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Multi-Scenario Forecast of Sustainable Development in Sichuan of China Based on Coupling Evolution Analysis

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Abstract: *Sustainable development involves economy, energy, environment and technology, which intertwine with each other in complicated ways. To achieve sustainable development, it is imperative to study the coordinated development of the four. In this paper, a system dynamics model is constructed to reflect interaction between the economy, energy, environment, and technology by using the data in Sichuan Province between 2010 and 2020. Then five scenarios (current situation, economy development priority, energy development priority, environment protection priority, technology innovation priority) are set up and simulated. Finally, different scenarios are evaluated using the coupling coordination degree model. The results indicate that: in the short term, the system is more coordinated under environment protection priority scenarios; while in the long term, the energy development priority scenario can better achieve the coordinated development. The paper provides recommendations to formulate effective measures and promote sustainable development in Sichuan province.*

Keywords: *Economy-energy-environment-technology, System dynamics, Coupling coordination degree*

1. Introduction

In recent years, the concept of sustainable development has received increasing attention around the world. Sustainable development covers 17 goals, among which the concept of three pillars (economic, social, and environmental) has gained wide recognition and support [1]. Energy is a central component of the physical and social infrastructure needed to eradicate poverty and support economic growth [2]. Technology is a critical driver of sustainable development, capable of addressing social, environmental and economic challenges and impacts simultaneously [3].

Sichuan is a resource-based Province and the center city of western China. In 2020, its oil and gas production accounted for 11.8% of China's overall production and ranked 6th out of 31 Provinces in GDP. In addition to economy and energy, Sichuan holds a position in technology and environment. However, few studies look at the economy, energy, environment, and technology as a whole in central and western China's resource-based regions. As a result, this paper concentrates on two issues. First, can Sichuan Province achieve coordinated development? Second, under what types of policies is it possible to achieve coordinated development in Sichuan? To better answer these issues, the system dynamics method is used in this paper to build a dynamics model of the economy-energy-environment-technology system, and five scenarios are set up to simulate the quadratic system in multiple scenarios. Then, based on the scenario simulation results, the coupling coordination degree is measured. Through contrasting and analyzing the findings, Sichuan's sustainable development path is explored, serving as a reference for other resourced-based regions in China to design their sustainable development policies.

2. Literature review

Sustainable development includes three main goals: economy, society and environment, integration of them can lead to a better development [1]. Energy is essential for 2030 Sustainable Development Agenda and socioeconomic development [4], which influences the environment and natural resources sustainably management, and the physical and social infrastructure establishment for sustainable development [5]. Inevitably, the process of economy and energy development impacts on the environment. In West Asian and Middle Eastern countries, an inverse U-shaped relationship between economic growth and ecological footprint was found [6], and Mexico's carbon emissions were positively correlated with both energy consumption and economic growth [7]. Technology is a critical component for regions and nations to achieve sustainable development, without whom the enhanced sustainability performance cannot be improved [8]. Increased levels of technology can reduce ecological footprints and promote economic growth [9]. Moreover, technological innovation and economic structural transformation have a positive effect on energy efficiency [10].

The coupling coordination degree model (CCDM) has lately been employed in researches to assess system performance in the context of sustainable development. Liu studied the ecological environment and economy through the CCDM, guiding Chinese regional sustainable development strategies [11]. Liu argued that an intensive study of energy, economy, and ecosystem is important for sustainable regional development and examined the energy-economy-ecosystem in 11 provinces in China using the CCDM [12]. However, CCDM focuses on the static analysis of the system, if it can be combined with dynamic simulation and forecasting methods, it will be more scientific and comprehensive to analyze a system. System dynamics (SD) is a complex system modeling method that has been widely used to simulate economy, energy, environmental, and technology fields. Linderhof developed an SD model including economy, energy, and environmental subsystems and simulated four policy scenarios, investigating potential ways to achieve a low-carbon economy [13]. Zuo constructed a sustainable development model, using an SD model to explore the economy-energy-environmental development under energy and environmental policies [14].

