323

model [5]. Lu Jin measured the level of coordinated development of energy, economy and environment subsystems in four major regions of China from 1995 to 2014[6]. Li Li constructed ESDA and PLS models to the spatial distribution of coordinated energy-economy-environment development in China [7]. Through the research results at home and abroad, it is found that the breadth and depth of research is expanding as the research in the field of energy, economy and environment system continues to deepen.

Nowadays, coordinated regional development is an important part of the national sustainable development strategy, and the coordinated development of energy, economy and environment is a top priority for sustainable development. In this context, taking Sichuan province as an example, and focusing on the theme of "coordination and development", the coordinated development level of the energy-economy-environment system in Sichuan province from 2011 to 2020 is analysed through the establishment of an indicator system and the entropy TOPSIS method and the coupled coordination model, and from the perspective of the coordinated development of the system, the coordinated development of the energy-economy-environment system in Sichuan province is analysed. The coordination of the energy-economy-environment system is divided into: energy-economy, energy-environment, economy-environment and energy-economy-environment, and finally sustainable development suggestions are made based on the coordinated development to provide scientific reference for the sustainable development of Sichuan Province.

2. Indicator System Construction and Research Methodology

2.1. Indicator System Construction

Table 1. Evaluation indicators for the coupled and coordinated development of the energy economy and environment in Sichuan Province

System level	System elements	Indicator layer	Weighting
Energy	Total Indicators	Total energy consumption	0.025
		Total energy production	0.032
		Investment in energy industry	0.024
	Structural Indicators	Natural gas consumption as a percentage	0.041
		Coal consumption as a percentage	0.030
		Share of oil consumption	0.051
	Benefit Indicators	Energy consumption elasticity coefficient	0.039
		Energy consumption per unit of GDP	0.052
		Energy consumption per unit of industrial added value	0.026
Economy	Total Indicators	Gross regional product GDP	0.032
		Total industrial output value	0.022
		Total retail sales of social consumer goods	0.035
		Total fixed asset investment	0.032
		Total import and export trade	0.028
	Structural Indicators	Share of primary industry in GDP	0.037
		Share of secondary industry in GDP	0.042
		Share of tertiary industry in GDP	0.045
	Benefit indicators	GDP per capita	0.031
		Consumer price index of the population	0.063
Environment	Degree of environmental pollution	Industrial wastewater emissions	0.022
		Industrial sulphur dioxide emissions	0.050
		Industrial smoke (dust) emissions	0.053
	Investment in environmental management	Total investment in environmental pollution control	0.056
		Total investment in environmental pollution control as a proportion of GDP	0.036
	Effectiveness of environmental management	Green space per capita in parks	0.025
		Green space coverage rate of built-up areas	0.023
		Comprehensive utilization rate of industrial solid waste	0.048

The energy-economy-environment system is coupled by the energy subsystem, the economic subsystem and the environmental subsystem, reflecting the characteristics of a complex and open system. The selection of indicators should take into account the principles of comprehensiveness, scientificity and comparability, and take into account the actual situation of energy, economy and environment in Sichuan Province, and draw on relevant research results [6-10] to construct an evaluation index system for the coordinated development of energy, economy and environment in Sichuan Province, as shown in Table 1. The energy sub-system reflects the development and utilisation of energy in Sichuan Province and its future development potential, and is decomposed in terms of total volume, structure and efficiency; the economic sub-system reflects the economic development in Sichuan Province and its future development potential, and is decomposed in terms of total volume, structure and efficiency; the environmental sub-system reflects the environmental pollution in Sichuan Province and its management level, and is decomposed in terms of the degree of environmental pollution, environmental management investment and environmental management. The environmental sub-system reflects the environmental pollution situation and the level of control in Sichuan Province, and is decomposed in three aspects: the degree of environmental pollution, the investment in environmental control and the effect of environmental control.

