# Optimization Model of Photovoltaic Module Cleaning Strategy Based on Particle Swarm Algorithm

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**Abstract.** Photovoltaic (PV) power generation in desert areas has significant economic benefits. Accumulated dust on PV panels can significantly reduce their power output, so it is necessary to clean them after a certain period of operation. However, traditional periodic cleaning strategies often cannot maximize the economic benefits of PV power generation. Therefore, optimizing the cleaning strategy with equal intervals is essential. In this study, we establish a model to calculate PV power generation revenue and optimize the cleaning strategy based on environmental variables from some PV power stations in central Australia. We consider the cost of cleaning PV panels and the impact of environmental variables such as solar radiation intensity, relative humidity, and wind speed on dust accumulation. This model can calculate the dust accumulation on a specific day based on environmental data and then estimate the corresponding power generation revenue for that day. Meanwhile, a variant of the particle swarm algorithm is used to automatically adjust the cleaning interval under different environmental conditions, achieving the maximum power generation efficiency. After comparison and analysis with different datasets, it is verified that the optimization strategy generated by the proposed algorithm model can increase the economic benefits by more than 70 US dollars than Equal time interval cleaning strategy, which demonstrates its stability and reliability.

**Keywords:** Photovoltaic module; Particle swarm algorithm; Cleaning strategy; Power generation efficiency.

## 1. Introduction

In recent decades, solar energy has been widely used as a clean and environmentally friendly energy source, and solar photovoltaic panels are one of the most common and effective ways to use solar energy. The desert area is an ideal area for establishing photovoltaic power stations, etc.

However, because the wind and dust in the desert are heavy, the surface of photovoltaic panels is prone to accumulating dust. Salim et al. [1]studied the impact of dust accumulation on the efficiency of photovoltaic power generation in Saudi Arabia and found that the efficiency of photovoltaic panels decreased by more than 30% after 8 months without cleaning conditions. Li Xingcai et al. [2] proposed an integrated physical model to predict the effect of deposition on the transmittance of solar panels and finally found that the effect of deposition increased significantly with increasing particle concentration and size. All the above facts prove that the surface area dust of photovoltaic panels will significantly reduce the power of photovoltaic panels and greatly reduce the economic benefits of the establishment of photovoltaic power stations.

In addition, many local meteorological factors at the photovoltaic power station will also affect the power of the photovoltaic panels. S. Mekhilef et al. [3] used mathematical modeling and test methods to analyze the influence of dust accumulation rate, wind speed, and humidity on the power generation performance of photovoltaic panels. Zaihidee et al. [4] analyzed the influence of dust characteristics, wind speed, humidity, rainfall, photovoltaic module materials, and photovoltaic module installation parameters on the dust deposition degree of photovoltaic panels through an experimental summary. Ilse K. et al. [5] analyzed the key parameters of airborne dust concentration, dust characteristics, and particle deposition rate and verified the correlation between dust accumulation and these environmental factors through outdoor experimental statistics.

Researchers around the world have offered different solutions for the cleaning of photovoltaic panels. In 1967, NASA, in order to solve the problem of solar panel dust removal in the Apollo plan,

proposed the concept of electric curtain dust removal [6], and the technology has been applied in the space field. Michele Gabrio Antonelli[7]designed a low-cost, unmanned robotic device to remove anhydrous dust and sand from the surface of the photovoltaic panels. After testing, it was found to have good performance in terms of cleaning time and driving stability. The equal time interval cleaning strategy is a commonly used cleaning strategy for photovoltaic solar panels. However, for areas where light intensity and other climate factors change greatly and have a long cleaning time interval in a year, an equal time interval cleaning strategy cannot take into account the cleaning cost and the power generation efficiency of photovoltaic solar panels.

