# Solar Radiation Distribution Method for a Photovoltaic Greenhouse based on the Maximization of Annual Economic Benefits

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# Solar radiation distribution method for a photovoltaic greenhouse based on the maximization of annual economic benefits

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## Abstract

A solar radiation distribution method is proposed based on the maximization of economic benefits for photovoltaic power generation and agricultural production in a photovoltaic greenhouse to solve the problem of low overall economic benefits because of an unreasonable solar radiation distribution between photovoltaic power generation and agricultural production in the photovoltaic greenhouse. First, a mathematical model of the solar radiation yield of photovoltaic greenhouse crops is proposed based on a rectangular hyperbolic modified light response model of crops to represent the relationship between solar radiation energy and crop production. Second, a mathematical model of the average annual revenue of a photovoltaic greenhouse is established to determine the maximum annual economic benefit of the photovoltaic greenhouse, and the model is constrained by the requirements of the light intensity of photovoltaic power generation and environmental conditions for the growth of greenhouse crops. Finally, the correctness of the model is verified by actual operation data of a photovoltaic greenhouse in Xinjiang, and the optimal solar radiation distribution proportion is calculated. This study provides theoretical support for the design of photovoltaic greenhouses.

## 1 Introduction

Photovoltaic greenhouses (PVGs) have become one of the hot spots in the field of facility agriculture in recent years. The characteristics of a PVG are as follows: greenhouse allows reuse of the land with a PV power generation to build a framework, saving the construction cost and providing safe and reliable green power for agricultural production. According to the research of PVGs, some scholars have studied environmental control methods that are conducive to the growth of crops based on the internal environmental control of a PVG 1-3; others have studied the crop types that are suitable for PVG planting in different regions and external environments 4-7. To make the internal environment of a PVG more suitable for the growth of agricultural products, some scholars have used software such as ANSYS 8 and Ecotect 9, 10 as well as CFD 11-13 and other analysis methods to establish an internal environment model of a PVG to achieve the best growth environment.

As is well known, the energy source of photovoltaic power generation comes from light, and the energy source of greenhouse agricultural production is also light. Photovoltaic power generation in a photovoltaic greenhouse (PVPG-PVG) and agricultural production in a photovoltaic greenhouse (AP-PVG) have a relationship of shared land, resulting in the solar radiation energy per unit area being supplied to both photovoltaic power generation and agricultural production. It is very important to distribute the light proportions of PVPG-PVG and AP-PVG reasonably without affecting the normal growth of crops. Based on this, reference 14 makes a detailed description of the model of "all photovoltaic power of a PVG is transmitted to the grid" and discusses the advantages and disadvantages of the model, demonstrating that this model is not suitable for PVGs in China. Reference 15 takes a typical commercial PVG in Europe as an example and specifically analyzes the impact of PVG photovoltaic coverage on crop growth. Reference 16 shows the differences in the impact of different PVG tilt angles on the internal microclimate. Reference 17 studies the possibility of using translucent photovoltaic modules in a greenhouse. The results show that a translucent photovoltaic module could replace the greenhouse coating when the cost is reduced by 23%. Reference 18 shows that the photovoltaic power generation in a PVG has shading benefits on crops and proposes that the spacing of photovoltaic modules can be used to adjust the shading effect on crops, but no specific measures are given. Reference 19 proposes the use of a chessboard layout method to arrange the photovoltaic modules in a PVG, and the method can make PVG crops receive more light. Reference 20 studies the relationship between the microclimate and tomato yield of a PVG in winter and summer in the southern Mediterranean, and the results show that a 40% covering by photovoltaic modules has little impact on tomato yield. Reference 21-25 compares and analyzes the photovoltaic modules in a PVG in terms of the power generation and greenhouse environment for a straight-line arrangement, staggered arrangement and checkerboard arrangement. The research shows that the straight-line arrangement is more suitable for PVG photovoltaic modules, but the proportion of photovoltaic modules is not given. Based on this background, to maximize the overall economic benefits of a PVG as the goal, with the environmental requirements of crop growth and photovoltaic power generation as constraints, this paper establishes an optimal mathematical model of the solar radiation distribution based on the optimal overall economic benefits of a PVG. Additionally, this paper not only provides calculation methods and a theoretical basis for the distribution area proportion of PVG photovoltaic modules but also introduces an intelligent algorithm to obtain the optimal value of the solar radiation distribution of a PVG, aiming to maximize the overall economic benefit of the PVG and provide a basis for PVG agricultural production.

## 2. Solar radiation distribution model of a PVG

Currently, there are three typical operation modes of PVGs in China: 1. Off-grid connected mode: the PVG is completely disconnected from the power grid, and the power required for greenhouse production is completely supplied by photovoltaic power generation. 2. Semi-grid connected mode: photovoltaic power generation in the PVG is first supplied to greenhouse production, and surplus or insufficient power is consumed or supplied by the power grid. 3. Full grid-connected mode: all the electric energy generated by photovoltaic power generation in the PVG is supplied to the grid, and the electric energy required for AP-PVG is supplied by the grid. In the actual production of PVGs, the semi-grid connected mode is the most commonly used mode. Therefore, this paper takes the semi-grid connected mode as the research object and takes the full grid-connected mode as the most contrast.

Based on the semi-grid connected mode for PVG operation, the power generated by PVPG-PVG should first be self-sufficient; excess power should be transmitted to the grid, and insufficient power should be supplemented by the grid. The solar radiation per unit area of the PVG needs to be allocated to PVPG-PVG and AP-PVG at the same time. A reasonable distribution of solar radiation is the key to improve the overall economic benefits of a PVG. Therefore, the goal is to maximize the annual output income of a PVG, and a solar radiation distribution model of a PVG is established to optimize the solar radiation proportions of PVPG-PVG and AP-PVG. The annual output income of a PVG includes the annual income of PVPG-PVG, the annual income of a grid-connected PVG (the gateway measurement is positive, indicating that if the value for a PVG on grid power is greater than that off grid power, the income is positive; conversely, if the value for a PVG on grid power is less than that off grid power, the income is negative), the annual income of AP-PVG and the annual investment cost of the PVG.

## 2.1. PVPG-PVG annual income model

An analysis of photovoltaic power generation shows that regional and meteorological conditions have a great impact on photovoltaic power generation and thus affect the income of a PVG. The grid as the standby power supply of a PVG needs an additional reserve cost. Photovoltaic power generation and light abandonment caused by the grid dispatching strategy have a greater impact on the income of a PVG. Because the capacity of PVPG-PVG is generally small and has little impact on the power grid and the focus of this paper is the impact of the light distribution of PVPG-PVG and AP-PVG on the average annual revenue of a PVG, the following assumptions are made in this paper:

(1) The power generation capacity of photovoltaic modules is not limited and affected by geographical conditions such as region, temperature, and altitude;
(2) The impact of light abandonment caused by the power grid dispatching strategy on PVG revenue is temporarily not considered;
(3) For the time being, the cost of the grid as the standby power supply of a PVG is not considered.

