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Research on Coupling Coordination Development for Photovoltaic Agriculture System in China

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Abstract: To explore the law of coupling coordination development of China's photovoltaic (PV) agriculture system, this study measured the comprehensive development level of the agriculture and PV industries from 2007 to 2016 using China's agricultural and photovoltaic industry statistics. Once this was achieved, the coupling coordination degree of the PV agricultural system was measured and a development mode of this system was determined. Finally, we explored the development trend of the coupled and coordinated evolution of the system. The main research results show that: (1) Although the development level of the agriculture and PV industries are both in an upward trend, the rising rate of development by the PV industry far exceeds the agriculture industry. (2) As agricultural and PV industries expand, they both show stock resource-led characteristics, but the incremental resources of the PV industry are gradually taking the lead. (3) The coupling coordination degree of the agriculture and PV industries fluctuates as it rises, but the coupling is low. It has not yet evolved to a higher level of coupling, and the speed of upgrading and evolution is slow. (4) In the next 10 years, the evolution speed of the two industries will be significantly improved, and the coupling between them will enter the coordination stage. PV agriculture will further develop in a sustainable direction.

Keywords: PV agriculture; stock and incremental characteristics; coupling coordination degree model; prediction

1. Introduction

Photovoltaic (PV) agriculture is a new type of agriculture that applies solar power to a wide range of fields such as modern agricultural cultivation, aquaculture, irrigation, pest control, and power supplies for agricultural machinery. The combination of agriculture and PV began in the 1970s, and it was considered to have good prospects for future application [1]. However, economic, technical, and institutional barriers hindered the promotion of PV application in agriculture at that time [2]. Since the 1990s, PV technology has made great progress, which in turn has led to the large-scale application of PV power generation in agriculture in recent years [3], and PV agriculture has gradually grown up in scale. Moreover, the new era has given PV agriculture more applications. On the one hand, in order to cope with global warming, it is necessary to introduce clean energy into agricultural production. On the other hand, the continuous growth of the global population requires agriculture to produce more food. This also means more power consumption, and PV agriculture has a very broad application prospect [4]. In recent years, power station construction for China's PV agriculture industry has experienced rapid development. In 2009, the installed capacity of China's agricultural PV power plants was less than 0.001 GW, and in 2014 it reached 1.18 GW. According to Frost and Sullivan, the annual installed capacity of China's agricultural PV power plants in 2018 will reach 3.26 GW, and the cumulative installed capacity will reach 12.42 GW. In addition, China's 13th Five Year Plan has raised PV agriculture to a higher level and has been linked to PV poverty alleviation, while encouraging PV power generation to combine with farming and aquaculture to make full use of barren hills, barren slopes, fish ponds, greenhouses, and other resources to vigorously develop PV agriculture. Under the current rapid development of the PV industry, PV agriculture—seen as an icebreaking move for the development of the industry—plays an important role, with broad development prospects [5]. From an agricultural perspective, PV agriculture will break the bottleneck of China's traditional agricultural development, and is an inevitable choice for further developing the rural economy and improving the lives of farmers. It is also part of a trend of changes in agricultural production methods. In the short term, PV agriculture is an effective measure to solve the current dilemma of the PV industry. In the long run, the development of PV agriculture is of great significance to China's agricultural transformation.

The combination of PV and agriculture appeared earlier in the field of agricultural irrigation. Katzman and Matlin used the example of Nebraska and Texas in the United States, where the cost of fuel and other factors were combined to analyze the cost-effectiveness and commercial viability of solar PV irrigation systems, and the years of optimal application were predicted [6]. Since then, NASA's Lewis Research Center launched a global market forecasting study in the 1980–1981 program year for PV systems in the agricultural sector, where it analyzed the obstacles to the international marketing of PV products in the United States, and then proposed the relevant recommendations [1]. However, subsequent research focused on the barriers to the application of solar PV in agriculture, mainly from economic, institutional, and social perspectives [2], and as a result there was little literature on the application of PV in agriculture produced in the 1990s [3].

As predicted by Katzman and Matlin, the optimal application time for PV in agriculture was not until after 2000, both from a cost-effective perspective and from a commercial viability perspective. The problem of barriers to the application of PV agriculture was still mentioned in the early stage literature in the 21st century, including Radulovic's proposal to promote the application of PV in the Indian agricultural sector, proposing to overcome "political barriers" [7]. Mousazadeh also analyzed the issue of "replacement cost barriers" in related research [8]. Nonetheless, recent research has made optimistic predictions on the application prospects of PV agriculture. They all believe that PV agriculture is a good choice for meeting agricultural production energy demands and realizing agricultural green production [4,9,10]. Meanwhile, in addition to its application in agricultural irrigation [11–13], the application of PV in agriculture presents a trend of diversification, including agricultural electric vehicles [14], farm lighting [15], and agricultural greenhouse systems [16–18]. Due to technological advances, the economic uncertainty of various PV agricultural technologies has been greatly reduced, and many studies have proved that these technologies are economically feasible [14,16,19]. Moreover, its social [18] and environmental effects [20–22] have also been confirmed.

It can be seen from the above that the current research has achieved much in the application prospects, technology and economic feasibility of PV agriculture. However, most of the research has been aimed at the related effects of PV agriculture projects, and has not involved the interaction of the two elements in the PV agriculture system. For that reason, we tried to conduct research from the perspective of "coupling coordination". "Coupling" is originally a concept in physics, referring to the phenomenon that two or more elements or movements connect with each other through various interactions [23,24], and "coordination" means that the elements in the system are harmonious [23]. The concept of "coupling coordination" was introduced through industrial economics. After that, it was often used to describe the interaction effect of industrial organizations and the dynamic relationships existent in market structure, performance, and behavior. Through research and analysis of the principle of coupling between industries, economists have found the optimal combination of interactions between two or more industries, which enables them to promote each other, support each other, and coordinate development. In summary, its application in industrial economic research mainly includes the following aspects: research on the overall development level of industry [25–27], construction and application of the coupling coordination degree model [28–31], and prediction studies measuring degrees of coupling coordination [25,28]. The coupling between the agriculture and PV industries is based on systems theory. The dynamic positive correlation of interdependence, mutual coordination, and mutual promotion between the two industrial systems is formed by the interaction of production factors such as space resources, capital, technology, and human resources. The coupling coordination development of PV agriculture will promote the continuous and deepening of subsystems in the system from low to high and simple to complex, before finally reaching the overall optimal status of the system. Therefore, constructing a coupled interaction model of the PV agriculture system and measuring and predicting the industrial coupling coordination degrees within the system is of great significance to the sustainable development of PV agriculture.

The contributions of this paper are mainly reflected in the following three aspects: (1) The comprehensive development level of China's agriculture and PV industries from 2007 to 2016 is analyzed. Based on the traditional evaluation method, the overall development level is broken down into the dual development characteristics of "stock and increment", and the impact of stock resources and incremental resources on the overall development level of the two industries is estimated. (2) Shortcomings in the evaluation of inter-industry coupling degrees under the traditional weighting method are observed. Based on synergy theory, an optimized weighting method is proposed to measure the degree of coupling coordination as well as to determine the coupling coordination development mode between the agriculture and PV industries. (3) The modified GM(1,1) model (Grey model(first-order equation, 1 variable)) was used to predict the evolutionary trend of coupling coordination in the PV agriculture system, and an evolutionary law of industrial coupling synergy development was obtained.

2. Materials and Methods

2.1. Analytical Framework

To measure the coupling coordination degree of the PV agriculture system, it is necessary to measure the development level of the agriculture and PV industries. Therefore, it is first necessary to construct an index system for measuring the development level of agriculture and the development level of the PV industry. In addition, we further forecast the coupling coordination degree of China's PV agriculture system from 2007 to 2016. The specific analytical framework is shown in Figure 1.

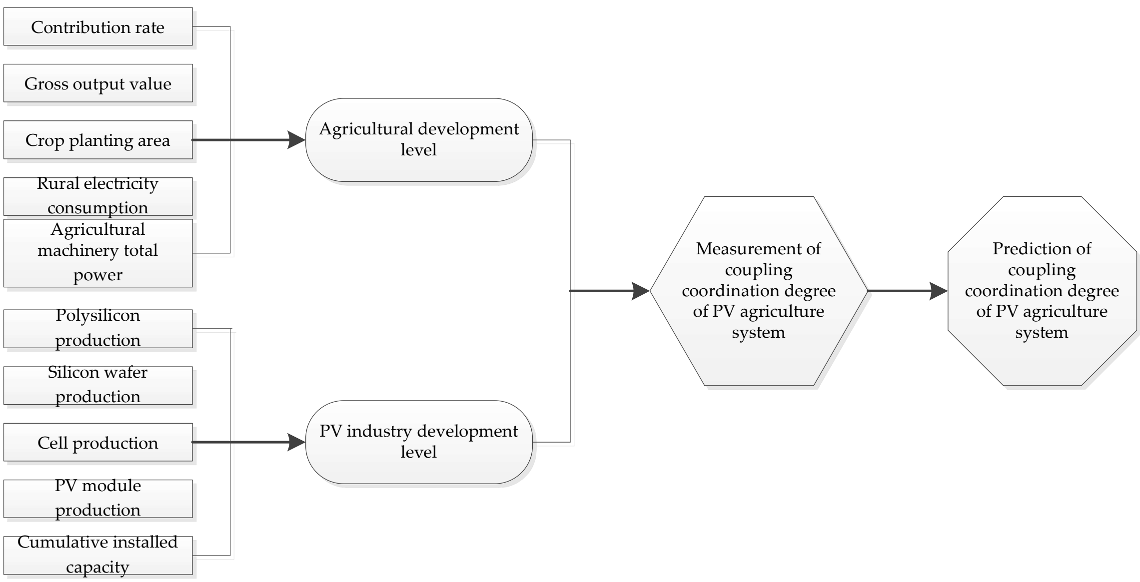

Figure 1. Analytical framework. PV: photovoltaic.