The particle swarm algorithm is a type of intelligent random optimization algorithm that simulates flock foraging and group migration processes. Currently, the particle swarm algorithm is widely used in the power system economic scheduling [9], logistics optimization [10], and artificial intelligence [11] fields due to its global optimal capability, ease of implementation, and strong adaptability for multimodal function optimization problems. Many variants of the particle swarm algorithm have emerged for different usage targets.[8] Ting Li et al. [9] introduced the multi-objective particle swarm algorithm (MOPSO) and explained how to solve the ED problem in the economic scheduling of power systems and combine the particle swarm algorithm with a chaotic optimization strategy; Qi Changxing et al. [12] proposed a particle swarm algorithm combined with a chaotic optimization strategy, which avoids local optimization and enhances the global search ability. In this paper, considering the influence of light intensity, humidity, and wind speed on the power generation rate of photovoltaic panels and the cost of cleaning photovoltaic panels, a model is established to calculate the power generation income of photovoltaic panels, which improves the power generation income of photovoltaic solar panels for a long time. At the same time, a variant of the particle swarm algorithm that can be applied to the scheme under the influence of coupling factors is constructed, and the photovoltaic panel cleaning strategy is innovatively designed. This method can also be applied in other fields, such as engineering design optimization and power grid stability control. After using the relevant data of two photovoltaic power stations in the central desert region of Australia, it was found that the cleaning strategy obtained by this algorithm gained more than the existing equal time interval cleaning strategy under different climates and theoretical power generation.

## 2. Profit calculation model establishment

### 2.1 The influence of meteorological factors on photovoltaic panel power

According to the introduction, changes in many meteorological factors may affect the dust accumulation rate of photovoltaic panels and then affect the power of photovoltaic panels, and the effects of these meteorological factors may be coupled. However, according to the study of Wasim Javed et al. [13], among many meteorological factors, the influence of wind speed and relative humidity on the power of photovoltaic panels is the most significant. Therefore, in this article, we assume that the meteorological factors affecting the photovoltaic panel power are only the relative humidity and wind speed.

We define $\Delta A$ as the reduction of photovoltaic panel power, the reduction of wind speed to photovoltaic panel power, and the reduction of humidity to photovoltaic panel power, as $\Delta I$, $\Delta B$, and $I$are the single-value functions of wind speed and humidity, respectively.

The daily generating efficiency of photovoltaic panels per month is:

$$\eta_{i,j} = 1 + \Delta B_{i,j} + \Delta I_{i,j} \tag{1}$$

Where: $I$ represents the number of days, $i+1$ is the next day, $j$ represents the month, the wind speed on the day $I$ of month j is $\Delta B_{i,j}$, and the humidity on the photovoltaic panel on the I day of the $j$ month is $\Delta I_{i,j}$.

According to Wasim Javed et al., the influence of wind speed (V) on the photovoltaic panel power is a segment function affected by the relative humidity I size:

$$\Delta B_i = \begin{cases} 0.0057V_i - 0.0159 & R_i<35\% \\ 0.0034V_i - 0.0131 & 35\%<R_i<50\% \\ -0.002V_i - 0.002 & 50\%<R_i<65\% \\ -0.0041V_i + 0.0024 & R_i>65\% \end{cases} \quad (2)$$

Where: $V_i$ is the wind speed on Day $I$ and $R_i$ is the relative humidity on Day $i$.

At low relative humidity, it was positively correlated with the wind speed. According to the study [14] by Figgis et al., this may be because the dust particles contain a small amount of water at this time, and the high-speed wind is easy to re-suspend it, which makes it less sticky and easier to be taken away by the wind, reducing the dust accumulation rate of photovoltaic panels and thus improving the power of photovoltaic panels. However, when the relative humidity exceeds 50%, it is negatively correlated with the wind speed. According to Beattie et al. [15], this may be due to the higher relative humidity, which increases the energy required for dust resuspension to overcome the friction of the wind, which in turn affects the threshold wind speed of deposited dust particles, resulting in greater power loss for photovoltaic panels. This conclusion was confirmed in a wind tunnel study by Ibrahim et al.[16] in 2004: as relative humidity increased from 18% to 67%, the wind speed threshold for separating 50% stainless steel particles from the glass surface increased from 3.6 to 1% (13.4).

