Research on coordinated development of urban energy system and economic system--Based on coupling coordination model

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Abstract. Energy provides an important impetus for urban economic growth, with 80% of the world's energy consumption concentrated in cities. With the acceleration of economic development and urbanization, China has become the world's largest consumer of energy. Based on the data of Chengdu, China, in 2009-2018, this paper constructs an urban energy-economic evaluation index system, and uses the entropy weight method and the coupling coordination model to analyze the coordinated development between urban economic growth and energy consumption. The results show that both the energy system and the economic system can be in a coordinated development in 2008 and 2014, and the energy system and economic system are basically in an uncoordinated development in other time periods. The development process of the coupling and coordination of energy and economic systems is generally a four-stage development: coordinated - uncoordinated - coordinated - uncoordinated. Therefore, based on the above research, it is proposed to promote the simultaneous optimization and development of urban energy systems and economic systems.

1. Introduction

Until 2017, the main sources of global energy are still oil, natural gas and coal [1]. In the context of economic globalization, China's contribution to global economic growth is about one-third [1]. After the reform and opening up, China's urbanization process has obviously accelerated, accompanied by a large consumption of energy. By the end of 2017, China's energy consumption growth also accounted for about one-third of the global energy increment [2]. China's energy consumption is closely related to economic growth [3], because the economic development of China's regional cities is based on a large amount of energy consumption [4].

The development of urban economic systems and energy systems is particularly important for sustainable urban development. The research methods of energy systems and economic systems mainly include, for example, constructing a coordination model of energy-economic system, and quantitatively analyzing the coordinated development level of energy system and economic system in Jiangsu Province [5]. The system dynamics model is used to model and simulate China's energy-economic system, and to analyze the relationship between China's economic growth rate and energy intensity [6]. In order to analyze the relationship between energy consumption and economic
development, the S-curve model of energy consumption and per capita GDP is constructed, and the energy consumption patterns in different stages of economic development are described [7]. At the same time, the decoupling analysis indicators and models of economic growth and energy carbon emissions are constructed, and the decoupling state between the two is discussed [8]. According to the Tapio decoupling model analysis, it is considered that the decoupling value of economic growth and energy consumption in Wuhan is highly elastic, and its GDP growth is inertially dependent on energy consumption [9]. From a new perspective of energy inventory index (EEII) and regional economic growth, applying cluster analysis and panel data modeling, it was found that EEII had a negative correlation with per capita GDP [10]. Regarding the construction of the evaluation index system for urban energy-economic system, many people are establishing an evaluation index system for coordinated development of energy-economic-environment systems [11-13], and studying the relationship between energy, economy and environment in development. The above proves that the importance of energy consumption for economic development cannot be ignored.

Therefore, in order to study the influence mechanism of energy system and economic system in urban development process, this paper first selects indicators to construct urban energy system and economic system, and then uses entropy weight method and coupling coordination degree model to study the coordinated development between urban energy and economic systems. Help managers to make recommendations for promoting energy sustainability, economic sustainability, and sustainable urban development.

2. Materials and methods

Referring to the previous research, based on the objectivity of the evaluation system, the construction of the urban energy economic system evaluation index system is shown in Table 1. From the perspective of energy saving, judge the attributes of each indicator. Among them, energy consumption includes coal, natural gas, and electricity consumption due to the lack of data. The indicators in the economic system are positive indicators. This paper selects Chengdu as the research object. In order to ensure the data is true and reliable, the indicator data are derived from the 2008-2017 Sichuan Statistical Yearbook [14], the China Statistical Yearbook [15] and the China Urban Statistical Yearbook [16]. Due to the different measurement units of the data, the Min-max standardization method is used to standardize the data in order to eliminate the dimensional influence. The Min-max normalization method is a linear transformation of raw data [17]. An original value \( y \) of an attribute is normalized by Min-max to a value in the interval \([0, 1]\), which is:

### Table 1. Urban Energy-Economic system evaluation framework.

| Subsystems       | Secondary indicators                                      | Code | References |
|------------------|-----------------------------------------------------------|------|------------|
| Energy system    | Energy consumption (tons of standard coal)                | X1   | [18]       |
|                  | Annual average growth rate of total energy consumption (%)| X2   | [19]       |
|                  | Per capita energy consumption (tons of standard coal)     | X3   | [20]       |
|                  | Power generation (10,000 kWh)                             | X4   | [21]       |
|                  | Energy consumption per unit of GDP (ton of standard coal / ten thousand CNY) | X5 | [20]       |
|                  | Industrial energy consumption above designated size (ton of standard coal) | X6 | [22]       |
| Economic system  | Per capita GDP (CNY)                                      | X7   | [23]       |
|                  | Local budgetary revenue (ten thousand CNY)                | X8   | [24]       |
|                  | Annual growth rate of industrial output value (%)         | X9   | [25]       |
|                  | Average annual growth rate of GDP                         | X10  | [26]       |
|                  | Retail sales of social goods (ten thousand CNY)           | X11  | [27]       |
|                  | The tertiary industry accounts for the proportion of GDP (%) | X12 | [28]       |
For the positive indicator: \( Y_{ij} = \frac{y_{ij} - \min(y_{ij})}{\max(y_{ij}) - \min(y_{ij})} \)

For the negative indicator: \( Y_{ij} = \frac{\max(y_{ij}) - y_{ij}}{\max(y_{ij}) - \min(y_{ij})} \)

After the data is normalized, the relationship between urban energy system and economic system is studied by using 2.1 and 2.2 methods respectively.

2.1. Entropy weight method

The entropy weight method [29, 30] determines the objective weight according to the magnitude of the index variability. The entropy weight method is used to weight the 12 indicators of the urban energy system and the economic system respectively to obtain the evaluation values of each system. Its empowerment steps are as follows:

Information entropy of the j-th indicator: \( E_j = -K \sum_{i=1}^{n} P_{ij} \ln (P_{ij}) \)

The weight of the j-th indicator: \( W_j = \frac{1-E_j}{n-\sum_{j=1}^{n} E_j} \quad (j = 1, 2, ..., n) \)

Among them, \( P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \), the constant \( K = \frac{1}{\ln (m)} > 0 \), \( m \) represents the number of years, \( n \) is the number of indicators, \( E_j \) is the entropy value, \( W_j \) is the entropy weight and \( \sum_{j=1}^{n} W_j = 1 \).

2.2. Coupling coordination model

Coupling theory was originally used for physics research, and its coupling refers to the measure by which two or more entities depend on each other. This paper will use the physical coupling function to construct the coupling coordination model of urban energy system and economic system, and analyze the dynamic development relationship of coupling coordination between urban energy consumption and economic growth. Establish a coupling coordination model [31, 32] as follows:

\[ C = \left\{ \left[ F_{(x)} \times G_{(y)} \right] / \left[ F_{(x)} + G_{(y)} \right] \right\}^{1/2}, T = \alpha F_{(x)} + \beta G_{(y)}, D = \sqrt{C \times T} \]

Among them, \( C \) is the coupling degree, \( F_{(x)} \) is the comprehensive evaluation index of urban energy system, \( G_{(y)} \) is the comprehensive evaluation index of urban economic system, and \( D \) is the coupling coordination degree of urban energy system and economic system. \( T \) is the comprehensive reconciliation index of the urban energy system and the economic system. \( \alpha \) and \( \beta \) represent the contributions of the two systems, respectively, so that \( \alpha = \beta = 1/2 \). Table 2 is a classification of the coupling coordination type.

| D       | Coordination type           |
|---------|----------------------------|
| 0.8<D≤1 | I : Advanced coordinated development |
| 0.5<D≤0.8 | II : Basic coordinated development |
| 0.3<D≤0.5 | III : Basic uncoordinated development |
| 0<D≤0.3 | IV : Serious uncoordinated development |