While the CCDM is applied to evaluate the level of system's coordinated development, the SD model is suitable for forecasting long-term trends and dynamic results of various policies for its capability of dealing with complicated dynamic relationships. The combination of the two methods not only allows system dynamic simulation but also provides a reference for policy formulation by setting policy scenarios to predict the system coupling coordination under different scenarios. Therefore, this paper combines the two methods and sets up different scenarios to analyze economy-energy-environment-technology system in-depth and explore a path to achieving sustainable development.

3. Empirical study

3.1. Modelling of the SD model

3.1.1. Data sources

The data sources include Sichuan Provincial Statistical Yearbook (2011-2021), National Statistical Yearbook (2011-2021), National Statistical Bulletin (2020), the Sichuan Ecology and Environment Statement (2020), and other available statistics.

3.1.2. Causal relationships

GDP, as an important indicator economic development, can directly influence industrial output, energy consumption, research and development (R&D), environmental protection investment, etc. Energy production and consumption are influenced by economic growth, whereas both are often accompanied by energy pollutants and industrial waste emissions, causing environmental pollution and damage. The increasing environmental pollution level affects the total population and thus has a dampening effect on economic growth. Technology investment is influenced by economic growth, and increased investment in it can boost energy efficiency and lower pollution from energy use.

3.1.3. Description of the four subsystems and Stock Flow Diagrams

The economy-energy-environment-technology system is deconstructed into the economy subsystem, energy subsystem, environment subsystem, and technology subsystem.

The economy subsystem. It is at the core and is the driving force of the whole system, providing economic support. The economy subsystem mainly includes: GDP, GDP growth, output of the industry and GDP per capita. GDP growth rate affects GDP increment, which in turn affects GDP, and industrial output is affected by both GDP and labor force.

The energy subsystem. The energy subsystem mainly includes: total energy production, total energy consumption, energy intensity, coal consumption, natural gas consumption, oil consumption. Total energy consumption is influenced by GDP and energy intensity, while fossil fuel consumption is influenced by total energy consumption and the ratio of each fossil fuel consumption.

The environment subsystem. The environment subsystem mainly includes: environment protection

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investment, discharge of industrial wastewater, waste gas and solid waste, and capacity for treating solid waste. Environment protection investment is influenced by the GDP and the rate of environment protection investment, and the discharge industrial pollutants is influenced by the secondary industry.

The technology subsystem. The technology development is inseparable from technological talents, as well as sufficient funds as economic guarantee. The technology subsystem mainly includes: R&D investment, full-time equivalent of R&D personnel, patent authorization, and transaction value in technical markets. Utilizing the simulation software Vensim, the system's stock flow diagram is created, as seen in Figure 1.

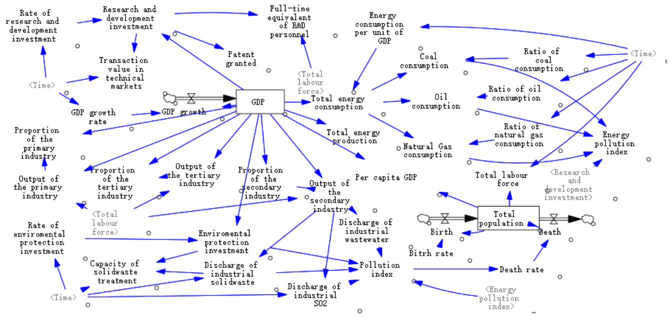

Figure 1: The stock flow diagram of the economy-energy-environment-technology system.