This method applies calculations based on the installed solar irradiance and the installed solar area and replaces daily solar irradiance with annual solar irradiance. The annual power generation of PVPG-PVG can be expressed as follows:

$$E(x) = K_1 K_2 P(1-x)ST \tag{1}$$

E(x), PVPG-PVG annual power generation (kW.h); K1, conversion rate of photovoltaic modules of the PVG; K2, conversion efficiency of the photovoltaic inverter of the PVG; P, annual solar radiation in the PVG area (MJ/$m^2$), the conversion relationship between solar; x, proportion of the solar radiation distribution for agricultural production in the PVG; S, sum of south-facing roof area in the PVG ($m^2$); T, effective illumination time (h).

Based on the semi-grid connected mode for PVG operation, at the beginning of the construction of a PVG, a PVG power price agreement has been signed with the State Energy Administration and the State Grid that clearly stipulates the self-use price $Q_1$ and the power transmission price $Q_2$ of PVPG-PVG. The self-use part of electric energy is $E_1(x)$, and the power transmission part of electric energy is $E_2(x)$. These values can be obtained by gateway metering devices. The annual revenue of PVPG-PVG grid connection is as follows:

$$E(x) = E_1(x) + E_2(x) \tag{2}$$

$$M_{ph}(x) = E_1(x)Q_1 + E_2(x)Q_2 \tag{3}$$

$Q_1$, the price of self-use electric energy of the PVG ($/kW.h); $Q_2$, the price of grid-connected PV of the PVG ($/kW.h); $M_{ph}(x)$, annual income of PVPG-PVG.

## 2.2. Annual revenue model of pvg grid connection

Based on the semi-grid connected mode for PVG operation, the main function of the power grid for a PVG is that when the power generation of PVPG-PVG is greater than the load power of greenhouse agricultural production, the power grid can absorb the surplus electric energy; when the power generation of PVPG-PVG is less than the load power of greenhouse agricultural production, the power grid can provide sufficient power for the PVG. The first part has been discussed in the previous section. This section mainly discusses the annual power consumption of a PVG. A PVG needs to pay for the grid to obtain power from the grid, so $M_{grid}$ is negative. Assume that the electricity price provided by the power grid to the PVG is Q3, and the additional costs generated by the grid as a standby power supply for the PVG are temporarily not considered. Moreover, the annual power consumption of the PVG is $E_3(x)$, which can be obtained by a gateway metering device installed at the PVG merging point; then, the annual electricity charge of the PVG from the grid is as follows:

$$M_{grid} = -E_3(x)Q_3 \tag{4}$$

$M_{grid}$, electricity supplied by the grid to the PVG; $Q_3$, the price of electricity from grid supply, it refers to the special price set by the power grid for the PVG to obtain electric energy from the power grid ($/kW.h).

## 2.3. Annual income model of AP-PVG

The annual income of AP-PVG is closely related to the annual crop yield, so it is necessary to first calculate the annual output. Based on a large number of references, the relationship between radiation energy and crop yield in AP-PVG is very complex, and there is no exact mathematical expression to describe the relationship between them. However, from basic knowledge of crop science, it can be concluded that light radiation energy provides the basic conditions for the growth of crops, and the yield of crops is the result of cumulative growth. Therefore, the relationship between crop light and yield can be approximately simulated by using a crop light response model. Based on this, an AP-PVG annual yield mathematical model based on a rectangular hyperbolic modified light response model of crops is proposed in this paper. The relationship between the light intensity and dry matter accumulation of PVG crops was characterized by the rectangular hyperbolic modified light response model of crops, and then the annual yield of AP-PVG was obtained. The rectangular hyperbolic modified light response model 26-28 is shown in equation (5).

$$P_{\mathrm{n}}(I) = \alpha \frac{1-\beta I}{1+\gamma I} I - R_d \tag{5}$$

$\alpha$、$\gamma$, light response coefficient; $\beta$, correction factor; I, photosynthetically active radiation of crops (μmol/m$^2$·s); $R_d$, crop respiration rate (μmol/m$^2$·s).

In a PVG, the solar radiation of greenhouse crops is distributed as $P_X$ (kW/m$^2$). After the unit transformation of the crop respiration rate, the solar radiation yield model of PVG crops is as follows (6):

$$f_1(x) = 44\eta(\alpha \frac{1-\beta Px}{1+\gamma Px} Px - R_d / 1000\mu) K_{prod} t_{resp} 10^{-6} \tag{6}$$

$P_x$, photosynthetically active radiation of crops (kW/m2); $\eta$, the effective ratio of photosynthetic radiation, 0.47 on sunny days and 0.5 on cloudy days; $\mu$, unit conversion value of photosynthetic radiation to convert (μmol/m$^2$·s) to (w/m$^2$), it is assigned a value of 4.55 in this paper; $K_{prod}$, the cumulative coefficient of production, it is assigned a value of 5 in this paper; $t_{resp}$, response time, it is assigned a value of 3600 s in this paper.

The annual income model of AP-PVG is as follows:

$$M_{agri} = f_1(x)Q_4 \tag{7}$$

$M_{agri}$, annual income of AP-PVG ($); Q4, the price of agricultural products per ton ($/T), it takes the annual average price of agricultural products.

## 2.4. PVG annual income model

To maximize the overall annual income of a PVG, a mathematical model of the overall annual income of a PVG based on the solar radiation distribution is established as follows:

$$M = M_{ph} + M_{agri} + M_{grid} - M_{\cos t} \tag{8}$$

$M_{cost}$, Average annual cost of the PVG, including the annual construction cost, annual operation cost and annual maintenance cost of the PVG ($).

## 2.5. Constraints of a PVG

The constraint conditions are the boundary conditions of the parameters of a PVG, and the boundary conditions considering the parameters can make the calculation results more suitable for an actual production situation. The annual income model of a PVG includes photovoltaic power generation and crop growth. Therefore, the constraints include photovoltaic power generation constraints and agricultural production constraints.

2.5.1. Constraints of photovoltaic power generation

The energy source of PVPG-PVG is light radiation. For the photovoltaic modules, the output voltage cannot reach the rated voltage because of the low light radiation. Moreover, the total radiation of PVPG-PVG and AP-PVG should be less than the local annual average maximum radiation. Therefore, the light radiation constraint condition of PVPG-PVG is as follows:

$$\begin{cases} P_{\min} \le P \\ P + P_x \le P_{\max} \end{cases} \tag{9}$$

$P_{min}$, minimum light radiation value of photovoltaic power generation; $P_{max}$, maximum solar radiation of photovoltaic power generation.

2.5.2. Constraints oF agricultural production

AP-PVG needs to meet the requirements of light, temperature and humidity for crop growth. Among them, illumination is provided by solar radiation, and temperature and humidity are regulated by electric energy. Therefore, AP-PVG illumination must meet the requirements of crop growth; that is, the solar radiation of a PVG should meet the following requirements:

$$PAR_{\min} \le Px / 1000\mu \le PAR_{\max} \tag{10}$$

$PAR_{min}$, minimum solar radiation value of crops (μmol/$m^2$·s); $PAR_{max}$, maximum solar radiation value of crops (μmol/$m^2$·s).