2.2. Index System and Data Sources

In line with the principles of science, system, and the availability of data, and taking into account the matching relationship with agriculture and PV industry evaluation indication, this study builds a comprehensive development level index system for the agriculture and PV industries according to the connotation and influencing factors of the coordinative development of PV agriculture systems. The index system is shown in Table 1.

Table 1. Evaluation index system for comprehensive development level of agriculture and PV industries.

Subsystem	Evaluation Indication	Unit	Subsystem	Evaluation Indication	Unit
Agriculture A	Contribution rate A_1	%	PV industry P	Polysilicon production P_1	10^4 tons
	Gross output value A_2	10^9 USD		Silicon wafer production P_2	GW
	Crop planting area A_3	10^3 hectare		Cell production P_3	GW
	Rural electricity consumption A_4	10^9 kW·h		PV module production P_4	GW
	Agricultural machinery total power A_5	10^4 KW		Cumulative installed capacity P_5	GW

Because some of the data of China's PV industry began to be counted in 2007, this paper measured the coupling degree between PV and agriculture from 2007 to 2016. The data selected in the study (see Table A1) were derived from the China Agricultural Yearbook, China Statistical Yearbook, China PV Industry Development Report, PV Power Industry Research Report, Clean Energy Industry Report, China PV Industry Development Research Report, China Renewable Energy Development Report, and other information recorded between 2007 and 2017.

2.3. Methods

2.3.1. System Development Level Measurement and Decomposition Model

(1) System development level measurement model

Suppose that system S consists of k subsystems, and is denoted by $S_1, S_2 \ldots S_k$, respectively. The whole system is denoted as $S = f(S_1, S_2 \ldots S_k)$, and f is a composite function.

Step 1: Standardization processing of the original data.

Use the range standard method to standardize the original data of k subsystems:

$$X_{ij}^{t} = \begin{cases} \frac{x_{ij}^{t} - \min_{ij}^{t}}{\max_{ij}^{t} - \min_{ij}^{t}}, X_{ij}(+) \\ \frac{\max_{ij}^{t} - x_{ij}^{t}}{\max_{ij}^{t} - \min_{ij}^{t}}, X_{ij}(-) \end{cases} \tag{1}$$

where x_{ij}^{t} represents the original value of the jth indicator of the t-year of the subsystem S_i, $i \in [1, 2 \ldots k]$. $\max_{ij}^{t}$ and $\min_{ij}^{t}$ are the maximum and minimum values of jth indicator of the t-year of the subsystem S_i, respectively. X_{ij}^{t} and X_{ij}^{t} represent the data after the standardization of the subsystem S_i in the t-th year.

Step 2: Entropy–weight method to calculate indication weights.

The proportion of the jth indicator in the t-year to all indicators is

$$p_{ij}^{t} = X_{ij}^{t} / \sum_{t=1}^{n} X_{ij}^{t} \tag{2}$$

The information entropy of the jth indicator is

$$E_{ij} = -(\ln n)^{-1} \sum_{t=1}^{n} \left(p_{ij}^{t} \times \ln p_{ij}^{t} \right) \tag{3}$$

The utility value of the jth indicator is

$$D_{ij} = 1 - E_{ij} \tag{4}$$

The weight of the jth indicator is

$$W_{ij} = D_{ij} / \sum_{j=1}^{m} D_{ij} \tag{5}$$

Step 3: Calculate comprehensive development level index of two subsystems.
The comprehensive evaluation function of subsystem S_i is

$$X_i^t = \sum_{j=1}^{m} w_{ij} X_{ij}^t,\ \sum_{j=1}^{m} w_{ij} = 1 \tag{6}$$

(2) System development level decomposition model

Although the traditional industry evaluation method can comprehensively and systematically collect the industry's effectiveness evaluation indicators and thus comprehensively evaluate the industry, it fails to highlight the dynamic characteristics of the indicators. Therefore, this study decomposed the factors affecting the overall development level into stock and incremental factors, and built an evaluation model with the dual characteristics of stock and increment that can systematically measure the driving force of the "stock resources" and "increment resources" for the industry at different stages of development [32].

Step 1: Suppose Δx_{ij}^t and ∇x_{ij}^t represent the original values of stock and the incremental resources of the subsystem S_i in the t-th year, respectively. The calculation formula is

$$\Delta x_{ij}^t = \sum_{t=0}^{t} x_{ij}^t \quad \nabla x_{ij}^t = x_{ij}^t - x_{ij}^{t-1} \tag{7}$$

Step 2: Standardize it by the efficiency coefficient method:

$$\Delta X_{ij}^t = \frac{\Delta x_{ij}^t - \Delta \min_{ij}^t}{\Delta \max_{ij}^t - \Delta \min_{ij}^t} \tag{8}$$

$$\nabla X_{ij}^t = \frac{\nabla x_{ij}^t - \nabla \min_{ij}^t}{\nabla \max_{ij}^t - \nabla \min_{ij}^t} \tag{9}$$

where $\Delta \max_{ij}^t$ and $\Delta \min_{ij}^t$ represent the maximum and minimum values of stock resources sequence of the subsystem S_i in the t-year in the jth indicator, respectively. $\nabla \max_{ij}^t$ and $\nabla \min_{ij}^t$ indicate the maximum and minimum values of the incremental resources sequence of the subsystem S_i in the t-year of the jth indicator, respectively.

Step 3: Calculate the annual comprehensive development level of stock resources and incremental resources using the equation

$$\Delta X_i^t = \sum_{j=1}^{m} \Delta X_{ij}^t \times \Delta \lambda_{ij} \quad \nabla X_i^t = \sum_{j=1}^{m} \nabla X_{ij}^t \times \nabla \lambda_{ij} \tag{10}$$

where ΔX_i^t and ∇X_i^t represent the annual comprehensive development level of the stock and the increment of the subsystem S_i in the t-th year, respectively. $\Delta \lambda_{ij}$ and $\nabla \lambda_{ij}$ respectively represent the weights of the jth stock and increment indicators in the subsystems.

Step 4: Calculate the overall development level of the subsystem S_i in the t-year using the equation

$$X_i^t = \gamma_i^t \Delta X_i^t + \delta_i^t \nabla X_i^t,\ \gamma_i^t + \delta_i^t = 1 \tag{11}$$

where γ_i^t and δ_i^t represent the coefficient of contribution of annual stock and the incremental resources of the subsystem S_i to the overall development level of the industry, respectively. $\gamma_i^t > \delta_i^t$—the contribution of the industry stock factor to overall industrial development is greater than the increment factor—is contrary to $\gamma_i^t < \delta_i^t$—the contribution of industry stock factors to the overall industrial development is less than the increment factor. Using the value of X_i^t calculated in Equation (6), it is possible to solve the variation of the subsystem S_i stock and the increment contribution coefficient for different years.

2.3.2. Coupling Coordination Degree Evaluation Model

This paper used the capacity coupling coefficient model in physics for a reference to measure the coupling coordination degree between subsystems S_i [33].

Step 1: Calculate system coupling degree.

The coupling degree model containing k subsystems is

$$C^t = \left\{ \frac{\prod_{i=1}^{k} X_i^t}{\left[\frac{\sum_{i=1}^{k} X_i^t}{k}\right]^k} \right\}^v \tag{12}$$

where C^t represents the coupling degree value of k subsystems in the t-th year, v represents the adjustment coefficient, and v usually takes $1/k$. The value of C^t can directly reflect the coordination degree of k subsystems, and the value range of C^t is [0,1]. The closer the value of C is to 1, the better the coupling between subsystems is.

Step 2: Calculate system degree of coupling coordination.

In order to accurately reflect the level of interaction between subsystems, this paper adopted a more stable and broadly applicable coupling coordination degree to reflect the comprehensive development level of the system using the equation

$$P^t = \sum_{i=1}^{k} \alpha_i X_i^t \quad \sum_{i=1}^{k} \alpha_i = 1 \tag{13}$$

$$D^t = \sqrt{C^t \times P^t} \tag{14}$$

where α_i is the weight of each subsystem, P^t is the comprehensive evaluation index of k subsystems in the t-year synergy effect, and D^t is the degree of coupling coordination of k subsystems in the t-year.

Step 3: Optimize weights.