3.1.4. Model validation

Before conducting the simulation, the model validity must be checked by considering the degree of fit between the model and the reality. In this paper, absolute relative error (ARE) and mean absolute relative error (MARE) are used in this study to test the validity [15]. The formulas are as follows.

$$ARE_{it} = \left| (\hat{Y}_{it} - Y_{it}) / Y_{it} \right| \tag{1}$$

$$MARE = \frac{1}{N \times T} \sum_{i=1}^{N} \sum_{t=1}^{T} ARE_{it} \tag{2}$$

where t is time, I is selected variable, N is the number of selected variables, T is the number of selected years, $\hat{Y}_{it}$ and Y_{it} are the predicted value and the true value, respectively. Taking 2010 as the initial year, the time boundary is 2010-2030, where 2010-2020 is the simulation test period, 2021-2030 is the simulation period, and the simulation step is 1 year. Typical indicators such as output of the industry, energy consumption, discharge of industrial wastewater, total population, and R&D investment are selected for validity testing, and Figure 2 shows the results. The ARE of most indicators are less than 0.1, and the MARE is 0.026, indicating that the constructed model can reflect the system in Sichuan Province realistically.

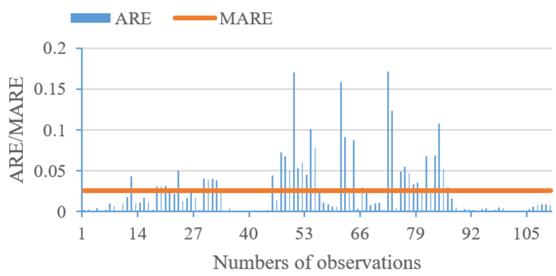

Figure 2: Validation results.

3.1.5. Scenarios setting

Policy simulation is a necessary feature and advantage of system dynamics, exploring the influence on the whole system through changing values of key parameters. According to Sichuan Province's 14th Five-Year Plan and other documents, the GDP growth rate, energy intensity, ratio of natural gas consumption, ratio of coal consumption, rate of environment protection investment, and rate of R&D investment are selected as the regulation parameters. Base on the current scenario, five scenarios are established by adjusting these parameters. Parameter setting of scenarios is shown as in Table 1.

Table 1: Parameter setting of scenarios.

Parameter	Scenarios				
	Current situation	Economy Development Priority	Energy Development Priority	Environment Protection Priority	Technology Innovation Priority
GGR(%)	4.00	6.00	5.00	4.00	5.00
EI	0.53	0.53	0.25	0.53	0.53
RCC(%)	27.67	27.67	23.00	27.67	27.67
RNGC(%)	16.37	16.37	20.00	16.37	16.37
REPI(%)	0.85	0.85	0.85	1.10	0.85
RRDI(%)	2.40	2.40	2.40	2.40	3.20

Notes: GDP growth rate (GGR), energy intensity (EI), ratio of coal consumption (RCC), ratio of natural gas consumption (RNGC), rate of environment protection investment (REPI), rate of research and development investment (RRDI).

3.2. Construction of coupling coordination degree model

3.2.1. Indicator system

The indicator system is constructed according to the 14th Five-Year Plan and relevant literature. It depicts the economic production and industrial structure; the energy consumption, structure and efficiency; the environmental governance and pollution; and the technology input and output. As shown in Table 2.

Table 2: Indicator system and weights for the economy-energy-environment-technology system.

Subsystem	Indicator	Direction	Unit
Economy subsystem	GDP	+	100 million yuan
	Per capita GDP	+	10,000 yuan /capita
	Proportion of the primary industry	+	%
	Proportion of the secondary industry	+	%
	Proportion of the tertiary industry	+	%
Energy subsystem	Total energy production	+	10,000 tons SCE
	Total energy consumption	-	10,000 tons SCE
	Ratio of coal consumption	-	%
	Ratio of oil consumption	-	%
	Ratio of natural gas consumption	+	%
	Energy intensity	-	TCE / 10,000 yuan
Environment subsystem	Discharge of industrial wastewater	-	10,000 tons
	Discharge of industrial SO_2	-	10,000 tons
	Discharge of industrial solid waste	-	10,000 tons
	Capacity of solid waste treatment	+	%
	Environmental protection investment	+	100 million yuan
Technology subsystem	Research and development investment	+	100 million yuan
	Full-time equivalent of research and development personnel	+	man-year
	Patent authorization	+	item
	Transaction value in technical markets	+	100 million yuan

Notes: GDP = Gross domestic product; SCE = Standard coal equivalent; TCE= Ton of standard coal equivalent.