Temperature and humidity control use a fan and spray system to adjust the temperature and humidity. Therefore, the energy supply source is electric energy, which may be obtained from either photovoltaic power generation or grid power supply. The temperature and humidity of a PVG must meet the requirements of crop growth. To simplify the calculation, the average values of temperature and humidity requirements in the whole life cycle of crops are taken as follows:

$$\begin{cases} T_{\min} \le T \le T_{\max} \\ E_{temp} = cm\left|T - T_{real}\right| \times 2.778 \times 10^{-7} \\ H_{\min} \le H \le H_{\max} \\ E_{humi} = P_{humi} t \end{cases} \tag{11}$$

$T_{min}$, minimum value of PVG temperature control; $T_{max}$, maximum value of PVG temperature control; $H_{min}$, minimum value of PVG humidity control; $H_{max}$, maximum value of PVG humidity control; c, specific heat capacity of air (J/kg.°C); m, air quality (kg).

# 3. Computing method

To solve the problem of low economic benefits of a PVG, an optimization method of the solar radiation distribution for PVPG-PVG and AP-PVG based on maximizing the economic benefits is proposed. Based on a theoretical analysis of PVG annual income, a particle swarm optimization algorithm can accurately and quickly obtain the calculation results 29-33. The calculation steps are as follows:

1) The initial number of particles in particle swarm optimization is 50, and the initial values of particle swarm optimization are selected according to the rule of $(x_{\max} - x_{\min}) / n + x_{\min}$ between the constraints [$x_{min}$, $x_{max}$].
2) The velocities and positions of particles are updated according to the particle velocity and position update formulas (12):

$$\begin{cases} v_n = wv_{n-1} + c_1 k_1 (p_{best} - x_{n-1}) + c_2 k_2 (g_{best} - x_{n-1}) \\ x_n = x_{n-1} + v_n \end{cases} \tag{12}$$

W, inertia factor; $c_1$, $c_2$, acceleration constant; $k_1$, $k_2$, random value of [0,1]; $x_n$, the nth position value of x; $v_n$, the nth speed value of x.

3) A fitness function is used to judge whether the objective function achieves the expected effect. Under the appropriate fitness function setting, the operation speed can be accelerated. In the objective function, $\alpha = 0.001$, $\beta = 0.0001$, and $\gamma = 0.004$. The fitness function is shown in equation (13):

$$H_{fitness} = \frac{f(x) - f(x-1)}{f(x)} \le \varepsilon \tag{13}$$

f(x), $X_{th}$ calculation value of the objective function; ε , the fitness function; it is assigned a value of 0.01 in this paper.

4) When the convergence condition is reached, the operation ends.

The flow chart is shown in Figure 1:

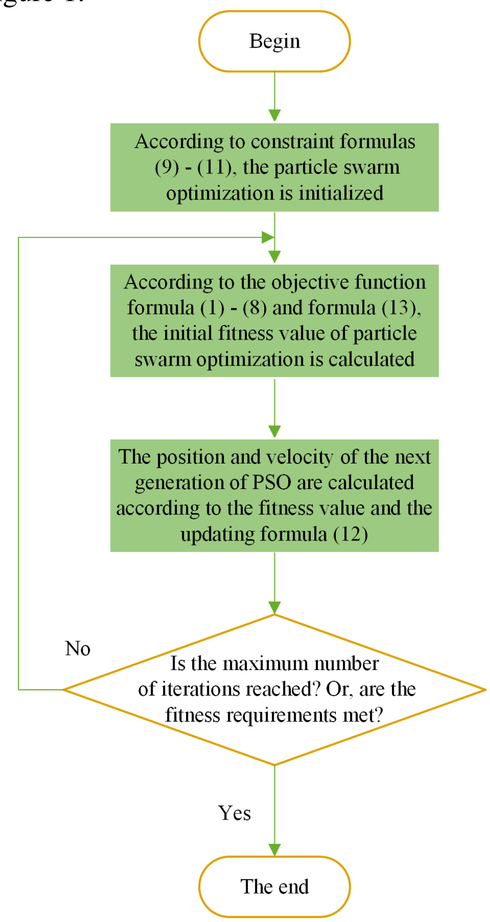


Figure 1. Flow chart of particle swarm optimization

## 4. Example analysis

Based on the operation data of a polysilicon multi-span PVG in Northwest China, the correctness of the optimization model is verified. Based on the light distribution model, this paper analyzes the impact of price fluctuation on the income of a PVG. The polysilicon multi-span PVG contains 13 independent PVGs. Each PVG has the same size, but different crops are planted. To simplify the calculation, the light and humidity are set as the constraint conditions. The specific data of a single PVG are as follows: the length of the multi-span greenhouse is 68 m, the span is 7 m, and the ridge height is 3.1 m. The polysilicon PV module is 1.65 m in length and 0.992 m in width. The rated power is 250 W, and the installation angle is $38^0$. The specific parameters are shown in Table 1.

Table 1. Main parameters of the PVG

| | | | | | |
|---|---|---|---|---|---|
| $K_1$ | 0.17 | $K_2$ | 0.98 | $T_{min}$ | 16 °C |
| P | 18.93 $MJ/M^2$ | T | 800 h | $H_{min}$ | 43% |
| $E_2$ | 8432.4 kW.h | $E_3$ | 3434.6 kW.h | $PAR_{min}$ | 750 |
| $Q_1$ | 0.06 $/kW.h | $Q_2$ | 0.11 $/kW.h | $M_{cost}$ | 9688.57 $ |
| $Q_3$ | 0.05 $/kW.h | $Q_4$ | 285.7 $/t | $PAR_{max}$ | 1000 |
| $T_{max}$ | 28 °C | $H_{max}$ | 100% | | |

## 4.1. Verify the correctness of the architecture model

To verify the correctness of the light distribution optimization model, in the full grid-connected mode, the actual PVG internal environment was simulated, the same crops were planted, and the crop annual yield was calculated by using the rectangular hyperbolic modified light response model. The average market price of the crop is collected, and the annual income of the PVG is calculated by using the light distribution optimization model. The annual income of the polysilicon multi-span PVG with the full grid-connected mode is counted, and the annual income of a single PVG in a typical case is calculated. By comparing the data relationship between the annual income calculated by the light distribution optimization model and the actual annual income, the correctness of the optimization model is verified, as shown in Table 2.