The α_i in the previous step is the contribution degree of each subsystem to the coupling synergy of the whole system ($\sum_{i=1}^{k} \alpha_i = 1$), which is usually subjectively assigned to α_i, and is often even simplified to $\alpha_i = 1/k$. In order to overcome the disadvantages of this subjective valuation method, we used synergy theory to redefine the weights of subsystems [34]. Synergy theory reveals the dynamic evolution mechanism of the system from low to high levels [35]. That is, a high degree of coordination is achieved when the degree of coupling between subsystems is high. When the development gap between subsystems is small, a high degree of coupling can reflect the strong coupling status between subsystems [36]. There are two ways to reduce the gap between subsystems and improve the degree of coupling. The first is to promote the development of low-performance systems, and the second is to reduce the development of high-performance systems [34]. Obviously the first method is a better choice to increase the degree of coupling. Therefore, it is necessary to increase the development investment of low-performance systems, which means that low-performance systems should produce higher value in the future. In practice, the high value output of low performance systems will attract more attention to promote its development. Therefore, the weight of low-performance systems should increase with the increasing gap between subsystems, which will further promote the improvement of low-performance systems. That is to say, low-performance systems should have higher contribution coefficients, and the contribution coefficients reflect the performance gap between subsystems.

Therefore, when defining weights, an optimized method is proposed to solve this problem using the equation

$$\alpha_i^* = \frac{\sum_{i=1}^{k} X_i^t - X_i^t}{(\sum_{i=1}^{k} X_i^t)/(k-1)} \tag{15}$$

where α_i^* is the redefined contribution degree of the subsystem S_i to the whole system. If the performance of the subsystem S_i is low, the weight α_i^* is high.

Step 4: Coupling coordination development evaluation criteria and type division.

Based on the optimized weights in 2.2, the coupling coordination degree D is calculated, and the D value is used to divide the industrial coupling coordination development into 4 basic types: decline type, antagonistic type, running-in type, and development type, which are then further divided into 10 subtypes (see Table 2). The value range of D is [0,1], and the value of D is closer to 1, indicating that the degree of coupling coordination between the two systems is higher. On the contrary, the degree of coupling coordination is worse. The research results of Liao Zhongbin [37], Yang Wei [38], and Xiang Li [39], demonstrate how the uniform distribution function method is used to divide the degree of coupling coordination between industries. The interval is set to reflect the coupling coordination relationship between industries more clearly and intuitively (see Table 2).

Table 2. Coupling coordination level division criteria.

No.	Coordination Range	Coordination Type	Coordination Subtype	No.	Coordination Range	Coordination Type	Coordination Subtype
1	0.00–0.09	Decline	Extreme imbalance	6	0.50–0.59	Running-in	Reluctant coordination
2	0.10–0.19		Serious imbalance	7	0.60–0.69		Primary coordination
3	0.20–0.29		Moderate imbalance	8	0.70–0.79	Development	Intermediate coordination
4	0.30–0.39	Antagonism	Mild imbalance	9	0.80–0.89		Good coordination
5	0.40–0.49		Close to imbalance	10	0.90–1.00		Quality coordination

2.3.3. GM (1,1) Grey Prediction Model

According to the grey system theory, although the signs of the objective system factors are complex and changeable, their development has its own objective laws. The dynamic prediction model based on the grey system theory is called grey prediction, the most widely used of which is the GM (1,1) of GM (1,N) model proposed by Deng Julong [40,41]. However, the defect of this model is that the dynamic time-varying property of the gray number parameter is neglected, which results in poor long-term prediction [42]. Therefore, an equal-dimension-complementary grey prediction model was constructed to correct the traditional GM (1,1) model [43]. The specific steps follow.

Step 1: Accumulate the original system sequence to generate a sequence $X_1 = \{x_1(i)\}(i = 1, 2, \ldots, n)$ using the equation

$$x_1(k) = \sum_{i=1}^{k} x_0(i) \tag{16}$$

Step 2: Average the generated X_1 using the equation

$$Z_1 = \{z_1(1), z_1(2), \ldots, z_1(n)\} \tag{17}$$

where $z_1(1) = x_1(1), z_1(k) = (x_1(k) + x_1(k-1))/2$

Step 3: Establish differential equations including

$$\frac{dx_1(k)}{dk} + ax_1(k) = u \tag{18}$$

where $k = 0, 1, \ldots, n-1$, and a and u are parameters to be estimated.

And rewritten in the form of a matrix:

$$\overline{Y} = B\overline{V} \tag{19}$$

$$\text{where, } \overline{Y} = \begin{bmatrix} x_0(2) \\ x_0(3) \\ \vdots \\ x_0(n) \end{bmatrix}, B = \begin{bmatrix} -z_1(1) & 1 \\ -z_1(2) & 1 \\ \vdots & \vdots \\ -z_1(n) & 1 \end{bmatrix}, \hat{\overline{V}} = \begin{bmatrix} \hat{a} \\ \hat{u} \end{bmatrix}.$$

Step 4: Estimated value is obtained by least square method:

$$\hat{\overline{V}} = \begin{bmatrix} \hat{a} \\ \hat{u} \end{bmatrix} = \left(B^T B\right)^{-1} \overline{Y} \tag{20}$$

Substitute the estimated value $\hat{a}, \hat{u}$ into the equation to get the GM (1, 1) differential equation:

$$\hat{x}_1(k+1) = \left(x_0(1) - \frac{\hat{u}}{\hat{a}}\right) e^{-\hat{a}k} + \frac{\hat{u}}{\hat{a}} \tag{21}$$

Step 5: Restore the above results to get the predictive value using the equation

$$\hat{x}_0(k+1) = \hat{x}_1(k+1) - \hat{x}_1(k) \tag{22}$$

Predict a value using the GM (1,1) model established by the known series, then add the new information data to the known series. Eliminate the oldest data, make the sequence equal dimension, and establish the new GM (1,1) model. In this way, rolling prediction is carried out, substituting data until the target is completed. The obtained series are as follows:

$$\hat{x}_0 = (\hat{x}_0(1), \hat{x}_0(2), \ldots, \hat{x}_0(n), \hat{x}_0(n+1), \ldots, \hat{x}_0(n+m)) \tag{23}$$

where $\hat{x}_0(1), \hat{x}_0(2), \ldots, \hat{x}_0(n)$ is the original data, and $\hat{x}_0(n+1), \ldots, \hat{x}_0(n+m)$ is the predictive data.

3. Empirical Analysis of the Development Level of the Agriculture and PV Industries

3.1. Analysis of the Comprehensive Development Level of the Agriculture and PV Industries

Based on systems theory, this study regards PV agriculture as a system consisting of two subsystems: The agriculture system is S_1, and the PV industry system is S_2. Employing formulas (1)–(6), MATLAB 9.1 software was used to calculate the comprehensive development evaluation indexes of the agriculture and PV industries, after which the ratio of the index was also calculated (see Table A2). The results are shown in Figures 2 and 3.

As can be seen in Figure 2, the comprehensive development evaluation index of the agriculture and PV industries from 2007 to 2016 increased year by year, during which time the agricultural development rate was relatively flat, while the PV industry increased significantly. Especially after 2013, the PV industry exceeded agriculture and has grown at a rapid pace. The reason for this is that since the implementation of the Renewable Energy Law on January 1, 2006, China has transitioned to a new era of renewable energy, accelerating energy transformation, and the popularity of PV has rapidly expanded and spread. With the country's high attention to the PV industry, relevant policy measures have also been introduced. In the past 10 years, China has introduced a series of measures to promote the healthy development of the PV industry, especially SCPRC (State Council of the People's Republic of China [2013] No. 24 document Several Opinions on Promoting the Healthy Development of China's PV Industry, which made 2013 an important turning point for PV industry development. However, as China's primary industry, the agricultural base is large, and the transformation of traditional agriculture into modern agriculture is still being explored. This has led to its development momentum being significantly weaker than that of the PV industry.

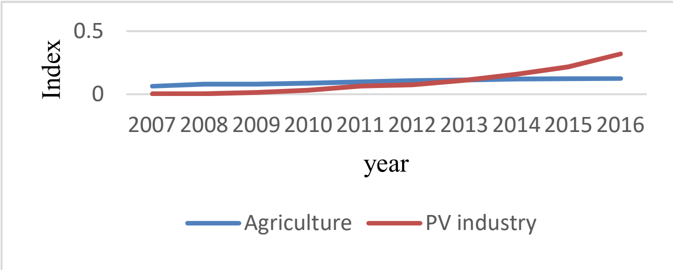

Figure 2. Comprehensive development evaluation index of the agriculture and PV industries.

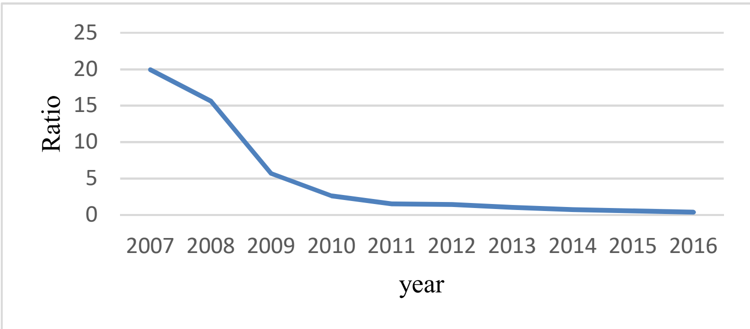

Figure 3. Ratio of comprehensive development evaluation index of the agriculture and PV industries.