3.2.2. Data processing and weight determination

Entropy method is an objective weight determination method and frequently applied to assess system's indicator weights [16,17]. However, due to the difference in the scale of each indicator and the existence of both positive and negative indicators, the original data must be standardized the before calculating weights. The detailed steps are as follows.

Data standardization:

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$$v_{ij}=\frac{V_{ij}-\min V_j}{\max V_j-\min V_j}, if\ V_{ij} \text{ is a positive indicator}$$
$$v_{ij}=\frac{\max V_j-V_{ij}}{\max V_j-\min V_j}, if\ V_{ij} \text{ is a negative indicator} \tag{3}$$

Where v_{ij} and V_{ij} are the standardized and original values of indicator j in year i; $\max V_j$ and $\min V_j$ are the maximum and minimum of indicator j in year i.

Detailed steps to calculate the weights by entropy method are as follows: Proportions of indicator j in year i:

$$P_{ij}=v_{ij}\Big/\sum_{i=1}^{n}v_{ij} \tag{4}$$

Information entropy of each indicator:

$$E_j=-\frac{1}{\ln(n)}\sum_{i=1}^{m}P_{ij}\cdot\ln P_{ij} \tag{5}$$

Weight of each indicator:

$$W_j=(1-E_j)\Big/\sum_{j=1}^{m}(1-E_j) \tag{6}$$

Comprehensive level of the subsystems in year i:

$$U_i=\sum_{j=1}^{m}W_j\times v_{ij} \tag{7}$$

3.2.3. Coupling coordination degree model

The CCDM of the quadratic system are established according to Wang [18]. The formulas are shown below:

$$C=\sqrt{\left[1-(\frac{\sqrt{(U_4-U_3)^2}+\sqrt{(U_4-U_2)^2}+\sqrt{(U_4-U_1)^2}+\sqrt{(U_3-U_2)^2}+\sqrt{(U_3-U_1)^2}+\sqrt{(U_2-U_1)^2}}{6}\right]\times\sqrt[3]{\frac{U_1\times U_2\times U_3}{U_4\times U_4\times U_4}}} \tag{8}$$

$$T=\alpha U_1+\beta U_2+\gamma U_3+\lambda U_4 \tag{9}$$

$$D=\sqrt{C*T} \tag{10}$$

Where C is the coupling degree, T is the overall development level, and D is the coupling coordination degree. Each subsystem is given equal importance in this paper, thus $\alpha=\beta=Z=T=1/4$. $U_i(i=1,2,3,4)$ represents each subsystem's comprehensive level, supposing $\max U_i=U_4$. According to relevant studies (Yang et al. 2020), coupling coordination degree is between 0 and 1, the higher it is the better the coordination effect between subsystems. This paper divides it into eight stages, as shown in table 3.

Table 3: Classification of the coupling coordination evaluation levels.

Coupling coordination degree	Coupling coordination types
0.88 – 1	Quality coupling coordination
0.76 – 0.87	Favorable coupling coordination
0.63 – 0.75	Moderate coupling coordination
0.51 – 0.62	Primary coupling coordination
0.38 – 0.50	Mild disorder
0.26 – 0.37	Moderate disorder
0.13 – 0.25	Serious disorder
0 – 0.12	Extreme disorder

4. The results of scenarios' coupling coordination degree

Different scenarios emphasize different developments. This paper uses the CCDM to better value each scenario, seeking the optimal solution for the system development. The results are shown in Figure 3.