Table 2. Comparison of the annual income calculated by the light distribution optimization model and the actual annual income under the full grid-connected mode.

| The number of PVGs | The annual income calculated by the light distribution optimization model ($) | The actual annual income ($) | Relative error (%) |
|---|---|---|---|
| 1 | 0.42 | 0.40 | 4.30% |
| 2 | 0.57 | 0.55 | 3.37% |
| 3 | 0.42 | 0.39 | 7.33% |
| 4 | 0.50 | 0.46 | 9.66% |
| 5 | 0.42 | 0.29 | 43.41% |
| 6 | 0.43 | 0.46 | -5.30% |
| 7 | 0.56 | 0.52 | 6.27% |
| 8 | 0.39 | 0.42 | -7.77% |
| 9 | 0.49 | 0.46 | 7.48% |
| 10 | 0.47 | 0.45 | 4.44% |
| 11 | 0.44 | 0.46 | -4.97% |

| | | | |
|---|---|---|---|
| 12 | 0.40 | 0.42 | -4.42% |
| 13 | 0.47 | 0.44 | 7.21% |

Table 2 shows that among the 13 independent PVGs of the polysilicon multi-span PVG, the relative error between the annual income of the PVG calculated based on the light distribution optimization model result for the No. 5 PVG and the actual annual income of the single PVG reaches 43.41%, while the relative error of the remaining 12 PVGs is within ± 10%. The main reason for the larger relative error of the No. 5 PVG was that the yield decreased by approximately 40% due to the lag of fertilizer application time. Excluding the No. 5 PVG, the average annual income calculated by the light distribution optimization model for the remaining 12 PVGs was 4597.8 $, while the actual average annual income was 4401.1 $, a relative error of 4.47%. The main source of error was the error caused by the method of using the rectangular hyperbolic modified light response model to characterize the relationship between crop light and yield. According to Ref. 27, the error range of the method using the rectangular hyperbolic modified light response model is [-15.9%, 15.9%]. Table II shows that the calculation results of the annual income of the light distribution optimization model are reasonable. The correctness of the solar radiation allocation optimization methods of PVPG-PVG and AP-PVG based on maximizing the economic benefits is verified.

Furthermore, to illustrate the contribution of this method to the overall revenue of the PVG, the annual income calculated by the light distribution optimization model is used to calculate that for the full grid-connected mode and semi-grid connected mode, and the light distribution results and annual income are obtained. The calculation results are shown in Table 3.

Table 3. Comparison of economic benefits under two operation modes

| Operation mode of PVG | Proportion of solar radiation distribution between PVPG-PVG and AP-PVG | Annual income ($) |
|---|---|---|
| Full grid-connected mode | 1/0 | 4157.14 |
| Semi grid-connected mode | 0.42/0.58 | 5071.43 |

Table 3 shows that the economic benefit of the semi-grid connected mode using 42% of the photovoltaic power generation is 22.0% higher than that of the full grid-connected mode. The main reason is that the total output and price of AP-PVG are basically the same in the two modes. However, in the semi-grid connected mode based on the solar radiation distribution, the annual investment and maintenance costs of the PV modules of the PVG are reduced, and the power obtained from the power grid is significantly reduced. The overall income of the semi-grid connected mode is significantly higher than that of the full grid-connected mode. Through the optimization calculation of the particle swarm optimization algorithm, using the PVG in the semi-grid connected mode, a solar radiation distribution ratio of 1/1.38 for PVPG-PVG and AP-PVG, respectively, can maximize the income of the PVG, and this result further verifies the correctness of this method.

Based on the analysis of the annual income of the PVG calculated based on the light distribution optimization model, the main factors affecting the solar radiation distribution are electricity price fluctuations, crop price fluctuations, single-crop planting and multi-crop mixed planting. The specific impact of each factor on the solar radiation distribution is analyzed below.

### 4.2. The impact of price fluctuations on economic benefits

Through the analysis of the solar radiation allocation optimization methods of PVPG-PVG and AP-PVG of a PVG, the fluctuations of the grid-connected PV price Q2, price of electricity from grid supply Q3 and price of agricultural products Q4 will affect the overall income of the PVG. The specific situation is analyzed in Figures 2-4. Due to the restriction of the constraint conditions of the PVG, the selection of the light distribution ratio of PVPG-PVG and AP-PVG should meet the needs of crop growth. Therefore, three typical light distribution ratios were selected in this paper, which were 0.58, 0.63 and 0.68.

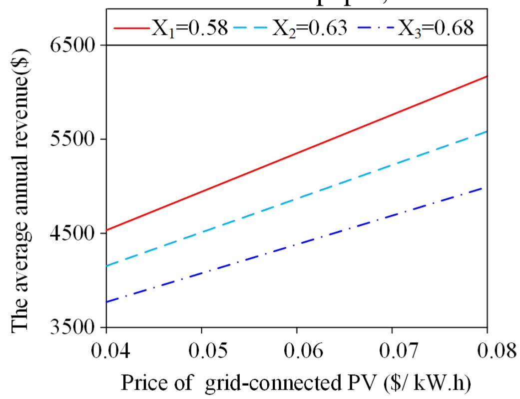


Figure 2. The impact of grid-connected PV electricity price fluctuation on the average annual revenue of a PVG. The vertical axis is the average annual revenue of the PVG, with the unit of ($10^3$ $), and the horizontal axis is the price of grid-connected PV, with the unit of ($/kW.h). According to the trend of China's grid-connected PV electricity price in recent years, the horizontal axis coordinate range is set from [0.04-0.08] ($/kW.h).

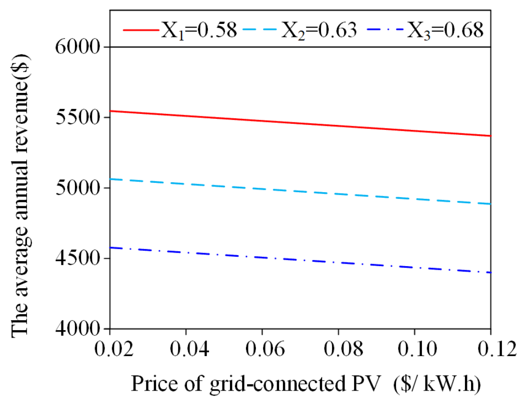


Figure 3. The impact of grid price fluctuation on the average annual revenue of a PVG. The vertical axis is the average annual revenue of the PVG, with the unit of ($10^3$ yuan), and the horizontal axis is the grid-connected PV price, with the unit of ($/kW.h). According to the trends of the domestic electricity price and industrial production electricity price in China in recent years and to explain the influence of power grid price fluctuation in a large range on the average annual revenue of the PVG, the horizontal axis coordinate range is set from [0.02-0.12] ($/kW.h).

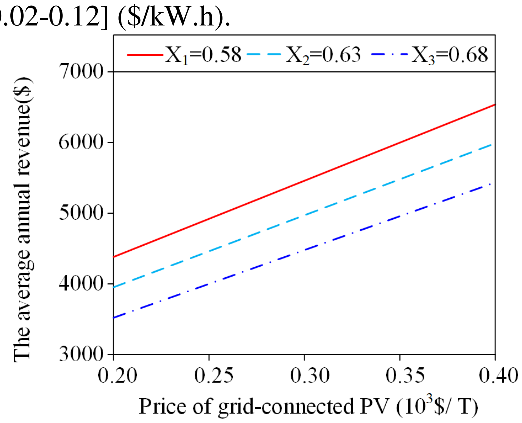

Figure 4. The impact of crop price fluctuation on PVG economic income. The vertical axis is the average annual revenue of a PVG ($10^3$ $), and the horizontal axis is the price of crops ($/T). The price of different crops planted in a PVG varies greatly, while the price fluctuation of the same crop is relatively small in a period of time. To explain the impact of crop price fluctuation on PVG economic returns, a crop with a large price fluctuation was selected as the research object, and the horizontal axis coordinate range was set from [0.2-0.4] (103 $/T).