Similarly, the effect of relative humidity I on photovoltaic panel power is a segment function depending on the size of wind speed (V):

$$\Delta I_i = \begin{cases} 0.0002R_i - 0.0137 & V_i<2 \\ -0.0003R_i + 0.0074 & 2<V_i<4 \\ -0.0005R_i + 0.0235 & V_i>4 \end{cases} \quad (3)$$

As we mentioned earlier, when the relative humidity is high, the moisture contained in the dust particles will affect the efficiency of the wind in carrying away the PV panel surface area dust, which is especially evident when the wind speed is high ($V > 4$ *m/s*).

### 2.2 Impact of seasonal variation on photovoltaic panel power

In addition to meteorological factors, seasonal changes will also have an impact on the initial power of photovoltaic panels. As we mentioned in our introduction, the solar radiation angle and temperature in different months of the year will affect the power of photovoltaic panels. In a short period of time (within a month), the variation of daily solar radiation angle and temperature is small and has no obvious regularity. There is a clear trend of change in the relevant data between months. Therefore, in this article, we treat the time factor on the premise of ensuring the accuracy of the algorithm. The treatment method is as follows:

$$p_{1j+1} = \frac{\sum_{i=1}^{n} p_{ij+1}}{\sum_{i=1}^{n} p_{ij}} p_{1j} \quad (4)$$

Where $n$ is the number of days of the month, $j$ is the month, $I$ is the number of days, $P_{i,j}$ is the power of day $I$ of month $j$. That is, the ratio of the initial power of each month to the initial power of the previous month is the ratio of the power generated in these two months. This formula reflects the general change in power in each month of the year. In our model, it is assumed that each cleaning can completely remove the dust from the photovoltaic panels; that is, after each cleaning, the power of the photovoltaic panel will be restored to the initial power value of the month.

### 2.3 Calculation of net income from power generation

After processing the data of the panels, the total power generation of the panels within one year is:

$$W = \sum_{i=1}^{n} \sum_{j=1}^{12} p_{ij} T \quad (5)$$

Where: $T$ represents the time of electricity generation per day.

The cost of a single cleaning of the photovoltaic panels consists of the following four parts [17]:

(1) Loss of power generation caused by cleaning

(2) Salary of cleaning personnel

(3) Cleaning equipment costs

(4) Cost of rolling brush head

Based on the above considerations, a single cleaning cost is assumed to be $C$.

Then the net profit of power generation on day $i$ is:

$$Q_i = dW_i - CL_i \tag{6}$$

Where $Q_i$ is the power generation on day $i$, and $L_i$ is the number of washes on day $i$.

Therefore, the net power generation income of the photovoltaic power station within one year is:

$$Q_z = dW - CL \tag{7}$$

In this formula, $Q_z$ is the net profit of the photovoltaic power station, $d$ is the on-in price per kilowatt of electricity, $W$ is the total power generation, $C$ is the single cleaning cost, and $L$ is the cleaning time.

## 3. Algorithm introduction

### 3.1 Introduction to the Particle Swarm Algorithm

The particle swarm algorithm is a general method to solve optimization problems. Its practical effect is characterized by fast solution speed, a relatively stable numerical value, and a simple algorithm. It is a commonly used algorithm in mathematical modeling. The particle swarm algorithm is called the Particle Swarm Optimization algorithm (PSO). The basic principle is to generate a group of random particles and find the optimal solution through multiple iterations. In the particle swarm algorithm, each particle has a position and speed, and the position of each particle represents the position of the current solution, and the speed represents the search direction of the current solution. Each particle updates its position and speed according to its own historical optimal solution, thus gradually converging towards the optimal solution. Compared with other optimization algorithms, the PSO algorithm has the advantages of fast convergence speed and good robustness, and it is widely used in machine learning, data mining, and engineering optimization.