2.2. Research Methods

2.2.1. Entropy TOPSIS Method

The entropy TOPSIS method, which is used in multi-objective decision-making with a limited number of options, is objective and reflects the variability between indicators [11] and is based on the following principles.

Step1:Standardized treatment:Positive indicators: $Y_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})}$; Negative indicators: $Y_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})}$.

Step2: Calculate the characteristic weight P_{ij} for the jth indicator in year i, then $P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}}$.

Step3: Calculate the entropy value e_j for the jth indicator, then $e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} P_{ij}(\ln P_{ij})$.

Step4: Calculating the coefficient of variation g_j, then $g_j = 1 - e_j$.

Step5: Calculate the weight W_j for the jth indicator, then $W_j = \frac{g_j}{\sum_{i=1}^{n} g_j}$.

Step6: Constructing a norm-weighted normalization matrix, then $G_{ij} = W_j \times Y_{ij}$.

$$G_{ij} = \begin{bmatrix} W_1Y_{11} & W_2Y_{ij} & W_3Y_{13} & \dots & W_mY_{1m} \\ W_1Y_{21} & W_2Y_{22} & W_3Y_{13} & \dots & W_mY_{2m} \\ W_1Y_{31} & W_2Y_{32} & W_3Y_{33} & \dots & W_mY_{3m} \\ \dots & \dots & \dots & & \dots \\ W_1Y_{n1} & W_2Y_{n2} & W_3Y_{n3} & \dots & W_mY_{nm} \end{bmatrix}$$

Where G_{ij} denotes the weighted criteria matrix; W_j denotes the weight of each indicator calculated using the entropy value method; and Y_{ij} denotes the standardized indicator value.

Step7: Determining the ideal solution.

Positive ideal solution: $G_j^+ = max\{G_{1j}, G_{2j}, \dots, G_{mj}\}$

Negative ideal solution: $G_j^- = min\{G_{1j}, G_{2j}, \dots, G_{mj}\}$

Step8: Calculating Euclidean distances.

$$D_i^+ = \sqrt{\sum_{i=1}^{m}\left(G_{ij} - G_j^+\right)^2} \tag{1}$$

$$D_i^- = \sqrt{\sum_{i=1}^{m}\left(G_{ij} - G_j^-\right)^2} \tag{2}$$

Step9: Calculate the development level rating for each indicator.

$$U_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{3}$$

2.2.2. Coupling Coordination Model

In discussing the coordination between the energy economy and environment in Sichuan Province, the coupling model modified by Wang Shujia et al [12] was borrowed and a binary system coupling model and a ternary system coupling model were established based on the actual situation in Sichuan Province, with the following expressions.
Modified binary system coupling model:

$$C = \sqrt{\left[1 - \sqrt{(U_2 - U_1)^2}\right] \times \left(\prod_{i=1}^{2} \frac{U_i}{maxU_i}\right)} \tag{4}$$

Modified ternary system coupling model:

$$C = \sqrt{\left[1 - \frac{\sqrt{(U_3-U_1)^2}+\sqrt{(U_2-U_1)^2}+\sqrt{(U_3-U_2)^2}}{3}\right] \times \left(\prod_{i=1}^{3} \frac{U_i}{maxU_i}\right)^{\frac{1}{2}}} \tag{5}$$

The larger the value of C, the higher the coupling level of each subsystem; conversely, the lower the coupling level. In order to better distinguish the type of coupling level, the coupling level of the energy economic and environmental system is classified into levels by drawing on the research results [13]:when the coupling level is between 0 and 0.3 the coupling level is low-level coupling, when the coupling level is between 0.3 and 0.5,the coupling level is antagonistic When the coupling degree is between 0.5 and 0.8,the coupling degree is the grinding stage,when the coupling degree is between 0.8 and 1,the coupling degree is the high level coupling.
However, the coupling degree is still lacking in the study of the coordination between the systems of energy, economy and environment. in order to better analyses the coordination between the systems, a coupling coordination degree model was developed based on the coupling degree model as follows:

$$D = \sqrt{C \times T}, T = \sum_{i=1}^{n} w_i \times U_i \ , \sum_{i=1}^{n} w_i = 1 \tag{6}$$