For the ratio (X_1/X_2) of the comprehensive development evaluation index of the agriculture and PV industries, if the value is greater than 1—meaning that the comprehensive index of agriculture is larger than the comprehensive index of the PV industry—then agriculture has a stronger comparative advantage, and should take the lead in exerting in the process of industrial integration. If the value of X_1/X_2 is less than 1—meaning that the comprehensive index of the PV industry is larger than the comprehensive index of agriculture—then the PV industry has a stronger comparative advantage, and should take the leading role in the industrial integration process. It can be seen in Figure 3 that, in the PV agriculture system, the comprehensive index of agriculture in the first seven years is larger than that of the PV industry, but closer to the PV industry year by year. In the next three years, the comprehensive index of the PV industry will exceed agriculture. This shows that the PV industry has gradually occupied a dominant position in the PV agriculture system.

3.2. Decomposition of the Comprehensive Development Level of the Agriculture and PV Industries

Using the development evaluation model based on stock and incremental characteristics and the comprehensive development evaluation index of the agriculture and PV industries (see Table A2), we calculated the contribution of stock and incremental resources to the development of the two industries in reality using formulas (7)–(11) (see Table A3 for specific values). The results are shown in Figures 4 and 5. It can be seen that the contribution coefficient of stock resources was greater than that of the incremental resources, except in 2014. Especially in 2009 and 2010, the coefficient of stock resources was much larger than that of the incremental resources. As a whole, agricultural stock resources contributed a lot to the development of the industry, and have become the main source of power for agriculture development. In the past three years, stock resources have continued to increase in status. This indicates that the investment strategy has shifted from large-scale factor-driven growth to innovation-driven growth. During this stage, agriculture can promote stock resource adjustments by improving supply quality, optimizing agricultural investment structure in the process of increasing investment, achieving optimal allocation and generation efficiency of stock resources, and laying the foundational advantage of agricultural stock resources. It can be seen that China's agriculture is currently in a stock-dominant development status, and this development model is conducive to the improvement of the coupling coordination degree of the two industries. Independent of agriculture, the coefficient of stock resources of the PV industry is always greater than that of incremental resources, and presents a strong-super-strong-strong trend, of which the coefficient of stock resources in 2012–2014 played a decisive role. However, in 2013–2016, with the gradual improvement of the development level of the PV industry, the coefficient of incremental resources has gradually increased. The contribution of the incremental resources of the PV industry to industrial development has gradually increased. It will be in this stage where the incremental resource advantage is weakened, and stock resources can take advantage. The development status of this "stock-to-increment" is not conducive to the benign coupling coordination development of the two industries.

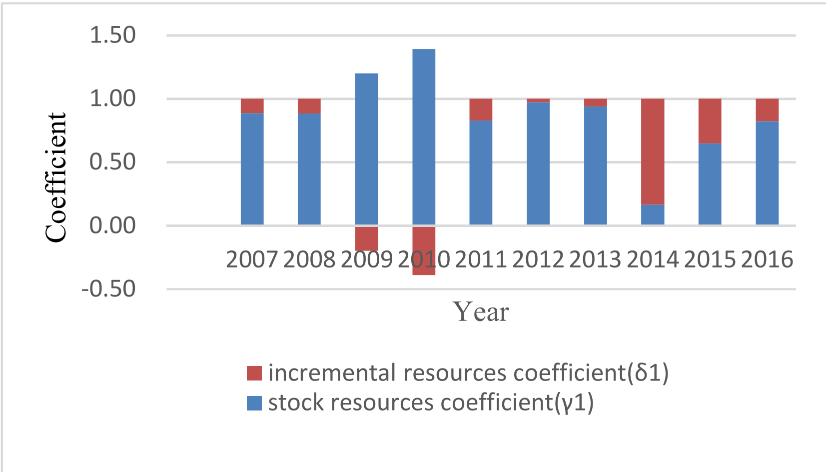

Figure 4. Agricultural stock resources coefficient and incremental coefficient change chart.

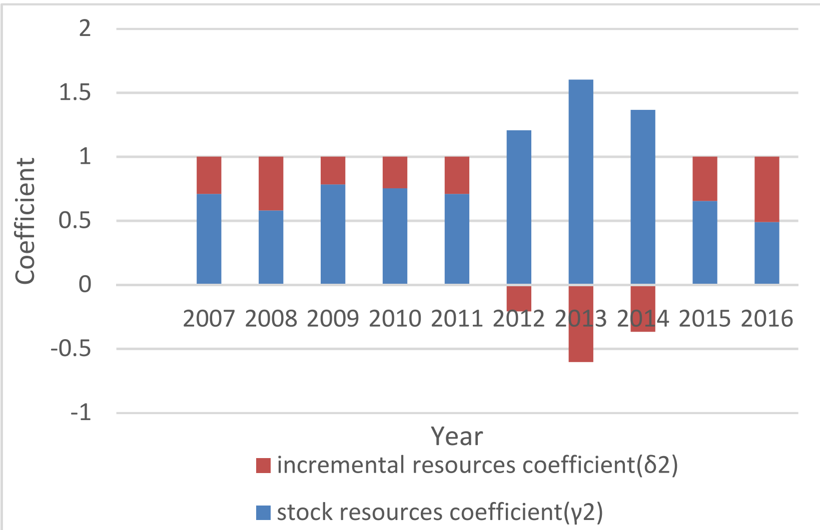

Figure 5. PV industry stock coefficient and incremental coefficient change chart.

It can be seen that optimizing stock and cultivating high-quality increments will contribute to the coupling coordination development of the agriculture and PV industries. Therefore, agriculture should gradually transform from scale to quality and efficiency, and smoothly pass through the capacity digestion stage of storage. The development of the PV industry should adopt an intensive and high-quality growth mode. While growing at a faster rate, we must also pay attention to the optimization of stock resources.

4. Empirical Analysis of Coupling Coordination Development of the PV Agriculture System

4.1. Analysis of Coupling Coordination Development under Traditional Weighting Method

Under the traditional weighting method, the assignment of α_i is subjective or average (i.e., $\alpha_i = 1/k$). In order to illustrate the limitations of the traditional qualitative method to determine the weight, we selected the weights of agriculture and PV industry development levels in the nine cases α_1 and α_2, namely $\alpha_1 = 0.1, \alpha_2 = 0.9; \alpha_1 = 0.2, \alpha_2 = 0.8; \alpha_1 = 0.3, \alpha_2 = 0.7; \alpha_1 = 0.4, \alpha_2 = 0.6; \alpha_1 = 0.5, \alpha_2 = 0.5; \alpha_1 = 0.6, \alpha_2 = 0.4; \alpha_1 = 0.7, \alpha_2 = 0.3; \alpha_1 = 0.8, \alpha_2 = 0.2; \alpha_1 = 0.9$, and $\alpha_2 = 0.1$, and substituted into formulas (12)–(14), so that the degree of coupling coordination D under different weights could be obtained (see Table A4). The results are further depicted in the form of a box diagram, as shown in Figure 6.

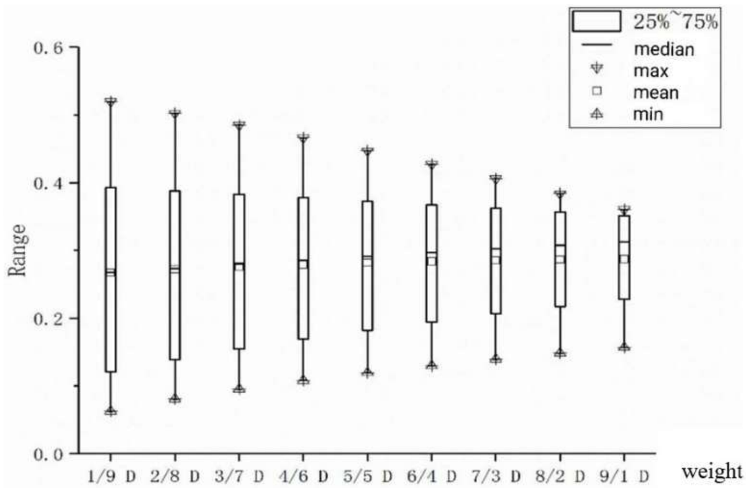

Figure 6. Degree of coupling coordination between agriculture and PV industries under different weights.

The box diagram depicts the degree of coupling coordination in nine subjective situations. It can be seen that the maximum, minimum, median, and mean have significant differences when α_1 and α_2 take different values. Take 2016 as an example. When $\alpha_1 = 0.1$ and $\alpha_2 = 0.9$, the D value is 0.5195, which belongs to the reluctantly coordinated running-in type. When $\alpha_1 = 0.9$ and $\alpha_2 = 0.1$, the D value is 0.3603, which belongs to a mildly imbalanced antagonistic type, and the difference is very significant. The subjective method causes the measurement results to seriously deviate from the actual situation, so the subjective weighting method has certain limitations.

4.2. Analysis of Coupling Coordination Development under Optimized Weighting Method

Using the optimized weighting method (Formula (15)), the new weights α_1^* and α_2^* were calculated based on the comprehensive development level of the two industries. α_1^* and α_2^* were then substituted into Formula (13) and (14) to get the optimized P^* and D^* values (see Table A5). The results are shown in Figures 7–9.

