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Optimizing Light Environment of the Oblique Single-axis Tracking Agrivoltaic System

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Abstract. A combination of food crops and solar panels on the same space can be called as an agrivoltic (AV) system. In our previous paper, we put forward a scientific method to match crops. This paper studies the solar radiation distribution during the effective growth period of crops in the agrivoltic system based on the oblique single-axis tracking bracket by building the model with Ecotect in a approximate method. On the basis of solar radiation distribution analysis, the right crop is choosed. Then, we puts forward an improved tracking algorithm for optimizing the solar radiation distribution for the selected crop. The algorithm is performed by controlling the shading area while ensuring power generation.

1. Introduction

An agrivoltic (AV) system is a system which can combine food crops and solar panels on the same land. There may be a 60 to 70 percent increase of the overall land productivity in AV systems and there is a gradient distribution of solar radiation from north to south and border effects are strong, the radiation distribution varies with different densities and heights of PV panels [1]. Solar photovoltaic panels can generate electricity with no pollution. Biofuels are possible substitutes to alleviate the current fossil fuels tense situation [2]. Under the solar panels, daily air temperature and humidity are similar to the full sun treatments and light loss is not consequentially detrimental for crop production [3]. Solar panels can create intermittent shading, to some extend, they intercept a component of solar radiation for the crop. In the high-latitude countries, shading percentage will be greater during summer and autumn than spring and winter [4]. In previous studies, some schoolars tended to grow crops under solar panels and didn't consider optimizing the system based on crop growth and power generation [5]-[7]. In fact, there is a balance between the amount of electricity production and shading percentage which is depending on characteristics of PV panels, geography, plant species, meteorology and season [8]. In this paper, China's Zhangjiakou is choosen as the location. By means of the software Autodesk Ecotect Analysis on the oblique single-axis tracking AV system model, photosynthetically active radiation (PAR) and sunshine hour's distribution were analyzed in the effective growth period of crops. Based on solar radiation distribution and different sunlight demands of crops, ordinary sponge gourd is identified as one suitable crop species. In order to optimize the solar radiaition distribution for the selected crop variety and ensure enough output from power generation, an improved single axis tracking algorithm is proposed. When tracking the sun, solar panels can automatically increase or

reduce the shadow area according to light demand under this algorithm. Aslo, the effects were compared before and after algorithm improvement.

2. Oblique single-axis tracking system

2.1. *Location*
Zhangjiakou (41.1°N, 114.7°E) is in the north of China, the city's solar energy resource is very rich, geographical sunshine hours reach 2756 to 3062 hours, total solar radiation per square meter ranges from1500 to1700 kwh, belonging to the second type solar radiation area.

2.2. *Oblique single-axis tracking system*
Each PV panel is 2 meters long, 1 meters wide, 0.1 meters thick. The system is east-west oriented and faces towards the south. The distance between the north and south center of PV arrays is 6 meters, the distance between the east and west center of PV arrays is 3 meters. The height of solar panel center is 2.5 meters from the ground. The tilt angle of single-axis is 39 degrees. Every PV string has 9 tracking brackets which are east-west oriented. In this model, we set four rows of photovoltaic strings. The total area of photovoltaic panels is 72 square meters. As is shown in Fig. 1.
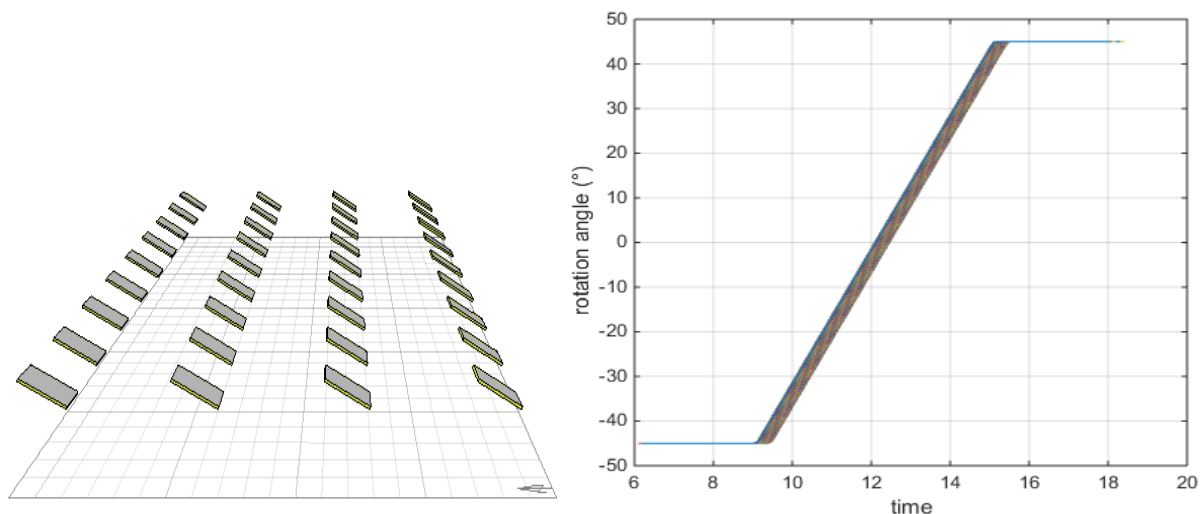