The schematic flow diagram of the particle swarm algorithm is as follows:

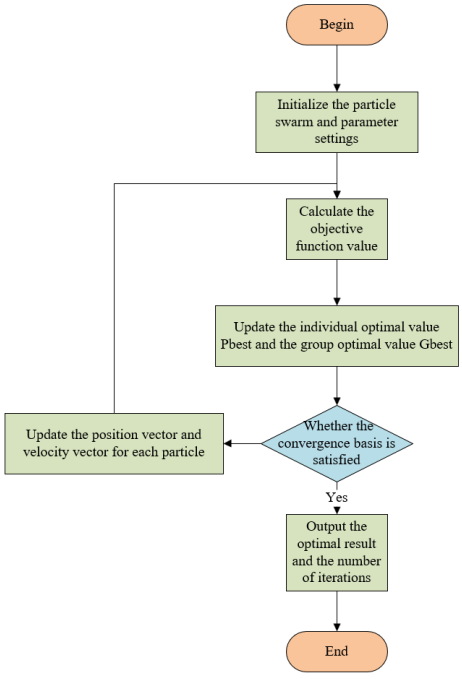



**Figure 1.** Particle Swarm Optimization Algorithm Principle Flowchart

### 3.2 Particle swarm algorithm deformation

The goal of the mathematical model in this paper is to obtain a satisfactory solution of the cleaning interval when considering the ambient wind speed, relative humidity, solar radiation, and cleaning cost, so as to obtain a higher profit. Therefore, the initialized particle population of this model is set to be cleaned every five days. At the same time, since the goal of this model is to obtain a satisfactory solution to the cleaning interval, so that the global optimal position and the individual historical optimal position change to the higher profit global optimal interval and the optimal cleaning interval in the local time period, we make the following changes to the algorithm:

Step 1: Enlarge the cleaning time interval by $1 + m$ times or by $1 - m$ times, and then multiply the changed cleaning times by the cost of a single cleaning to obtain the total cleaning cost.

Step 2: Calculate its total profit, respectively, and compare the total profit before the change with the enlarged total profit and the total profit after the reduction. There are three results:

(1) If the total profit is the largest before the change, the overall cleaning interval does not change.

(2) If the total profit is increased after the cleaning interval, the cleaning time caused by the global optimal cleaning time is:

$$D_j = c_2 E_j N m \tag{8}$$

In the formula: $D_j$ represents the actual amount caused by the native cleaning time of the $J$-time cleaning time. $c_2$represents social learning factor. $E_j$ represents the jet of the cleaning. $N$ represents a random number between 0-1. $M$ represents the total cleaning moment changes.

(3) If the total profit is the maximum after the cleaning interval is reduced, the cleaning time caused by the global optimal cleaning time will change as follows:

$$D_j = -c_2 E_j N m \tag{9}$$

Step 3: To judge whether the part is the optimal cleaning time, move the cleaning time forward or backward, and the movement amount is $\Delta b_j$:

$$\Delta b_j = m(E_{j+1} - E_{j-1}) \tag{10}$$

$\Delta b_j$ represents the theoretical variation caused by the j-th cleaning time at the local optimal cleaning time.

Step 4: We calculate the profit made during the period from $E_{j-1}$ to $E_{j+1}$, and on average, every day, as the local average generating income. The formula is as follows:

$$F_j = \frac{\sum_{i=E_{j-1}}^{i=E_{j+1}} G_i}{E_{j+1} - E_{j-1}} \tag{11}$$

Where: $F_j$ represents the average daily profit earned during the period from $E_{j-1}$ to $E_{j+1}$, and Gi represents the profit earned on day $i$.

Step 5: Before the change, forward adjustment, and backward adjustment, the average daily generation income for a period of time will also have three results:

(1) If the local average power generation income is the largest before the change, the cleaning time will not change

(2) After the local average power generation income is the largest after the cleaning time advances, the cleaning time changes to

$$H_j = -\Delta b_j c_1 N \tag{12}$$

Where: $H_j$ represents the actual change caused by the local optimal cleaning time at the jth cleaning time, and $c_1$ is the individual learning factor.