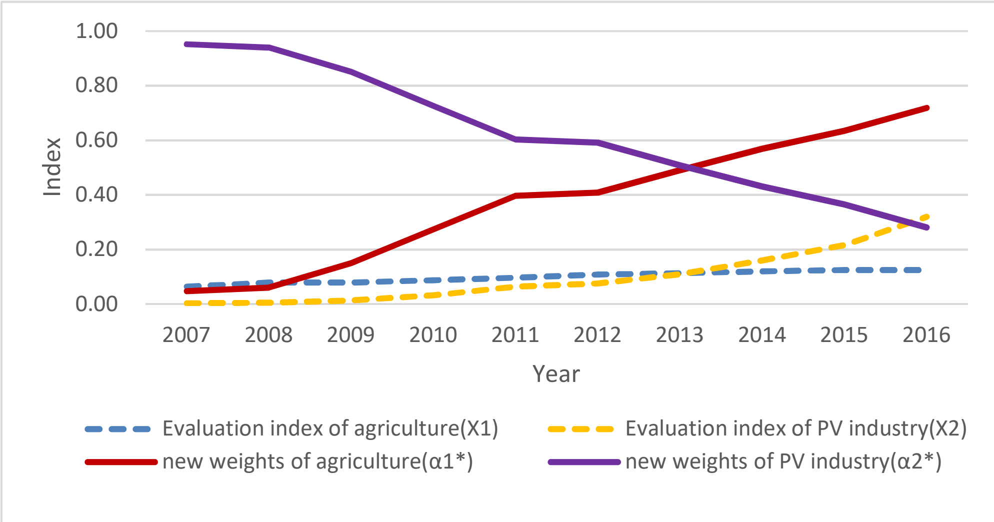

Figure 7. Comprehensive development evolution index and new weights.

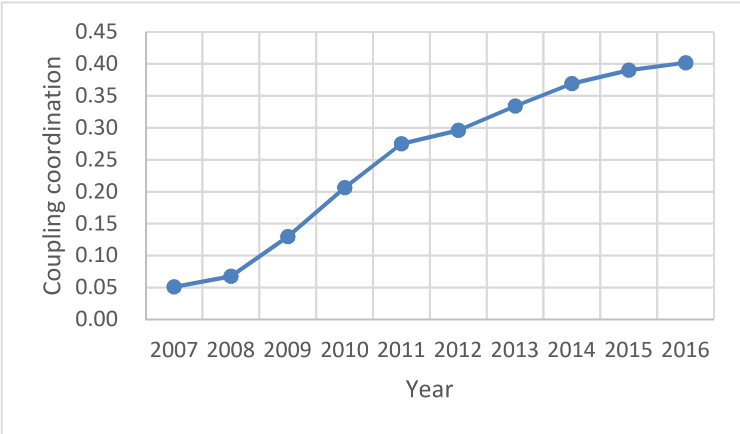

Figure 8. Degree of coupling coordination of PV agriculture system D* value.

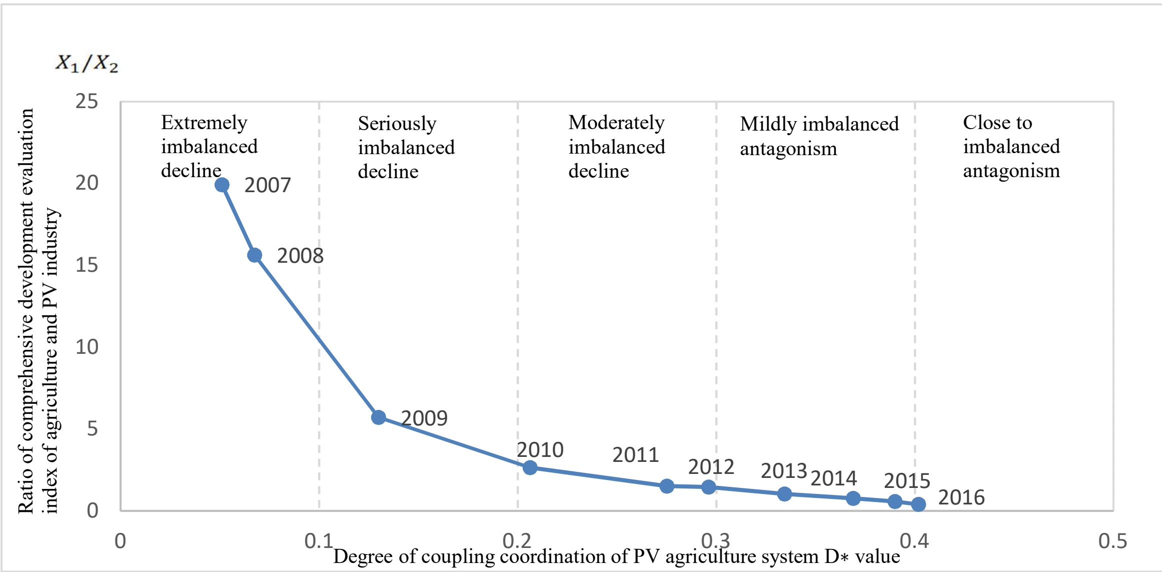

Figure 9. Coupling coordination development mode of the PV agriculture system.

It can be seen in Figure 7 that both X_1 and X_2 are on the rise, indicating that the development of the agriculture and PV industries has been improving, but the development speed of the PV industry is higher than agriculture. Before 2013, the comprehensive development evaluation index of the PV industry was lower than for agriculture. Therefore, more effort was required by the PV industry, and α_2^* was greater than α_1^*. After 2013, due to the rapid development of the PV industry, the comprehensive development evaluation index of agriculture sank lower than PV industry. Therefore, more effort has become required of the agriculture industry, and α_1^* has become greater than α_2^*. The evolution of the optimized degree of coupling coordination D* value is shown in Figure 8. It can be seen that from 2007 to 2016, the degree of coupling coordination of the PV agriculture system has been growing, gradually increasing from the initial extremely imbalanced decline stage to the mildly close to imbalance stage. From the perspective of development, it will develop toward a coordinated status. In general, the agriculture and PV industries have basically achieved a steady development of their own industries, and the role of mutual promotion and mutual improvement between the two industries has gradually increased. At the same time, although the degree of coupling coordination between the agriculture and PV industries has been steadily rising, the comprehensive development level of agriculture lags behind the PV industry with a lower starting point, resulting in an imbalance of the growth rate between the two industries. This will affect the further development of the coupling coordination of PV agriculture systems in the future.

In order to further explore the coupling coordination development model of the agriculture and PV industries, the coupling coordination development mode of the agriculture and PV industries was analyzed from two perspectives—the industrial coupling coordination degree and comprehensive development index ratio—according to the coupling coordination development law of the two industries from 2007 to 2016 (see Figure 9). With reference to Tang Xiaohua's division of industrial coupling coordination development mode into fluctuating synchronization, convergence of evolution, and unipolar dominance [27], the development mode favored by PV agriculture system coupling is unipolar dominance. To be more specific, agriculture was in an advantageous position to become a leading industry in the early stage of development. However, with the rapid development of the PV industry in the later stage, the dominant position of agriculture was gradually replaced by the PV industry. Viewed from the entire coupling period, a single industry is always dominant, which is consistent with the characteristics of unipolar dominance. In addition, the development speed gap between the agriculture and PV industries reached a maximum of about 20%. It is precisely because of the unbalanced development of the two industries that the PV agriculture system has had weak coupling coordination in the past 10 years, and the coupling process has been slow. This shows that the imbalance between the development of the agriculture and PV industries has made insufficient "thrust" in the process of coupling interaction development, restricting the benign coupling coordination development of the PV agriculture system.

4.3. Prediction of the Degree of Coupling Coordination of the PV Agricultural System

In order to further grasp the future changes of the coupling coordination degree of the PV agriculture system in China, we carried out dynamic simulation of the coupling coordination degree based on the grey prediction GM (1,1) model of grey system theory. We substituted the optimized coupling coordination degree of the PV agriculture system from 2007–2016 into formulas (16)–(23) and obtained the predictive value of 2007–2016 restoration; the predictive value and actual value are plotted as a radar chart (see Figure 10). It can be seen in Figure 10 that the degree of similarity between the predictive value and the actual value was high, indicating that the model could be used to predict future degrees of coupling coordination of the PV agriculture system. According to the above prediction model, the predictive degree of coupling coordination of the two systems was obtained in 2017. The 2008–2016 original value and the 2017 predictive value constitute a new series based on which the 2018 predictive value can be calculated, and so on to 2026. The predictive values of the degree of coupling coordination between the two subsystems from 2017 to 2026 are shown in Table 3.

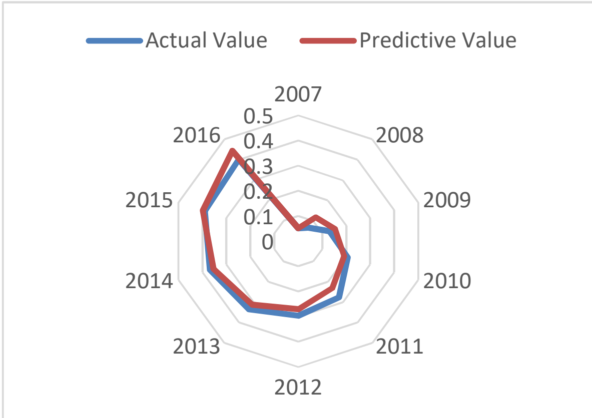

Figure 10. Comparison of actual and predictive values for 2007–2016.