Figure 1. Oblique single-axis model   **Figure 2.** The rotation angel set during April 1 to October 31

In the case of an oblique single-axis tracking pattern, the rotation angle of the axis ε is taken at any time according to the trajectory of the sun's motion. In the PV module coordinate system, the position of the sun can be expressed in terms of the height angle and azimuth. When the incident angle of sunlight is the smallest, the amount of solar radiation received on the PV module is the largest. This is the optimizing track under the oblique single-axis system. The rotation angle ε can be expressed by the following equation [9].

$$\varepsilon = -\arctan(\sin\gamma / \tan\alpha) \tag{2-1}$$

Where α, γ are respectively the azimuth and elevation angle of the sun. Fig. 2 shows the optimal tracking path set from April 1 to October 31 for oblique single-axis tracking in this model. The photovoltaic panel rotates round oblique single-axis, ranging from -45° to 45°. A negative value indicates that the solar panel was rotated eastward and a positive value indicates that the solar panel was rotated westward.

2.3. *PAR and sunshine hours distribution*

PAR and sunshine hours have the most important effects on plant growth, this two factors can be set as the light environment index for solar radiation quantitative analysis. Use Autodesk Ecotect Analysis to build the oblique single-axis tracking agrivoltaic system described above. The effective growth period of crop is mainly concentrated on the period from April 1 to October 31 and the common sunshine time period is set from 7:30 to 17:30. Therefore, the model is mainly analyzed around this time period. Since the solar radiation distribution between two adjacent rows of PV strings is approximately symmetrical. The distribution of the area between the adjacent front and rear rows of PV strings can be substituted for other areas. Therefore, the analysis grid area in the model is 6 meters long and 26 meters wide. It is 0.2 meters above the ground, locating exactly between the second and third rows of photovoltaic panels. Set 30 nodes in the east-west direction and 20 nodes in the north-south direction. As the solar panels are not fixed, in order to simulate PAR and sunshine hour's distribution condition in this tracking system, a method of approximate processing is carried out. According to Fig. 2, during April 1 to October 31, every day from 9:30 to 10:30, the rotation angle can be considered as -35°. Every day from 10:30 to 11:30, the rotation angle can be considered as -20° and so on. Table 1 shows the rotation angle value of different time periods. The deviation is within 5 degrees.

Table 1. The rotation angle approximate value

Time	7:30-8:30	8:30-9:30	9:30-10:30	10:30-11:30	11:30-12:30
Angle	-45°	-45°	-35°	-20°	-5°
Time	12:30-13:30	13:30-14:30	14:30-15:30	15:30-16:30	16:30-17:30
Angle	10°	25°	40°	45°	45°

Through the above approximation, according to the different time period to set the corresponding angle of the photovoltaic panels. The simulation results of daily average PAR and sunshine hour's distribution are shown in Fig. 3 and Fig. 4.
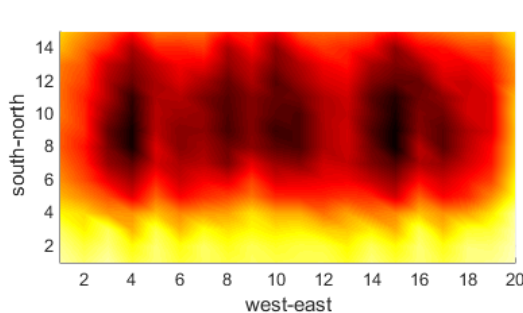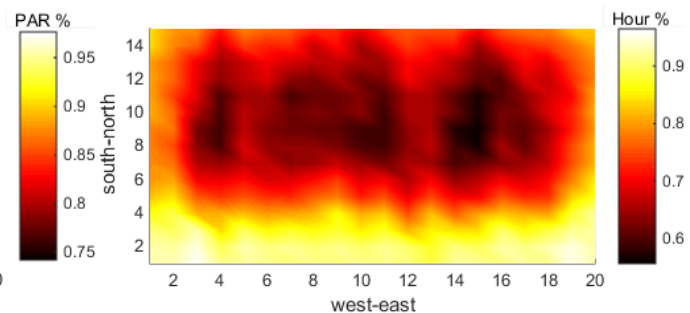