D denotes the coupling coordination degree, the larger the value, the higher the coordination level; T denotes the comprehensive evaluation value of the energy economic and environmental system, U_i denotes the evaluation value of the development level of each sub-system, and w_i denotes the weight of the energy economic and environmental system. In order to better evaluate the coordination level, the coupling coordination degree of the energy economy and environment system is classified into levels by drawing on existing research results [13], as shown in Table 2.

Table 2. Classification of coupling coordination levels and evaluation levels

Coherence D	Type of coupling coordination
[0.000-0.099)	Extreme disorder
[0.099-0.199)	Severe disorder
[0.199-0.299)	Moderate disorder
[0.299-0.399)	Mild disorder
[0.399-0.499)	Nearly dysfunctional
[0.499-0.599)	Barely coordinated
[0.599-0.699)	Primary coordination
[0.699-0.799)	Intermediate coordination
[0.799-0.899)	Good coordination
[0.899-1.000]	Quality coordination

2.2.3. Data Sources

The research period of this paper is 2011-2020, taking Sichuan Province as the research object, and the data in this paper mainly comes from the statistical yearbooks of Sichuan Province.

3. Empirical Results and Analysis

3.1. Time Series Analysis of the Comprehensive Development Level of the Energy and Economic Environment in Sichuan Province

Based on the entropy value TOPSIS, the comprehensive evaluation value of the energy subsystem, economic subsystem and environmental subsystem in Sichuan Province from 2011 to 2020 was calculated, based on which the weightings of each subsystem were combined to calculate the comprehensive evaluation value of the 3E system.

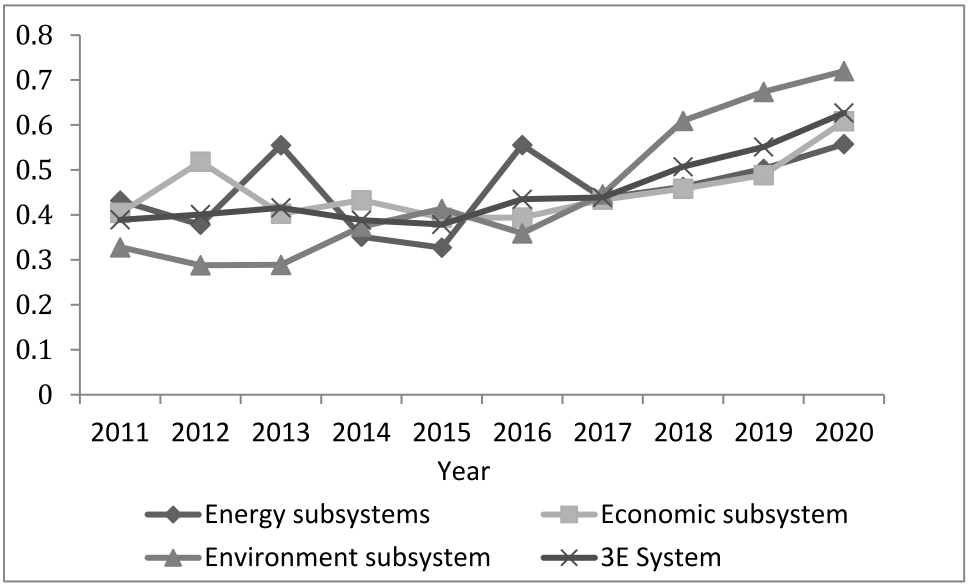

Figure 1. Comprehensive development level of the energy and economic environment in Sichuan Province, 2011-2020