Table 3. Prediction of the degree of coupling coordination for the PV Agriculture System.

Year	Actual Value	Predictive Value	Coordination Type	Year	Predictive Value	Coordination Type
2007	0.0510	0.0510	Extremely imbalanced decline	2017	0.4913	Close to imbalanced antagonism
2008	0.0675	0.1170	Extremely/Seriously imbalanced decline	2018	0.5250	Reluctant coordinated running-in
2009	0.1298	0.1535	Seriously imbalanced decline	2019	0.5573	Reluctant coordinated running-in
2010	0.2061	0.1911	Moderately/Seriously imbalanced decline	2020	0.5941	Reluctant coordinated running-in
2011	0.2751	0.2300	Moderately imbalanced decline	2021	0.6391	Primary coordinated running-in
2012	0.2961	0.2701	Moderately imbalanced decline	2022	0.6840	Primary coordinated running-in
2013	0.3343	0.3116	Mildly imbalanced antagonism	2023	0.7319	Intermediate coordinated development
2014	0.3689	0.3544	Mildly imbalanced antagonism	2024	0.7826	Intermediate coordinated development
2015	0.3900	0.3985	Mildly imbalanced antagonism	2025	0.8320	Good coordinated development
2016	0.4018	0.4442	Close to imbalanced antagonism	2026	0.8742	Good coordinated development

Incorporating the actual values for 2007–2016 with the predicted value for 2017–2026 in the same picture (see Figure 11), the overall development trend for 20 years can be seen. The coupling coordination degree of China's PV agriculture system D* will continue to grow in the next 10 years. Its coordination type was "close to imbalanced antagonism" in 2017, will be "reluctantly coordinated running-in" in 2018–2020, and will be "primary coordinated running-in" in 2021–2022. From 2023, it will enter a stage of coordination development, and will reach a stage of good coordination development between 2025 and 2026. The degree of coupling coordination has been continuously improved, indicating that the two industries will continue to develop in the direction of mutual promotion and coordinated synchronization, evolving to a higher level of coupling stage.

The prediction results have certain rationality. The development of China's PV agriculture in recent years is inseparable from policy support. In 2014, the National Energy Administration of China issued the Notice on Further Implementing the Policies Related to Distributed PV Power Generation, which incorporated PV agriculture into national key areas of concern. In 2016, The National Energy Administration of China issued the Implementation Opinions on Accelerating Energy Development and Construction in Poverty-Stricken Areas to Promote Poverty Alleviation and Strengthening the Challenge and officially incorporated PV agriculture into the precise poverty alleviation queue. The lagging effect of these policies, plus new policies (in 2017, the Status Council of China issued the 2017 Central Document No. 1, Implementing Rural New Energy Actions, Promoting PV Power Generation, and Gradually Expanding the Supply of Rural Electricity, Gas and Clean Coal), which will promote the development of China's PV agriculture in a coordinated and sustainable direction.

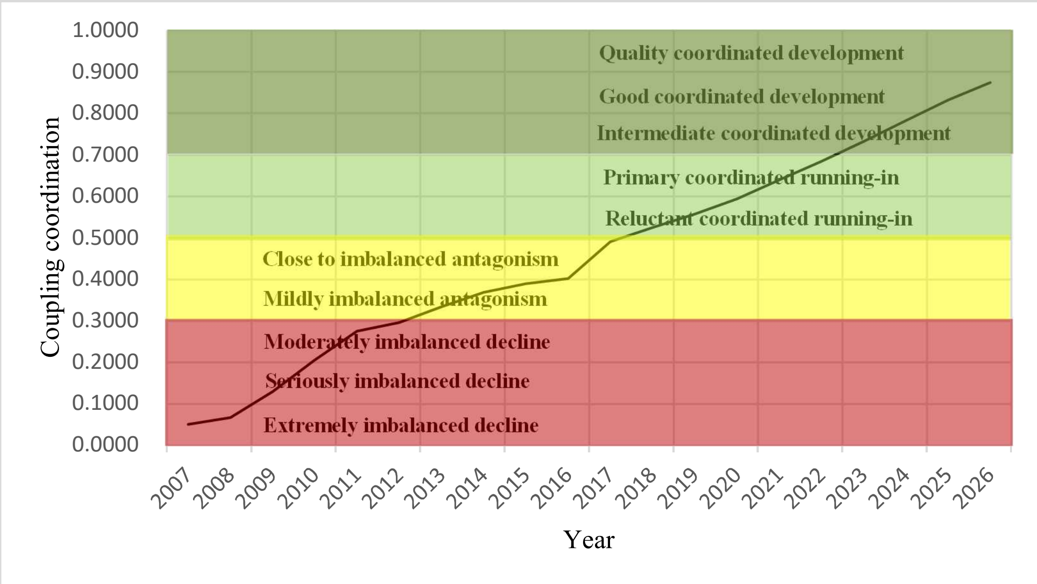

Figure 11. Prediction of coupling coordination of the PV agriculture system.

5. Conclusions and Recommendations

This study took the coupling coordination of the agriculture and PV industries as the starting point, measured the comprehensive development level of China's agriculture and PV industries from 2007 to 2016, and analyzed the effect of stock resources and incremental resources on the development level of the two industries. The traditional weighting method and optimized weighting method were used to empirically research the coupling coordination relationship of PV agriculture in 2007–2016. The degree of coupling coordination of the PV agriculture system was measured, and the development mode of it was analyzed. Finally, the modified grey system prediction model GM (1,1) was used to predict the coupling coordination of the PV agriculture system in the next 10 years. The main conclusions can be drawn as follows:

(1) The development level of the agriculture and PV industries is on the rise, but there is a significant difference in the extent of growth between the two industries. The rising rate of the PV industry far exceeds agriculture. In the first seven years, the comprehensive development evaluation index of agriculture was larger than the PV industry. Agriculture was the leading industry in the system, but its comprehensive development evaluation index approached the PV industry year by year. In the last three years, the comprehensive development evaluation index of the PV industry surpassed agriculture, and gradually has come to occupy the dominant position in the PV agriculture system.

(2) With the rapid expansion of the agriculture and PV industries, both industries are characterized by the predominance of stock resources. In the process of agricultural development, stock resources have a greater contribution to the development of the industry, and are the main source of power for agricultural development. Although the PV industry is generally dominated by stock resources, the contribution of incremental resources to industrial development has gradually increased. The advantages of stock resources have gradually weakened, and incremental resources have entered an advantageous status. Currently, the dominant position of agricultural stock is relatively firm, which is conducive to the improvement of the coupling coordination degree of the two industries. However, the PV industry has a development trend of "stock-to-increment", and its rapid "extensive" development trend will not be conducive to the future benign coupling coordination development of the two industries.

(3) The traditional method of weighting has strong subjectivity. The difference in the coupling coordination degree calculated under different weights was large, and did not reflect the true coupling coordination status of the PV agriculture system. It therefore affected the evaluation of its coupling coordination development, providing incorrect data. Based on synergistic theory, the optimized weighting method can measure the weights of the two systems more objectively. Using this method to evaluate the degree of coupling coordination, the results can fully explain the evolving degree of coordination between China's agriculture and PV industries. It is an effective method to measure the coupling relationship of PV agriculture systems.

(4) According to the optimized weighting method, the degree of coupling coordination of the system was measured. The results show that the coupling degree of the agriculture and PV industries mostly fluctuates, and the two industries have certain coupling and interaction development characteristics. They interact and influence each other, and their coupling coordination degree shows a good development trend year by year. However, the degree of coupling is low, and it has been in an unbalanced state. It has not yet evolved to a higher level of coupling, and the speed of upgrading and evolution has become slower. In recent years, the level of agricultural development has lagged behind the PV industry, and the gap has gradually increased. Due to an insufficient supply, agriculture cannot effectively support the current PV industry and restricts coupling development between the two industries. In addition, from the perspective of the coupling coordination development mode, the coupling mode of the PV agriculture system belongs to the unipolar dominant type—that is to say, the level of agricultural development in the early stage was superior and indicative of a leading industry. With the rapid development of the PV industry, the dominant position of agriculture has gradually weakened, while the PV industry has become a leading industry. The coupling period is always dominated by a single industry, and the change of the dominant position makes the industrial development level show an extremely significant scale imbalance. This is also one of the main reasons for the low coupling degree of China's PV agriculture system.

(5) Although China's PV agriculture system does not present a good coupling coordination status, the prediction results show that the speed of the two industries will significantly improve in the next 10 years, and the coupling will enter the coordination stage from the imbalance stage. The two industries will further develop in a sustainable direction of mutual promotion and coordination.

Based on the above research conclusions, combined with the actual situation of China's PV agriculture, the following four suggestions are given:

(1) Strengthen the balance between industries. In a system with multiple participating industries, mutual development between industries will be conducive to the formation of a benign coordination situation of industrial coupling. In such a scenario, the development gap between the agriculture and PV industries should be gradually reduced, and the interaction effect between industries should be improved. At the same time, an institutional system, management process, and professional team are needed to coordinate the development of the agriculture and PV industries so that the management and professional teams of the two industries can support and integrate into each other on the basis of an independent operation.