Through the analysis of the impact of the fluctuations of the price of grid-connected PV, price of electricity from grid supply and price of agricultural products on the average annual revenue of the PVG, it is found that:

1) Figure 2 shows that the price of grid-connected PV increases from 0.042 $/kW.h to 0.084 $/kW.h, the average annual revenue of the PVG increases from 4609.3 $ to 6362.4 $, and the economic benefit increases more obviously with the expansion of the scale of the PVG. With an increase in the ratio of the solar radiation distribution of AP-PVG, the average annual revenue of PV power generation decreased significantly, the energy consumption of the PVG increased significantly, and the overall revenue of the PVG decreased.
2) Figure 3 shows that with an increase in the price of electricity from grid supply, the power consumption cost of the PVG increases, and the overall average annual revenue of the PVG decreases. If electric heating is considered to provide temperature regulation for the PVG, the electricity obtained from the grid will increase dramatically. If the price of electricity from grid supply is too high, the average annual revenue of the PVG may be greatly reduced, or even negative. Due to limited space, an analysis of this problem will be conducted in detail in a subsequent paper.
3) Figure 4 shows that the average annual revenue of the PVG increases by 1078.3 yuan for every 100 yuan/T increase in the price of agricultural products, and the economic benefit of the PVG is more obvious. In addition, with an increase in the ratio of the solar radiation distribution of AP-PVG, the agricultural product yield increased, while the PV power generation decreased, resulting in a decline in the average annual revenue of the PVG.
4) From the comprehensive Figures 2-4, it can be found that if the ratio between the PVG economic benefit and the unit price fluctuation is defined as the ratio of economic benefit (REB), the REB of the price of grid-connected PV is 409.08 $/0.01 $/kW.h, the REB of the price of electricity from grid supply is -17.68 $/0.01 $/kW.h, and the REB of the price of agricultural products is 107.83 $/10 $/T. The results show that, within the constraint conditions, increasing the ratio of the solar radiation distribution of PVPG-PVG as much as possible can effectively improve the economic benefits of the PVG; the fluctuations of the price of grid-connected PV and the price of agricultural products have a greater impact on the economic benefits of the PVG, while the impact of the price of electricity from grid supply is small.

### 4.3. Effect of mixed planting crops on the economic benefits of a PVG

To improve the economic efficiency of PVG planting and the ability of internal environment regulation, in general, a PVG is often planted with a single crop. However, for some special cases, such as a very large PVG, mixed planting of crops still exists.

Through the analysis of the solar radiation allocation optimization methods of PVPG-PVG and AP-PVG, mixed planting of crops affects only the solar radiation yield model of the crops; the model of PV power generation, constraint conditions and calculation method are consistent with those of the original model. The solar radiation yield model of the ith crop of mixed planting crops in a PVG is as follows:

$$f_i(x) = 44\eta(\alpha \frac{1-\beta P_i x}{1+\gamma P_i x} Px - R_{di} / 1000\mu) K_{prod} t_{resp} 10^{-6} \tag{14}$$

The average annual revenue model of mixed planting crops of AP-PVG is as follows:

$$M'_{agri} = \sum_{i=1}^{n} f_i(x) Q_i \tag{15}$$

$M'_{agri}$, annual income of agricultural production from mixed planting in the PVG; $Q_i$, in a PVG with mixed planting of crops, the unit price of various crops ($/T). It is taken as the annual average price of the crop.

Through the analysis of the average annual revenue model of mixed planting crops of AP-PVG, it can be concluded that the impact of the fluctuations of the grid-connected PV price and the price of electricity from grid supply on the average annual revenue of a PVG is the same as that of single-crop planting, while the fluctuation of the agricultural product price has a great impact on the average annual revenue of the PVG. Mixed planting crops of tomato, cucumber and pepper are taken as an example to analyze the impact of fluctuation of the price of agricultural products on the economic benefits of mixed planting of crops in a PVG, as shown in Figure 5.

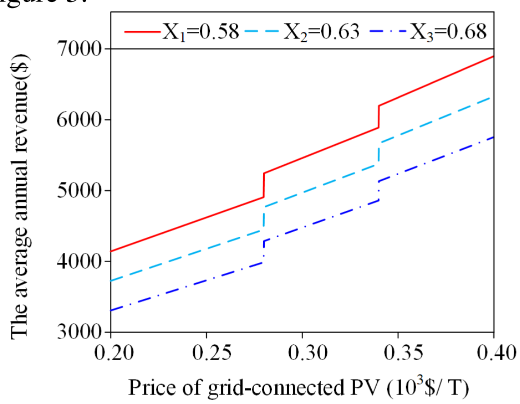


Figure 5. The impact of the fluctuation of the price of agricultural products on the average annual revenue of mixed planting crops in a PVG. The vertical axis is the average annual revenue of the PVG ($10^3$ $), and the horizontal axis is the price of mixed planting of different crops, with the unit of ($10^3$ $/T). The prices of different crops planted in a PVG vary greatly. To explain the impact of the fluctuation of the price of agricultural products for mixed planting crops in a PVG, three crops with similar prices were selected, and the horizontal axis coordinate range was set from [0.2-0.4] ($10^3$ $/T).

Figure 5 shows that the average annual revenue of a PVG with mixed planting crops will change greatly with different prices of agricultural products and variety of crops. Moreover, with a decrease in the rate of PVPG-PVG, the average annual revenue of the PVG will be reduced. Compared with that of single-crop planting, the average annual revenue of mixed planting crops is lower, but the ability to resist the risks caused by the fluctuation of the price of agricultural products will be improved.

## 5. Conclusion

1) Compared with the full grid-connected mode and off-grid connected mode, the semi-grid connected mode achieves a higher average annual revenue of a PVG. However, based on an analysis of solar radiation allocation optimization methods of PVPG-PVG and AP-PVG, the semi-grid connected mode has a higher average annual revenue. Therefore, it is necessary to optimize the distribution of solar radiation in a PVG;
2) The fluctuations of the price of grid-connected PV, the price of electricity from grid supply and the price of agricultural products affect the average annual revenue of a PVG. Furthermore, through an analysis of the REB, it is concluded that within the constraint conditions, it is helpful to increase the solar radiation ratio of PVPG-PVG as much as possible to improve the average annual revenue of a PVG;

3) Compared with that of the single-crop planting mode, the average annual revenue of a PVG with mixed planting crops may be reduced, but the ability to resist the risks caused by the fluctuation of the price of agricultural products will be improved;
4) The results of this study can provide some theoretical support for the design of PVGs, but some parameters of PVGs are ignored in the process of establishing the solar radiation yield model, which may lead to some deviation of the calculation results. The next research plan is to improve the calculation accuracy of this method. The parameters ignored in this method will be included in the calculation scope to increase the calculation accuracy.

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## Competing interests

The authors declare no competing interests.