Figure 1 shows that all three subsystems and the 3E system have shown a fluctuating upward trend over time, but each has a different trend. The energy subsystem value increased from 0.4317 to 0.5573, the economic subsystem value increased from 0.4042 to 0.6082, and the environmental subsystem value increased from 0.3280 to 0.7197, with increases of 29.10%, 50.48%, and 119.46%, respectively, with the environmental subsystem value increasing the most, followed by the economic subsystem, and the energy subsystem increasing the least. The energy sub-system had the lowest increase. The value of the 3E system, which is also on an upward trend, rose from 0.3890 to 0.6269, an increase of 61.52%. It can be concluded that the environment subsystem is the fastest growing of the three subsystems; the energy and economy subsystems are slower, especially the energy subsystem, which is much slower than the development of the 3E system, specifically.

From the perspective of the development level of the energy subsystem: the development level of the energy subsystem in Sichuan Province shows a fluctuating upward trend, reaching its lowest development level in 2015 and its highest in 2020. The reason for this is that in 2015 energy consumption in Sichuan Province was rising, while energy production was also rising, but energy consumption in Sichuan Province was always much greater than energy production, with serious contradictions between supply and demand. In 2020, with the adjustment of the energy structure, energy production was raised and the values of inverse indicators such as energy consumption per unit of industrial added value were decreasing. The trend of change in the development level of the energy subsystem is divided into two stages: the first stage is the "decline - rise - decline - rise" stage from 2011 to 2016, roughly showing a "W" shape; the second stage is the stable development from 2017 to 2020 The second stage, from 2017 to 2020, is a stable development phase, with an increasing level of development, due to the rapid development of new energy sources in Sichuan province and the optimisation of the energy structure, with the proportion of coal and oil consumption decreasing and the proportion of natural gas consumption, energy industry investment and energy production increasing.

The economic subsystem is on an upward trend, reaching its lowest level in 2015 and its highest in 2020. The first stage is the low and slow development stage from 2011 to 2018, with an overall low comprehensive evaluation value, and an abnormal growth in 2012. The second stage is the rapid development of high quality from 2019 to 2020. The reason for this is that Sichuan Province has adjusted its industrial structure, accelerated the elimination of surplus industries and vigorously developed tertiary industries such as the service industry, which gradually increased its share.

From the perspective of the development level of the environmental subsystem: the development level of the environmental subsystem in Sichuan Province is generally on an upward trend, especially between 2017 and 2018, with a large increase, generally speaking, there are two stages: the first stage is the "decline - rise - decline" stage from 2011 to 2016, the overall value of the comprehensive evaluation is low. The second stage is the rapid development of high quality from 2017 to 2020, because Sichuan Province has increased its efforts to protect the ecological environment, the total investment in environmental pollution control has increased significantly, and industrial waste water emissions, sulphur dioxide emissions and industrial smoke (dust) emissions are decreasing year by year. The green space per capita is also increasing year by year.

From the perspective of the comprehensive development level of the 3E system: the development level of the 3E system in Sichuan Province is generally on an upward trend, with small fluctuations from year to year. From 2011 to 2020, the trend of the comprehensive development level of the 3E system in Sichuan Province is roughly in the same direction as the economic subsystem, with continuous improvement. In the early stage, the development level of energy in Sichuan province was higher, followed by the economic development level and the lowest environmental development level. 2011 to 2014 the development level between the systems differed significantly, 2015-2017 the development level between the systems did not differ significantly, after 2017 the development level appeared to differ, the environmental subsystem was significantly improved, the economic subsystem was improved to a lesser extent compared to the environmental The reason for this is that while developing its economy, Sichuan Province has gradually realised the importance of energy conservation and emission reduction, and the abundance of energy resources in Sichuan Province, the use of large amounts

ISSN: 2688-9323

of coal and other energy resources can cause environmental problems, so the strengthening of the ecological environment, the successive introduction of a series of environmental protection policies, and the gradual strengthening of people's ecological and environmental protection awareness have led to the development of the environment sub With the implementation of the policy of removing production capacity in Sichuan Province and the development of new energy sources, the level of development of the energy subsystem is also developing steadily.