After the cleaning time is backward, the local average power generation income is the largest, and then the cleaning time changes to

$$H_j = \Delta b_j c_1 N \tag{13}$$

Step 6: The final amount of change at each cleaning time is

$$n_j = D_j + H_j + wK \tag{14}$$

In $n_j$, the actual change amount at the $j$ cleaning time, $w$ is the inertia factor, and $K$ is the inertia amount of the cleaning time.

Step 7: Calculate and record the total profit after the cleaning time changes.

If the change amount $n_j > 3j$ then set the change amount $n_j = 3j$, which is used to prevent the large change amount from missing the better satisfactory solution.

Giving new amounts of variation to inertia:

$$K = n_j \tag{15}$$

The flow chart of the spacing optimization algorithm is as follows:

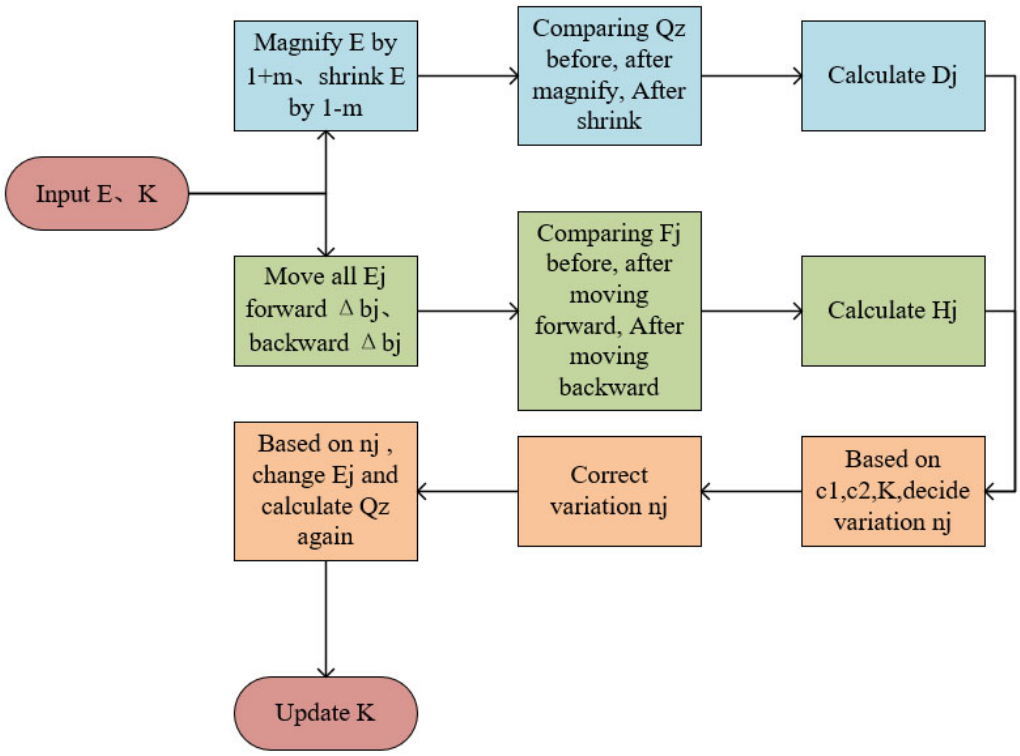



**Figure 2.** Algorithm Flowchart

## 4. Validation of the model

### 4.1 Data background

#### 4.1.1. selection of experimental data

The photovoltaic power measurement and climate data used in this article are sourced from two photovoltaic power stations in the central desert region of Australia. One of the photovoltaic power stations has a total of 30 photovoltaic panels, with a panel type of Sanyo HIP-210NKHE5. The rated power of each photovoltaic panel is 210 watts, and the tilt angle of all photovoltaic panels is fixed at 20 degrees. Another photovoltaic power station has a total of 3360 photovoltaic panels, with a panel type of Jinko Solar JKM315PP. Each panel has a rated power of 315 watts, and all photovoltaic panels have a fixed tilt angle of 15 degrees.