## Author contributions

W.Y. designed the study and wrote the original manuscript; Z.T. developed the concept and revised the manuscript; Z.W. collected experimental data and modified the grammar of the manuscript.

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## Figures

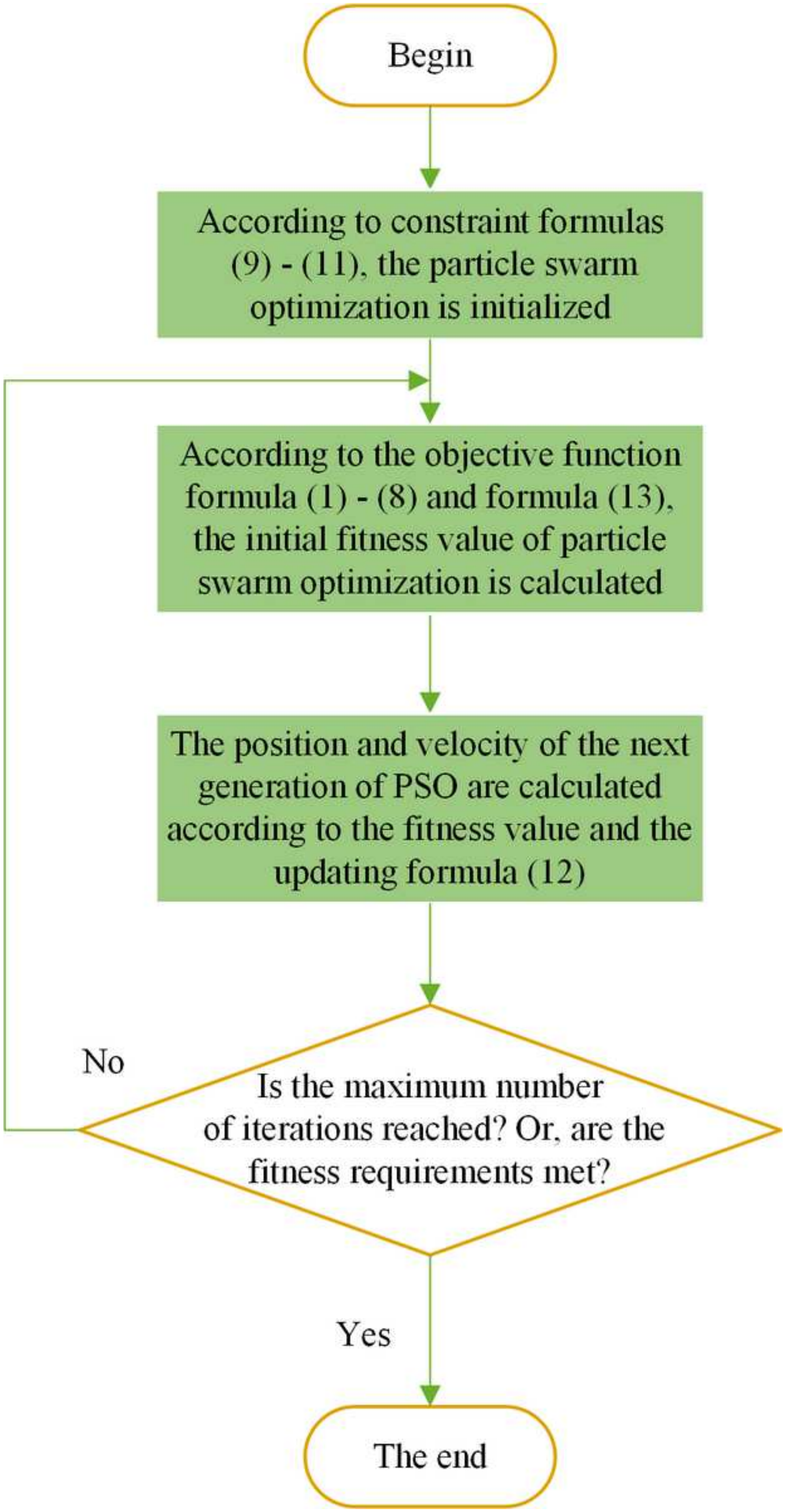


**Figure 1**

Flow chart of particle swarm optimization

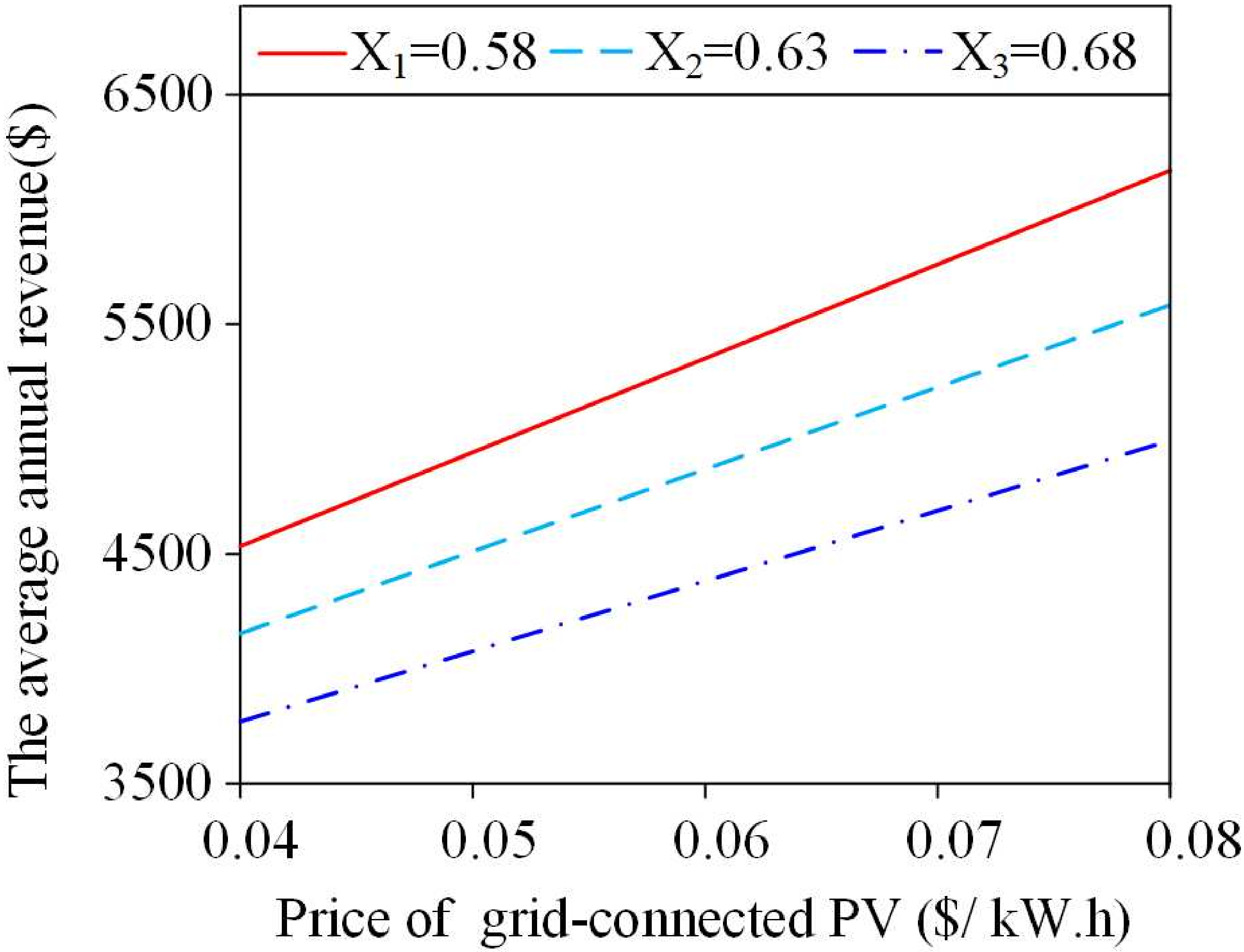


**Figure 2**

The impact of grid-connected PV electricity price fluctuation on the average annual revenue of a PVG. The vertical axis is the average annual revenue of the PVG, with the unit of (103 $), and the horizontal axis is the price of grid-connected PV, with the unit of ($/kW.h). According to the trend of China's