3.2. Analysis of the Degree of Coordination of the Coupled Energy and Economic Environment in Sichuan Province

According to the coupling coordination degree model, the coupling coordination degree of energy economy and environment in Sichuan Province from 2011 to 2020 was calculated, and the results are shown in Table 3.

Table 3. Analysis of the coupled energy and economic environment coordination in Sichuan Province, 2011-2020

Year	Energy - Economy	Energy - Environment	Economy - Environment	3E System
	Coherence	Coherence	Coherence	Coherence
2011	0.596	0.560	0.565	0.587
2012	0.599	0.527	0.519	0.542
2013	0.540	0.511	0.528	0.544
2014	0.584	0.589	0.605	0.588
2015	0.565	0.561	0.624	0.585
2016	0.525	0.575	0.595	0.577
2017	0.656	0.660	0.656	0.657
2018	0.674	0.656	0.650	0.646
2019	0.689	0.688	0.664	0.665
2020	0.752	0.717	0.742	0.730

It can be concluded from Table 3 that the level of coupling and coordination of the energy-economy-environment system in Sichuan Province from 2011 to 2020 shows an overall upward trend, with the type of coordination gradually developing from barely coordinated to intermediate coordination and the coupling and coordination mechanism being continuously improved, specifically.

From the coupling and coordination of energy and economy: the level of coupling and coordination of energy and economy in Sichuan Province from 2011-2020 is increasing, developing from barely coordinated to intermediate coordination. The type of coordination is roughly the barely coordinated stage from 2011-2016, entering the primary coordination stage after 2017, and reaching the intermediate coordination stage in 2020. The reason for this is that from the energy subsystem evaluation indicators, the total energy production in Sichuan province has been rising year by year during 2011-2012, which has contributed to the economic growth to a certain extent, making the coupling coordination between energy and economy increasing in 2011-2012. With the constraint of energy resources and the strengthening of ecological and environmental protection, the amount of energy production in

ISSN: 2688-9323

Sichuan Province decreased continuously during 2014-2016, which to a certain extent restricted the development of the economy, while the indicator weight of energy production accounted for a large proportion of the energy subsystem, and the comprehensive evaluation value of the energy subsystem was relatively low during 2014-2016, making the coupling coordination degree of energy and economy in 2014-2016 2016, but it is still barely coordinated and has not reached the point of dissonance. As the efficiency of energy use continues to improve, the inverse indicators in the energy subsystem continue to decline after 2016, while total energy production increases during this period and the benign development between energy and the economy makes the coupling coordination between energy and the economy rise after 2016, reaching an intermediate level of coordination in 2020.

In terms of coupled coordination between energy and the environment: the level of coupled coordination between energy and the environment in Sichuan Province rises continuously from 2011-2020, developing from barely coordinated to intermediate coordination. The type of coordination is roughly the barely coordinated stage from 2011-2016, entering the primary coordination stage after 2017, and reaching the intermediate coordination stage in 2020. Specifically, the degree of coordination between energy and the environment shows a fluctuating upward trend, with the degree of coupling coordination decreasing between 2011 and 2013, but still at the stage of barely coordinated, not reaching the point of disorder, because the energy structure was out of balance between 2011 and 2013, and energy consumption made environmental issues affected, while the inverse indicators in the environmental subsystem were also increasing, making the degree of coupling coordination After 2013, with the improvement of the environment and the adjustment of the energy structure, the inverse indicators in the energy subsystem and the inverse indicators in the environment subsystem also showed a decreasing trend during this period.