Figure 3. Par distribution   **Figure 4.** Sunshine hours distribution

In the analysis grid area, full sunshine PAR is 7.84 MJ/m^2·d, full sunshine hours is 10 h. PAR fluctuates between 5.82 MJ/m^2·d (741 μmol·m^{-2}·s^{-1}) and 7.66 MJ/m^2·d (984 μmol·m^{-2}·s^{-1}). Sunshine duration ranges from 5.6 hours to 9.6 hours. The two distributions are similar.

2.4. *Select the corresponding crop*

Different crops are characterized by their different light requirements. The majority of crops are strong light-demanding plants, the light saturation point (LSP) is an important indicator for crop growth. In order to ensure that crops can flower and produce fruit normally, the light adaption point (LAP) is defined as another indicator in our previous paper. From the experience of agricultural planting, we can know that, for melons and fruits, LAP is about 70% of LSP and for root vegetables and leafy vegetables, LAP is about 50% of LSP. Different crops have different time demand for solar radiation.

Sunshine duration is also a negligible indicator. By combining these indicators of crops and solar radiation distribution feature in the analysis area, then, the suitable crops can be determined. The relationship between the physical light intensity and photosynthetic intensity required by plants is shown in following formula [10].

$$1 \text{ MJ/m}^2 \cdot \text{d} = 127.79 \ \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \tag{2-2}$$

From literature research [11], for ordinary sponge gourd, LCP and LSP are respectively 0.21 MJ/m²·d (27 μmol·m⁻²·s⁻¹), 8.37 MJ/m²·d (1069 μmol·m⁻²·s⁻¹). Therefore, LAP is 5.85 MJ/m²·d (748 μmol·m⁻²·s⁻¹). It belongs to short daylight plant. Through the above analysis, ordinary sponge gourd can be planted in the area where PAR is between 5.82 MJ/m²·d and 8.37 MJ/m²·d and sunlight hours is between about 5.6 hours to 8 hours. That is, the red area in Fig. 3 and Fig. 4. In fact, when analyzing the light environment, the time interval is from 7: 30 to 17:30, the actual total sunshine time is longer than the simulation results in summer.

3. System Optimization

The daily solar radiation intensity changes with time approximately as a single peak curve, during the period before and after noon, the temperature is too high, the light intensity exceeds the light saturation point of plants and the photosynthesis of many plants will be inhibited. In AV system, the shadow caused by solar panels plays dual roles. On the one hand, PV panels can intercept excessive solar radiation. On anothor hand, the soil temperature in the shaded area will be lower than that of the unshielded.

However, the present AV system also reduces the amount of solar radiation in the morning and in the afternoon. These two time periods contribute very little to total power generation. Under this circumstances, the tracking algorithm can be adjusted to allow more light to be obtained in this two time periods. Fig.5 shows the optmization idea.
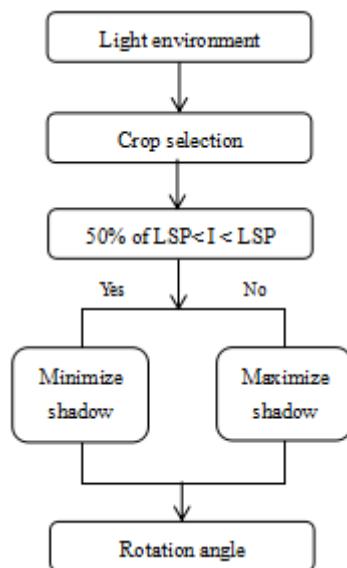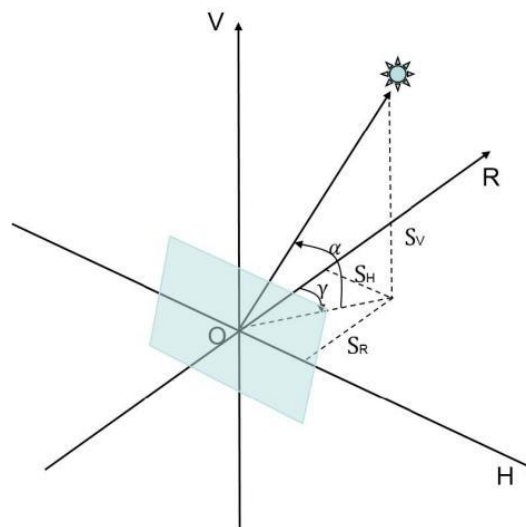