grid-connected PV electricity price in recent years, the horizontal axis coordinate range is set from [0.04-0.08] ($/kW.h).

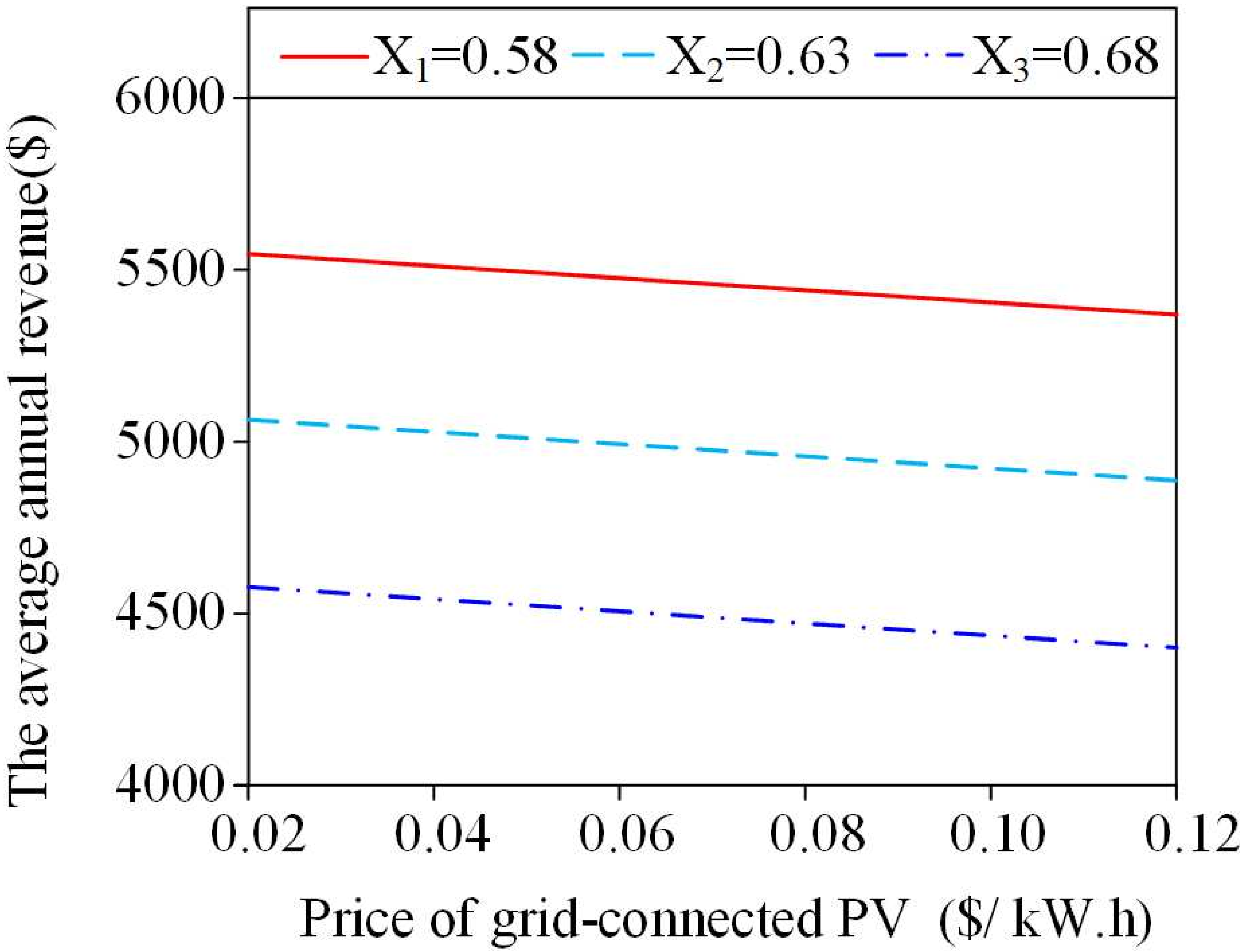


**Figure 3**

The impact of grid price fluctuation on the average annual revenue of a PVG. The vertical axis is the average annual revenue of the PVG, with the unit of (103 yuan), and the horizontal axis is the gridconnected PV price, with the unit of ($/kW.h). According to the trends of the domestic electricity price and industrial production electricity price in China in recent years and to explain the influence of power grid price fluctuation in a large range on the average annual revenue of the PVG, the horizontal axis coordinate range is set from [0.02-0.12] ($/kW.h).