In terms of the coupling between the economy and the environment, the level of coupling between the economy and the environment in Sichuan Province has been increasing from 2011 to 2020, from barely coordinated to intermediate level of coordination. The type of coordination is roughly the barely coordinated stage from 2011-2013, the primary coordination stage from 2014-2015, and the level of coordination starts to rise after a decline in 2016 and reaches the intermediate coordination stage in 2020. The reason for this is that as the level of economic development in Sichuan Province has increased, people have become more aware of environmental protection, and investment in environmental pollution control has increased year by year. However, the development of the economy has also had a negative impact on the environment, causing the coupling and coordination between the economy and the environment to show a slow decline between 2015 and 2016. With the gradual promotion of national policies and the construction of ecological civilisation, as well as the strengthening of investment in environmental pollution control, the ecological environment has improved, and the coupling coordination degree of economy and environment will reach the intermediate coordination level in 2020.

From the perspective of 3E system coupling coordination: the level of 3E system coupling coordination in Sichuan Province from 2011-2020 has been rising, developing from barely coordinated to intermediate coordination. The type of coordination is roughly the barely coordinated stage from 2011-2020, entering the primary coordination stage after 2017, and reaching the intermediate coordination stage in 2020. Specifically, the coordination of the 3E system shows a fluctuating upward trend, because before 2014, due to the unreasonable industrial structure, large industrial waste water and gas emissions and economic development constraints, resulting in the 3E system coupling coordination decreasing during this period, but still in the barely coordinated stage, not reaching the point of disorder. As Sichuan Province began to change its development philosophy from the previous sloppy and speed-oriented to quality-oriented and intensive, and from the pursuit of economic growth to the pursuit of

ISSN: 2688-9323

economic quality and efficiency, the level of 3E system coupling and coordination in Sichuan Province was significantly improved and reached an intermediate level of coordination in 2020.

4. Conclusion

The evaluation values of the energy, economic and environmental subsystems in Sichuan province were calculated by the entropy TOPSIS method, and the following conclusions and insights were obtained from an empirical analysis of the level of coupled coordination between energy, economic and environmental systems in Sichuan province with the help of a modified coupled coordination model: although the level of coordination between energy, economic and environmental systems in Sichuan province has been increasing between 2011 and 2020, it has only reached an intermediate level of coordination. However, it has only reached the intermediate level of coordination. Therefore, based on the evaluation of the level of coordinated development of the energy-economy-environment system, recommendations for the coordinated and sustainable development of energy, economy and environment are put forward.

Optimise the energy consumption structure and vigorously develop clean energy. The weighting of the indicators determined by the entropy method reveals that energy consumption per unit of GDP, the proportion of oil consumption and the proportion of natural gas consumption have a greater impact on the energy subsystem, so it is necessary to optimize the energy consumption structure, vigorously develop clean energy and increase the proportion of clean energy such as natural gas, to improve the level of coordinated development of the energy system.

Adjust the industrial structure and transform the mode of economic development. Firstly, modernised agriculture should be strengthened to increase the added value of agricultural products; secondly, industry should be met to achieve green development, industrial restructuring should be carried out and the utilisation rate of resources in industrial production should be improved; thirdly, new industries should be vigorously developed to establish a modernised industrial system to provide a guarantee for the quality and efficiency of the economy. In short, through industrial restructuring, the efficiency of industrial development will be improved and the interactive development between industries will be promoted, thus improving the coordinated development of the economic system.

Strengthen environmental protection, energy conservation and emission reduction. Industrial pollution emissions and total investment in environmental pollution control have a large impact on GDP. With the development of the economy, environmental pollutants are emitted in huge quantities, and as most environmental pollutants are generated by energy-intensive industries, environmental pollution control needs to be strengthened at source to promote energy conservation and emission reduction. Establish a sound pollutant emission management system and formulate relevant laws and regulations. Strengthen cooperation between government and enterprises, strengthen the role of environmental science and technology support, promote "multi-pollution collaborative treatment", and strengthen research on key technologies such as soil pollution treatment and remediation. Increase environmental pollution control equipment, equipment and environmental monitoring, so as to improve the coordinated development of environmental systems.

ISSN: 2688-9323

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