3. Results and discussion

3.1. Analysis of the impact of indicators on the development of urban energy system and economic system

Figure 1 shows the weights of the energy system indicators, sorted by \( X_2 < X_3 < X_5 < X_1 < X_4 < X_6 \), indicating how important this indicator is to evaluating the energy system. By the end of 2017, Chengdu's industry has grown steadily, with remarkable achievements in transformation and
upgrading. However, industrial enterprises above designated size are the main energy consumers in the city. Therefore, industrial energy consumption above designated size has the greatest impact on the development level of energy systems. The pace of urbanization is accelerating, and the influx of people has increased the pressure on cities to provide energy resources, especially electricity. The rate of energy consumption will change as the stability of the urban energy system changes, but the impact is not as great as the former two. Figure 2 shows that in the economic system, the average annual growth rate of industrial output has the greatest impact on the development of urban economic systems, and the ranking is X11 < X7 < X8 < X10 < X12 < X9. It can be seen from the statistics that the average annual growth rate of GDP reached the highest in 2011, and the overall trend of S curve is related to the adjustment of national policies and the form of international economic development. Actually, the retail sales of consumer goods in social consumption society are increasing year by year, indicating that people's living standards are also improving. As can be seen from Figure 3, 2008-2010: the development status of the economic system is better than the energy system; 2010-2011: the development status of the energy system is better than the economic system; 2011-2014: the development status of the economic system is better than the energy system; 2014-2016: Both are equivalent; 2016-2017: The development status of the energy system is better than the economic system.

3.2. Analysis of the coupled and coordinated development of energy system and economic system
After the data is substituted into the coupled coordination model, the coupling coordination degree values of the urban energy system and the economic system are obtained as shown in Figure 3, and the coupling coordination degree type shown in Figure 4 is obtained. Figure 5 shows the trend of the coupling degree between the energy system and the economic system. In 2013, the interaction between systems was the weakest. The intensity of the interaction between 2014 and 2016 was the largest in 10 years and remained basically unchanged during the period, until it weakened after 2016. Overall, the intensity of the interaction between systems varies widely. Table 3 shows that except for the coordinated development of energy system and economic system in 2008 and 2014, the energy system
and economic system were basically in an uncoordinated development at other times, and overall there is a four-stage development: coordinated-uncoordinated - coordinated - uncoordinated, but the system has been in a coordinated development for a very short period, which is not conducive to the coordinated and sustainable development of urban energy system and economic system.

![Figure 4. Trends in the coupling degree of urban energy systems and economic systems in 2008-2017.](image)

![Figure 5. Trends in the coordination of urban energy systems and economic systems in 2008-2017.](image)

### Table 3. Coupling coordination type of urban energy system and economic system.

| Year | Coordination type                  | Year | Coordination type                  |
|------|------------------------------------|------|------------------------------------|
| 2008 | Basic coordinated development      | 2013 | Basic uncoordinated development    |
| 2009 | Basic uncoordinated development   | 2014 | Basic coordinated development      |
| 2010 | Basic uncoordinated development   | 2015 | Basic uncoordinated development    |
| 2011 | Basic uncoordinated development   | 2016 | Basic uncoordinated development    |
| 2012 | Basic uncoordinated development   | 2017 | Basic uncoordinated development    |

### 4. Conclusions

At present, China is in the critical period of promoting high-quality economic development. As a supporting factor for the economy and people's livelihood, energy undertakes the important task of supporting economic growth and meeting the people's high quality of life. When the energy system and the economic system are at a relatively high level of coordinated development, the people can live a high quality life, and the economic development mode will shift towards low energy consumption and low input. However, it can be seen from the above research results that the coordinated development of the energy system and the economic system is generally poor. This reminds us that while pursuing the rapid development of the urban economy, we must also consider energy sustainability. This paper establishes an evaluation system of urban energy-economic system and introduces a coupling coordination degree model to better evaluate the coupling and coordinated development of urban energy system and economic system in space. In response to the above analysis of results, the following recommendations are made.
4.1. Introduce advanced technology to improve energy efficiency of enterprises
At present, China's energy utilization rate is lower than the world's advanced level, and it is not enough to only focus on the effective use of energy. The effective utilization of energy also proves the degree of development of a country's science and technology. Since the introduction of advanced technology in industrial processes will greatly improve energy efficiency, it is necessary to pay attention to strengthening energy management, improving energy use systems, retrofitting technology and improving process.

4.2. Develop new energy sources and promote energy sustainability
With the development of the economy, the increase of population, and the improvement of social life, the world's energy consumption will increase rapidly in the future. As the cornerstone of the future energy of human society, new energy is an alternative energy source for fossil energy. In the context of science and technology, first of all, accelerate the research and development of new energy, rely on technological innovation, improve the efficient use of clean energy, and continuously make breakthroughs in key technologies. Second, increase the structural adjustment and policy support for the new energy industry. Then, promote the healthy development of the new energy industry, realize a virtuous cycle of the new energy industry economy, and achieve energy sustainability.

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