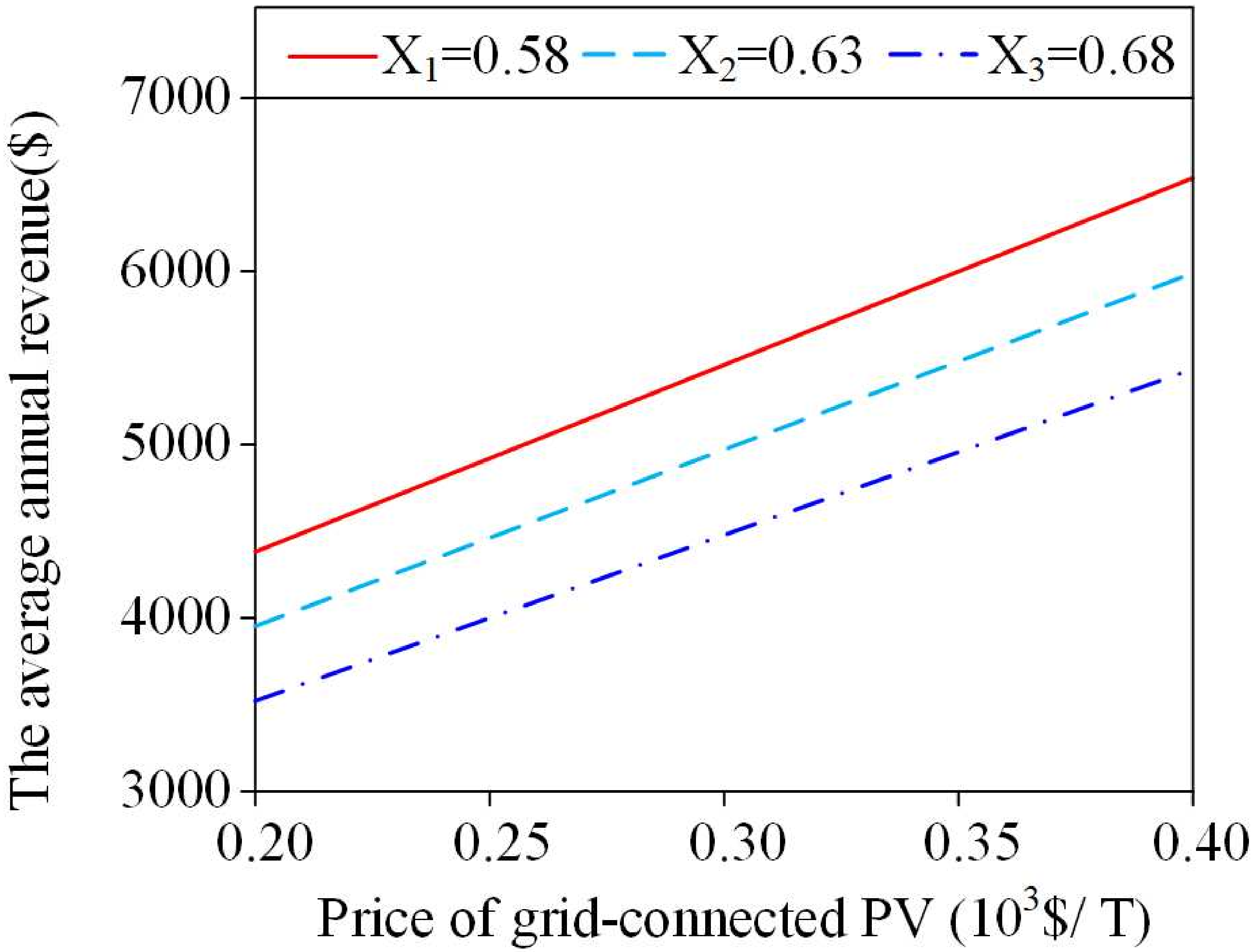


**Figure 4**

The impact of crop price fluctuation on PVG economic income. The vertical axis is the average annual revenue of a PVG (103 $), and the horizontal axis is the price of crops ($/T). The price of different crops planted in a PVG varies greatly, while the price fluctuation of the same crop is relatively small in a period of time. To explain the impact of crop price fluctuation on PVG economic returns, a crop with a large price fluctuation was selected as the research object, and the horizontal axis coordinate range was set from [0.2-0.4] (103 $/T).

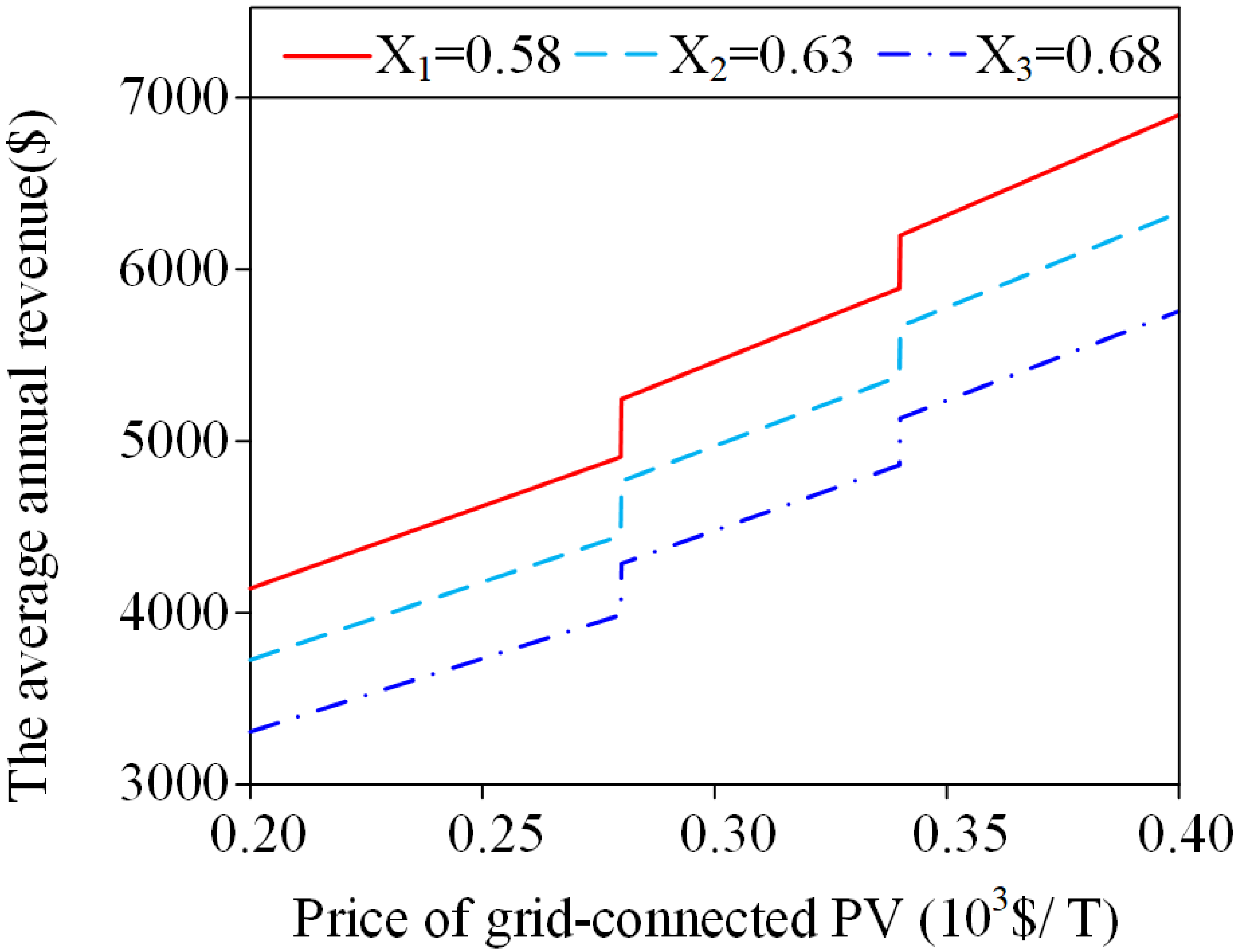


**Figure 5**

The impact of the fluctuation of the price of agricultural products on the average annual revenue of mixed planting crops in a PVG. The vertical axis is the average annual revenue of the PVG (103 $), and the horizontal axis is the price of mixed planting of different crops, with the unit of (103 $/T). The prices of different crops planted in a PVG vary greatly. To explain the impact of the fluctuation of the price of agricultural products for mixed planting crops in a PVG, three crops with similar prices were selected, and the horizontal axis coordinate range was set from [0.2-0.4] (103 $/T).