(2) Establish the dominant position of agriculture. PV agriculture is needed to develop the PV industry on the basis of agricultural facilities, and to maximize the land revenue of projects. It is a new, modern agricultural development model. PV agriculture should first develop agriculture, which will provide it with a stable foundation. If agricultural operations are unstable, PV will inevitably be affected. Therefore, in the process of development, PV agriculture should be based on agriculture, and various industries should promote each other. A development model with agricultural income as the main body is needed, which will produce many simultaneous benefits. Agriculture needs structural adjustment, and traditional agriculture needs to be replaced with scientific and information-based wisdom agriculture. This will inject a new impetus into the development of modern agriculture.

(3) Strengthen the supervision of the implementation of industrial policies. A niche market should be created for PV agriculture through policy implementation [7]. At present, China attaches great importance to PV agriculture and has given support to many policies. With the policy environment becoming more and more fair and transparent, the specific measures for the "bundling" of the development of the PV industry have gradually improved and created conditions for the rapid development of PV agriculture. However, the supervision of policy implementation is not enough, and some phenomena, such as occupying land and building ground power stations in the name of PV agriculture, has appeared. As financial and economic incentives are the most common means [3], there has even been publicity and hype surrounding PV agriculture for tax incentives and financial subsidies. Therefore, when formulating policies, we must fully consider the rigor of the policies, and at the same time monitor and evaluate the effects of policy implementation from the perspective of its full life cycle. This requires the government to establish a quantitative index system, establish a sound performance evaluation system, and assesses the effectiveness of government policies.

(4) Focus on optimizing the stock resources of the industry and actively cultivate quality incremental resources. We must avoid blindly complying with the scale-type industrial development mode, rationally adjust the stock resources of the agriculture and PV industries, deeply explore the economic potential contained in the industrial stock resources on the basis of de-capacity, de-stocking, and de-risking, and use the incremental resources to revitalize the stock resources and effectively to resolve excess capacity. At the present stage this is mainly based on optimizing stock resources, and supplemented by cultivating increment resources, which will be more conducive to promoting the high-quality coupling coordination development between the agriculture and PV industries.

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Conflicts of Interest: The authors declare no conflict of interests regarding the publication of this paper.

Appendix A

Table A1. Indicator data of the comprehensive development level of the agriculture and PV industries.

Subsystem	Indicator	Unit	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Agriculture A	Contribution rate A_1	%	2.7	5.2	4	3.6	4.2	5.2	4.3	4.7	4.6	4.4
	Gross output value A_2	10^9 USD	3656.80	4158.95	4564.30	5478.37	6226.91	6961.28	7637.06	8122.61	8547.39	8792.38
	Crop planting area A_3	10^3 hectare	153464	156266	158614	160675	162283	163416	164627	165446	166374	166650
	Rural electricity consumption A_4	10^9 kW·h	5509.9	5713.2	6104.4	6632.3	7139.6	7508.5	8549.5	8884.4	9026.9	9238.3
	Agricultural machinery total power A_5	10^4 KW	76589.6	82190.4	87496.1	92780.5	97734.7	102559.0	103906.8	108056.6	111728.1	97245.6
PV industry P	Polysilicon production P_1	10^4 tons	0.11	0.45	2	4.5	8.4	7.1	8.5	13.6	16.5	19.4
	Silicon wafer production P_2	GW	1.18	1.3	4.4	10.8	19.7	25.6	29.51	38.03	48.01	64.79
	Cell production P_3	GW	1.088	2	4.92	10.8	19.8	21	25.1	33.5	41	49
	PV module production P_4	GW	1.753	2.525	4.382	10.8	21	23	27.4	35.6	45.8	57.7
	Cumulative installed capacity P_5	GW	10	14	28.4	86.4	293.4	650	1744.8	2805.1	4318	7742

Appendix B

Table A2. Evaluation index of the comprehensive development level of the agriculture and PV industries.

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Evaluation index of agriculture (X_1)	0.0638	0.0797	0.0793	0.0869	0.0974	0.1091	0.1138	0.1207	0.1244	0.1249
Evaluation index of the PV industry (X_2)	0.0032	0.0051	0.0139	0.0328	0.0641	0.0754	0.1098	0.1596	0.2163	0.3198
X_1/X_2	19.9375	15.6275	5.7050	2.6494	1.5195	1.4470	1.0364	0.7563	0.5751	0.3906

Table A3. Contribution coefficient of stock and incremental resources of the agriculture and PV industries.

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Agricultural stock resources coefficient (γ_1)	0.8859	0.8839	1.1996	1.3907	0.8285	0.9740	0.9405	0.1643	0.6482	0.8227
Agricultural incremental resources coefficient (δ_1)	0.1141	0.1161	-0.1996	-0.3907	0.1715	0.0260	0.0595	0.8357	0.3518	0.1773
PV industry stock resources coefficient (γ_2)	0.7083	0.5818	0.7845	0.7539	0.7090	1.2066	1.6027	1.3662	0.6558	0.4908
PV industry incremental resources coefficient (δ_2)	0.2917	0.4182	0.2155	0.2461	0.2910	-0.2066	-0.6027	-0.3662	0.3442	0.5092

Appendix C

Table A4. Coupling coordination degree of the PV agriculture system under different weights.

	$\alpha_1 = 0.1$ $\alpha_2 = 0.9$	$\alpha_1 = 0.2$ $\alpha_2 = 0.8$	$\alpha_1 = 0.3$ $\alpha_2 = 0.7$	$\alpha_1 = 0.4$ $\alpha_2 = 0.6$	$\alpha_1 = 0.5$ $\alpha_2 = 0.5$	$\alpha_1 = 0.6$ $\alpha_2 = 0.4$	$\alpha_1 = 0.7$ $\alpha_2 = 0.3$	$\alpha_1 = 0.8$ $\alpha_2 = 0.2$	$\alpha_1 = 0.9$ $\alpha_2 = 0.1$
2007	0.0628	0.0808	0.0955	0.1082	0.1195	0.1299	0.1395	0.1485	0.1569
2008	0.0773	0.0976	0.1143	0.1289	0.1420	0.1540	0.1651	0.1755	0.1853
2009	0.1207	0.1386	0.1545	0.1689	0.1822	0.1946	0.2062	0.2172	0.2277
2010	0.1846	0.1973	0.2091	0.2204	0.2311	0.2413	0.2511	0.2605	0.2696
2011	0.2569	0.2631	0.2693	0.2752	0.2811	0.2868	0.2925	0.2980	0.3034
2012	0.2783	0.2842	0.2900	0.2956	0.3012	0.3066	0.3120	0.3172	0.3224
2013	0.3319	0.3325	0.3331	0.3337	0.3343	0.3349	0.3355	0.3361	0.3367
2014	0.3927	0.3878	0.3828	0.3777	0.3726	0.3673	0.3621	0.3567	0.3513
2015	0.4466	0.4366	0.4263	0.4158	0.4050	0.3939	0.3825	0.3708	0.3587
2016	0.5195	0.5024	0.4847	0.4662	0.4471	0.4270	0.4060	0.3838	0.3603

Table A5. Coupling coordination degree and type of PV agriculture system.

	X_1	X_2	α_1 *	α_2 *	P *	C	D *	Coordination Type
2007	0.0638	0.0032	0.0478	0.9522	0.0061	0.4265	0.0510	Extremely imbalanced decline
2008	0.0797	0.0051	0.0601	0.9399	0.0096	0.4755	0.0675	Extremely imbalanced decline
2009	0.0793	0.0139	0.1491	0.8509	0.0237	0.7125	0.1298	Seriously imbalanced decline
2010	0.0869	0.0328	0.2740	0.7260	0.0476	0.8920	0.2061	Moderately imbalanced decline
2011	0.0974	0.0641	0.3969	0.6031	0.0773	0.9785	0.2751	Moderately imbalanced decline
2012	0.1091	0.0754	0.4087	0.5913	0.0892	0.9832	0.2961	Moderately imbalanced decline
2013	0.1138	0.1098	0.4911	0.5089	0.1118	0.9998	0.3343	Mildly imbalanced antagonism
2014	0.1207	0.1596	0.5694	0.4306	0.1375	0.9903	0.3689	Mildly imbalanced antagonism
2015	0.1244	0.2163	0.6349	0.3651	0.1580	0.9629	0.3900	Mildly imbalanced antagonism
2016	0.1249	0.3198	0.7191	0.2809	0.1796	0.8988	0.4018	Close to imbalanced antagonism