The data website provides all photovoltaic power and climate data (wind speed, direction, relative humidity, etc.). The statistical time interval is 5 minutes. We take the average of all statistical data for a day to obtain the average power and climate data for that day. For data loss caused by inverter failure, we will use the values from the previous day at the same time to fill in. And the power of the photovoltaic panel on the first day of operation shall be taken as the initial actual working power of the photovoltaic panel without any external meteorological factors.

### 4.1.2. Particle Swarm Optimization Parameter Selection

The parameter selection refers to the reference values provided by Eberhart scholars and sets the individual learning factor and social learning factor to 1.495. However, based on current research, the acceleration constant can be adjusted to a certain extent according to the model background. Due to the inherent properties of the model, the original inertia factor w is modified from 0.6 to 0.3 to reduce the vibration of the model.

## 4.2 Comparison of Model Calculation Results

### 4.2.1. Equal time interval cleaning strategy

The equal time interval cleaning strategy is a cleaning strategy chosen by most existing photovoltaic power plants. In this article, we compared the trend of total revenue with cleaning time for photovoltaic power plants with the Jinko photovoltaic panel model under environmental conditions in 2011 and the Sanyo photovoltaic panel model under environmental conditions in 2011 and 2014. The variation range of cleaning time intervals is from 10 days to 100 days. Finally, it was found that under three environmental conditions, the highest profit was achieved when the interval days were 53 days, 41 days, and 37 days, with the highest cleaning net profit of $2456, $3374, and $8688, respectively.