In Economy development priority scenario, the coupling coordination degree exhibits a growing trend while the increase rate is sluggish year after year. It rises from moderate coupling coordination to favorable coupling coordination in 2026, and eventually reaches 0.778 in 2030. The scenario emphasizes only the economy growth rate and does not consider the impacts economic development on environment and energy, which may be the reason for the slight incoordination. This result suggests that achieving coordinated development in Sichuan Province requires more than just high economic growth.

In energy development priority scenario, the coupling coordination degree grows further, rising from 0.683 in 2021 to 0.811 in 2030. This scenario prioritizes energy development and maintains the economy at a medium rate of development. Although the benefits do not become obvious right away, they gradually do as the energy intensity and structure are adjusted. By 2028, its degree surpasses that of environmental protection priority scenario and is still rising.

The coupling coordination degree under environment protection priority scenario grows faster in the early stage. It rises from moderate coupling coordination to favorable coupling coordination in 2023, and slows down in the later stage, reaching 0.774 in 2030 finally. The scenario emphasizes environmental protection, but lower economic growth rates, energy efficiency and neglect of technological inputs make it less coherent in later stages of development. The results suggest that attention to the environment can improve coupling coordination degree in the short term, but enhanced investment in environmental pollution control alone is not sufficient to achieve further system coordination.

In technology innovation priority scenario, the degree of coupling coordination rises from moderate coupling coordination to favorable coupling coordination in 2024, and from 0.727 in 2021 to 0.776 in 2030. In its early stages, this scenario's development is only second to that of the priority scenario for environmental protection. However, in the later stage, as in the economy development priority scenario, the growth rate of coupling coordination slows down year by year. The results show that increasing the intensity of research funding alone is still not sufficient to enable the system to develop in a coordinated manner.

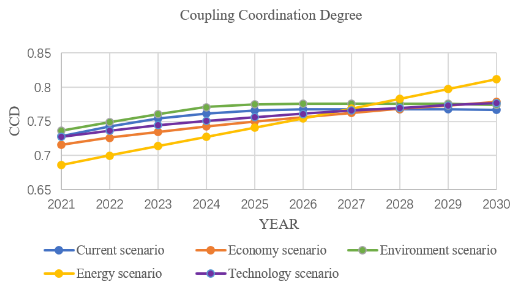

Figure 3: Coupling coordination degree under different scenarios.

5. Conclusions

This paper discovers that the system under the environment protection priority scenario develops well in the early stage, followed by the technology innovation priority scenario. However, the growth rates of both scenarios continue to slow down in the later stages. In terms of short-term development, the environmental protection priority scenario is conducive to achieving the system's coordinated development. Although the energy development priority scenario is inferior to other scenarios in the early stage, it has a significant advantage in the latter stage and tends to grow continuously. In terms of long-term development, the energy development priority scenario with energy intensity and energy structure adjustment can better achieve coordinated development.

This paper suggests that Sichuan Province can achieve the economy-energy-environment-technology system's coordinated development based on maintaining medium-speed economic growth by accelerating the energy structure transformation and increasing environmental protection investment. Then the following recommendations are given.

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On the one hand, the modern energy system's core contents are clean, low-carbon, safe, and efficient. Sichuan Province must benefit from the growth of the clean energy sector by systematically growing hydropower, advancing the development of wind and solar power. By establishing the largest modern natural gas production base in China and modernizing the Sichuan power system to use new energy as its principal source of electricity, the Sichuan Province can further alter and improve its energy structure. On the other hand, given the fact that there is still room for progress in environmental pollution control and the strain that Sichuan's future economic and energy development would place on the environment, Sichuan is not supposed to reduce its investment in pollution control. Furthermore, Sichuan should prioritize the construction of a sturdy ecological security barrier and concentrate on the growth stance of constructing a green development pioneer area due to its geographical location.

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