References

1. Brainard, W.A. The worldwide market for photovoltaics in the rural sector. In Proceedings of the IEEE Photovoltaic Specialists Conference, San Diego, CA, USA, 27–30 September 1982; pp. 1308–1313.
2. Jarach, M. An overview of the literature on barriers to the diffusion of renewable energy sources in agriculture. *Appl. Energy* **1989**, *32*, 117–131. [CrossRef]
3. Brudermann, T.; Reinsberger, K.; Orthofer, A.; Kislinger, M.; Posch, A. Photovoltaics in agriculture: A case study on decision making of farmers. *Energy Policy* **2013**, *61*, 96–103. [CrossRef]
4. Dinesh, H.; Pearce, J.M. The potential of agrivoltaic systems. *Renew. Sustain. Energy Rev.* **2016**, *54*, 299–308. [CrossRef]
5. Xue, J. Photovoltaic agriculture - New opportunity for photovoltaic applications in China. *Renew. Sustain. Energy Rev.* **2017**, *73*, 1–9. [CrossRef]
6. Katzman, M.T.; Matlin, R.W. The Economics of Adopting Solar Energy Systems for Crop Irrigation. *Am. J. Agric. Econ.* **1978**, *60*, 648–654. [CrossRef]
7. Radulovic, V. Are new institutional economics enough? Promoting photovoltaics in India's agricultural sector. *Energy Policy* **2005**, *33*, 1883–1899. [CrossRef]
8. Mousazadeh, H.; Keyhani, A.; Mobli, H.; Bardi, U.; Lombardi, G.; el Asmar, T. Technical and economical assessment of a multipurpose electric vehicle for farmers. *J. Clean. Prod.* **2009**, *17*, 1556–1562. [CrossRef]
9. Fang, Y.D.; Huang, S.H.; Qing, S.X.; Shen, W.J.; Wei, D.; Yang, M.X.; Zheng, B.; Li, Y.J. Analysis of Development Status and Prospect of Photovoltaic Agriculture. *J. Chang. Veg.* **2015**, *18*, 35–40. [CrossRef]
10. Malu, P.R.; Sharma, U.S.; Pearce, J.M. Agrivoltaic potential on grape farms in India. *Sustain. Energy Technol. Assess.* **2017**, *23*, 104–110. [CrossRef]
11. Campana, P.E.; Leduc, S.; Kim, M.; Olsson, A.; Zhang, J.; Liu, J.; Kraxner, F.; McCallum, I.; Li, H.; Yan, J. Suitable and optimal locations for implementing photovoltaic water pumping systems for grassland irrigation in China. *Appl. Energy* **2016**, *185*, 1879–1889. [CrossRef]
12. García, A.M.; García, I.F.; Poyato, E.C.; Barrios, P.M.; Díaz, J.R. Coupling irrigation scheduling with solar energy production in a smart irrigation management system. *J. Clean. Prod.* **2018**, *175*, 670–682. [CrossRef]
13. Elamria, Y.; Chevirona, B.; Lopezc, J.-M.; Dejean, C.; Belaud, G. Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. *Agric. Water Manag.* **2018**, *30*, 440–453. [CrossRef]
14. Xue, J. Assessment of agricultural electric vehicles based on photovoltaics in China. *J. Renew. Sustain. Energy* **2013**, *5*, 6745–6759. [CrossRef]
15. Bey, M.; Hamidat, A.; Benyoucef, B.; Nacer, T. Viability study of the use of grid connected photovoltaic system in agriculture: Case of Algerian dairy farms. *Renew. Sustain. Energy Rev.* **2016**, *63*, 333–345. [CrossRef]
16. Hassanien, R.H.E.; Ming, L.; Wei, D.L. Advanced applications of solar energy in agricultural greenhouses. *Renew. Sustain. Energy Rev.* **2016**, *54*, 989–1001. [CrossRef]
17. Wang, T.; Wu, G.; Chen, J.; Cui, P.; Chen, Z.; Yan, Y.; Zhang, Y.; Li, M.; Niu, D.; Li, B.; et al. Integration of solar technology to modern greenhouse in China: Current status, challenges and prospect. *Renew. Sustain. Energy Rev.* **2017**, *70*, 1178–1188. [CrossRef]
18. Li, C.; Wang, H.; Miao, H.; Ye, B. The economic and social performance of integrated photovoltaic and agricultural greenhouses systems: Case study in China. *Appl. Energy* **2017**, *190*, 204–212. [CrossRef]
19. Jones, M.A.; Odeh, I.; Haddad, M.; Mohammad, A.H.; Quinn, J.C. Economic analysis of photovoltaic (PV) powered water pumping and desalination without energy storage for agriculture. *Desalination* **2016**, *387*, 35–45. [CrossRef]
20. Vadiee, A.; Yaghoubi, M. Enviro-economic assessment of energy conservation methods in commercial greenhouses in Iran. *Outlook Agric.* **2016**, *45*, 47–53. [CrossRef]
21. Saini, V.; Tiwari, S.; Tiwari, G.N. Environ economic analysis of various types of photovoltaic technologies integrated with greenhouse solar drying system. *J. Clean. Prod.* **2017**, *156*, 30–40. [CrossRef]
22. Wettstein, S.; Muir, K.; Scharfy, D.; Stucki, M. The Environmental Mitigation Potential of Photovoltaic-Powered Irrigation in the Production of South African Maize. *Sustainability* **2017**, *9*, 1772. [CrossRef]
23. Yang, Y.Z. Methodology Review of Coupling and Coordinating Ecology, Environment and Economy System in China. *Sci. Technol. Manag. Res.* **2013**, *33*, 236–239. [CrossRef]

24. Liang, W.; Liu, M.F. A Study on the Coupling and Coordinated Development and Tempo-Spatial Variation of China's Strategic Emerging Industries and Traditional Industries. *Econ. Geogr.* **2017**, *37*, 117–126. [CrossRef]
25. Zhang, G.H.; Liu, Z.Z.; Wang, X.Y. Analysis and forecast of coupling degree between tourism-oriented development and eco-environment in coastal region of China. *Ecol. Environ. Sci.* **2013**, *22*, 792–800. [CrossRef]
26. Feng, X. Coupling Relationship between Urbanization and Ecological Environment of Xinjiang. *Areal Res. Dev.* **2016**, *35*, 123–127. [CrossRef]
27. Tang, X.H.; Zhang, X.J.; Li, Y. Dynamic Coordination Development in China's Manufacturing and Manufacturing-related Service Industries. *Econ. Res. J.* **2018**, *53*, 79–93.
28. Zhou, C.; Feng, X.G.; Tang, R. Analysis and Forecast of Coupling Coordination Development among the Regional Economy-Ecological Environment-Tourism Industry—A Case Study of Provinces Along the Yangtze Economic Zone. *Econ. Geogr.* **2016**, *36*, 186–193. [CrossRef]
29. Li, Y.; Li, Y.; Zhou, Y.; Shi, Y.; Zhu, X. Investigation of a coupling model of coordination between urbanization and the environment. *J. Environ. Manag.* **2012**, *98*, 127–133. [CrossRef]
30. Li, J.; Fang, H.; Fang, S.R.; Siddika, S. Investigation of the Relationship among University–Research Institute–Industry Innovations Using a Coupling Coordination Degree Model. *Sustainability* **2018**, *10*, 1954. [CrossRef]
31. Wang, Z.B.; Wang, H.; Guo, B.H. Coupling Improved Model and the Empirical Study of Regional Innovation System. *Chin. J. Manag. Sci.* **2014**, *22*, 566–573. [CrossRef]
32. Zhang, D.N.; Cheng, Y. Study on Development Level and Mode of Equipment Manufacturing Industry in China. *J. Quant. Tech. Econ.* **2014**, *31*, 99–114. [CrossRef]
33. Valerie. *The Penguin Dictionary of Physics*; Penguinuk: London, UK, 2009; ISBN 978-014-103-683-0.
34. Shen, L.Y.; Huang, Y.L.; Huang, Z.H.; Lou, Y.; Ye, G.; Wong, S.W. Improved coupling analysis on the coordination between socio-economy and carbon emission. *Ecol. Indic* **2018**, *94*, 357–366. [CrossRef]
35. Haken, H. *Synergetics: An Introduction, Nonequilibrium Phase Transitions and Self-Organization in Physics, Chemistry and Biology*; Springer: New York, NY, USA, 1977; ISBN 978-364-296-363-6.
36. Braden, J.B.; Kolstad, C.D. Measuring the demand for environmental quality. *Am. J. Agric. Econ.* **1993**, *75*, 244–245. [CrossRef]
37. Liao, C.B. Quantitative Judgement and Classification System for Coordinated Development of Enviroment and Economy—A Case Study of the City Group in the Pearl River Delta. *Trop. Geographys.* **1999**, *2*, 76–82. [CrossRef]
38. Yang, Y.; Wei, Z.S. Spatial-temporal Characterstics and Coupling Effect of Double- innovation Ability in China. *J. Quant. Techn. Econ.* **2018**, *35*, 3–22. [CrossRef]
39. Xiang, L.; Hu, L.Y. Study on the Coupling and Coordination of Tourism Industry and Urban Living Environment in the Yangtze River Economic Belt. *Inq. Econ. Issues* **2018**, *4*, 80–89.
40. Deng, J.L. *Grey System Theory Tutorial*; Huanzhong University of Science and Technology Press: Wuhan, China, 1990; ISBN 978-756-090-447-4.
41. Liu, S.F.; Deng, J.L. Scope of the GM(1,1) model. *Syst. Eng.-Theory Pract.* **2000**, *5*, 121–124.
42. Tang, W.M.; Xiang, C.H. The Improvements of Forecasting Method in GM(1,1)Model Based on Quadratic Interpolation. *Chin. J. Manag. Sci.* **2006**, *6*, 109–112. [CrossRef]
43. Shi, P.F.; Ling, X.M.; Xiong, Y.B. Coupling Measurement and Prospect Forecast of Regional "Beautiful China" Construction and Tourism Industry Development—A Case Study of 11 Provinces along the Yangtze River Economic Belt. *China Soft Sci.* **2018**, *2*, 86–102. [CrossRef]