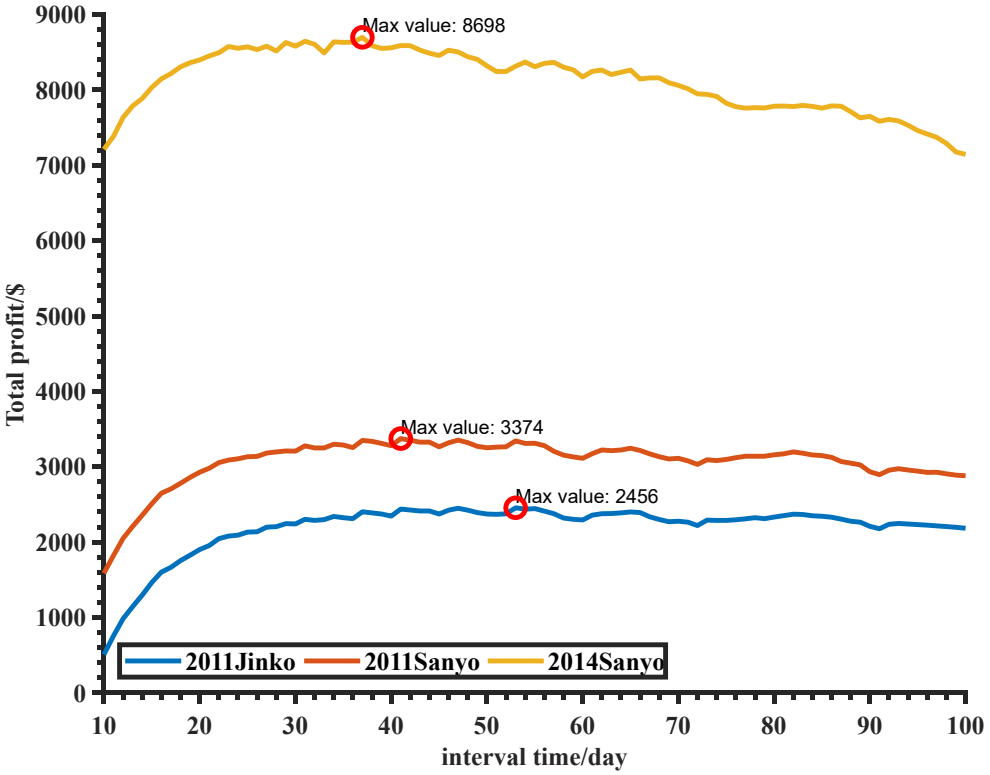



**Figure 3.** Total profit and iteration number of equal time interval cleaning

### 4.2.2. The cleaning strategy obtained from this model

We set the initial cleaning interval to clean every 5 days, and after 40 iterations, we found that under the three environmental conditions mentioned above, the cleaning strategy after 33, 33, and 35 iterations can achieve the highest profit, with the highest cleaning net profit of $255434468788, respectively. The rates of improvement were 3.99%, 2.13%, and 1.02%, respectively.

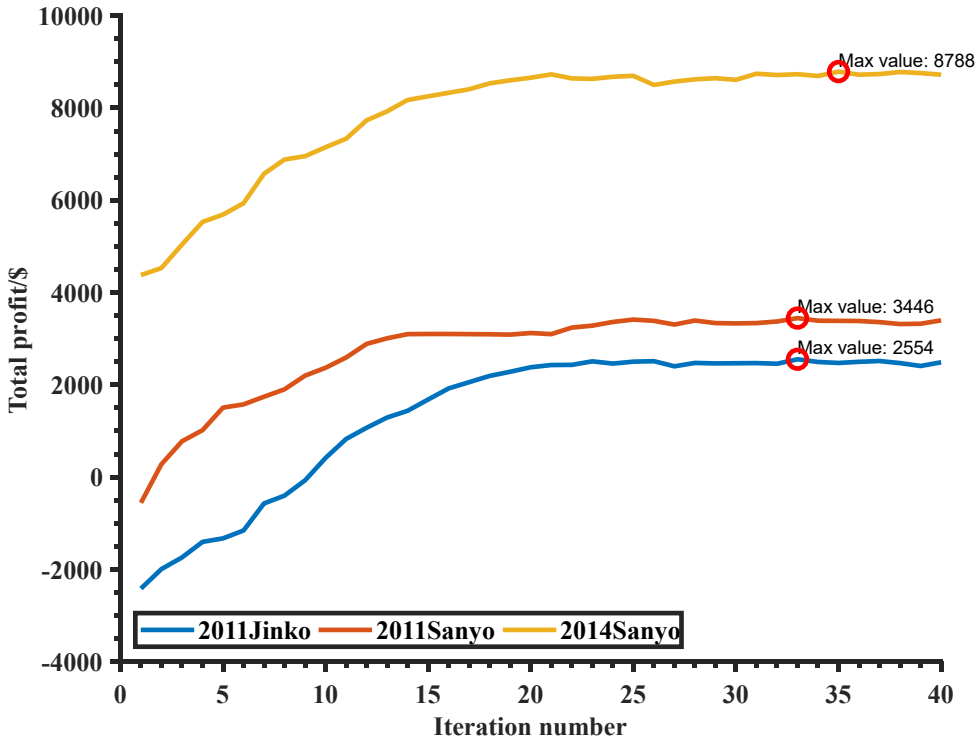



**Figure 4.** Total cleaning profit and iteration times for this model

The corresponding cleaning strategies for the three scenarios are

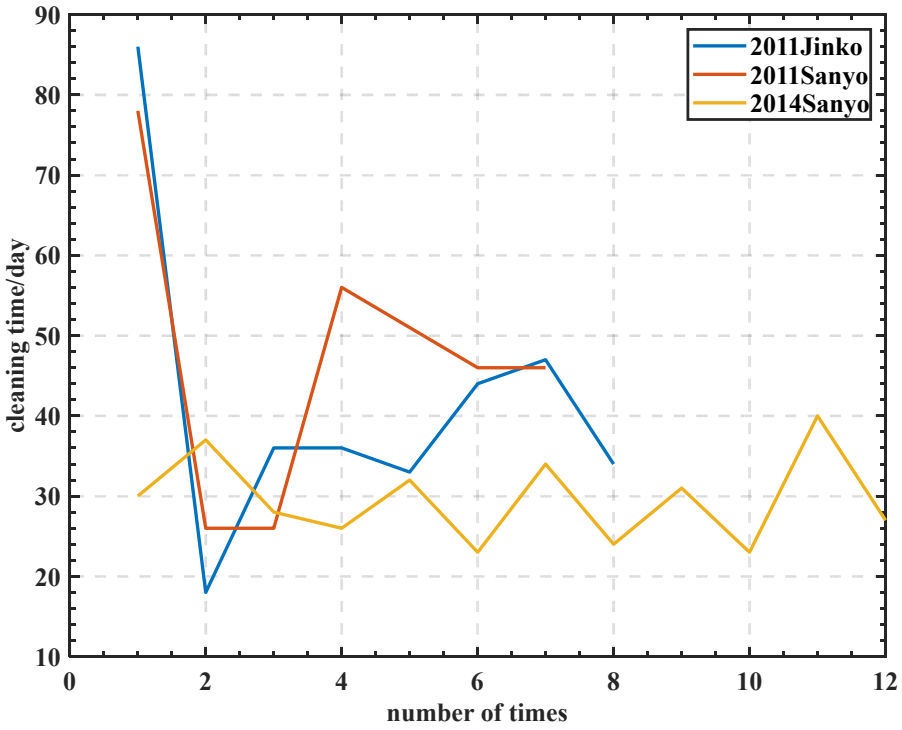



**Figure 5.** Cleaning strategy for this model

It can be seen that this algorithm has two advantages. On the one hand, it can allocate cleaning times for operating conditions with significant changes in power generation over time. On the other hand, when the power generation does not change much over time, the overall profit can be improved by fine-tuning the cleaning time interval.

This algorithm offers two distinct advantages. Firstly, it enables the allocation of cleaning times for operating conditions that exhibit significant changes in power generation over time. Secondly, when the power generation does not exhibit much variation over time, the overall profit can be enhanced by fine-tuning the cleaning time interval.

#### 4.2.3. Comparison between cleaning strategies

After comparing two cleaning strategies in different years and regions, it was ultimately found that this model can obtain practical and feasible cleaning strategies in different situations and improve total profits to varying degrees, with an increase of over $70. This proves that the cleaning strategy obtained by our algorithm can effectively improve total profits.

## 5. Conclusion

This article establishes a photovoltaic panel power generation calculation model that considers both light intensity, wind speed, and humidity based on relevant data from two photovoltaic power stations in the central desert region of Australia. At the same time, a PSO algorithm variant was established to optimize cleaning strategies. After comparing the resulting cleaning strategy with existing equal time interval cleaning strategies, it was found that the total benefits obtained under this cleaning strategy were higher than those obtained under existing equal time interval cleaning strategies in different situations.

This article constructs a mathematical model for the variation of photovoltaic solar panel power generation with factors such as light intensity, relative humidity, and wind speed based on actual data. By only changing the distribution of cleaning intervals without changing the overall cleaning frequency or cleaning method, the total revenue from power generation has been improved, providing a new approach for improving the power generation of photovoltaic panels. The algorithm only requires a few iterations to obtain a satisfactory solution and improve total revenue, and it has fewer adjustable parameters, making it highly practical.

However, this article did not consider the impact of extreme weather on the power generation of photovoltaic panels in the model. The constructed algorithm is greatly influenced by the values of various parameters, and parameter selection needs to be performed again in different environments to obtain high-quality, satisfactory solutions.

Future research may consider the impact of extreme weather on photovoltaic panel power generation in terms of models, as well as the impact of weather conditions at different time periods of the day on photovoltaic panel power generation. In terms of algorithms, a combination of the simulated annealing algorithm (SA) and the particle swarm optimization algorithm (PSO) will be introduced to improve the algorithm's ability to escape local optima and obtain better satisfactory solutions.

Overall, this article provides an optimization method for cleaning strategies and verifies it with actual data. This method has the potential to be applied in other fields, such as engineering design optimization and power grid stability control.

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