Figure 5. Optimizing idea   **Figure 6.** The PV module coordinate system

3.1. AV system optimization algorithm

Fig.6 shows the PV array coordinate system. For the PV module, the known rotation angle ε, in the PV module coordinate system, at some point, the normal vector of the PV module can be written as (3-1) and the sun vector is expressed as (3-2), where $S_V = \sin\alpha$, $S_H = \cos\alpha \cdot \sin\gamma$, $S_R = \cos\alpha \cdot \cos\gamma$.

$$\vec{v} = [0, -\sin\varepsilon, \cos\varepsilon] \tag{3-1}$$

$$\vec{S} = [S_V, S_H, S_R] \tag{3-2}$$

For single-axis tracking PV module, it has only one-degree-freedom and it is constrained by another angle. It can not always meet that ζ is equal to zero, that is, the sun position vector and the normal vector of PV modules are parallel. But at any time of each day, it is possible to obtain the optimum rotation angle. In the adjustable angle range, if ζ is the smallest at any time, the maximum PV production capacity will generate. When the angle of the sun position vector $\vec{S}$ and the PV module normal vector $\vec{v}$ is close to 90 degrees, solar panels have the smallest shadow area on the ground and obtain the minimum electricity production. Therefore, when the vector product of the sun position vector $\vec{S}$ and the PV module normal vector $\vec{v}$ is near zero, that is, ζ is close to 90°.

$$M = \vec{v} \cdot \vec{S} = -S_H \sin\varepsilon + S_V \cos\varepsilon \tag{3-3}$$

After simplification, the following formula is obtained, $\varphi = -\arctan(S_V / S_H)$

$$M = \sqrt{S_V^2 + S_H^2} \sin(\varepsilon + \varphi) \tag{3-4}$$

When M is zero or near zero, the following condition must be met.

$$\varepsilon - \arctan\frac{S_V}{S_H} = 0 \tag{3-5}$$

$$\varepsilon = \arctan(\tan\alpha / \sin\gamma) \tag{3-6}$$

When the rotation angle satisfies the above formula, we can achieve a minimum shading area at this moment. If the shading area is the largest, that is, at this moment the angle of the sun vector and the normal vector of the PV module is close to zero degree. Formula (2-1) describes the tracking algorithm at this time. It is also the basic optimizing tracking algorithm for the horizontal single-axis tracking mode or the oblique single-axis tracking mode. The light saturation points of different crops are different, when the light intensity is greater than the light saturation point of ordinary sponge gourd, the maximum shading tracing is performed at this time, that is, the best tracking power generation. So during the time period before and after noon, the best tracking can bring the maximum shade area, so as to reduce the soil temperature and light intensity. Otherwise, the crop photosynthesis will be inhibited. When light intensity is between 50% of LSP and 100% of LSP, light in this range plays a very important role on ordinary sponge gourd growth. If the best track is performed during this time period, it will result in the lack of high efficiency light energy for crop growth. Regarding this situation, it is a good choice to take the minimum shading track. In the earlier morning and later afternoon, the height of sun is very low, and the shadow projected on the ground are far away, so the shading area is very small. The optimizing track at this time can be conducted to increase the amount of power generation.

3.2. Algorithm implementation

Choose a day to implement the shaded area control algorithm, Fig.7 shows the total solar radiation curve received at the ground level in September 25th this day. From the figure we can see that during

7:30 to 17:10, the solar radiation intensity is greater than ordinary sponge gourd's LSP. Ordinary sponge gourd's LSP is 1069 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 50% of its LSP is 534.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Half of this crop's LSP approximately corresponds to 6:50 and 17:40. Consequently, before 6:50 and after 17:40, the system performs the optimizing tracking under the oblique single axis. For the two time periods from 6:50 to 7:30 and 17:10 to 17:40, the system performs minimum shading tracking. From 7:30 to 17:10, the system performs maximum shading tracing. Fig.8 shows the shading control algorithm for oblique single-axis tracking in September 25th. The yellow line indicates the height of the sun in time in the PV module coordinate system. The green line indicates the azimuth of the sun in time in the PV module coordinate system. The megenta line indicates the optimum rotation angle of the PV module over time in the PV module coordinate system.
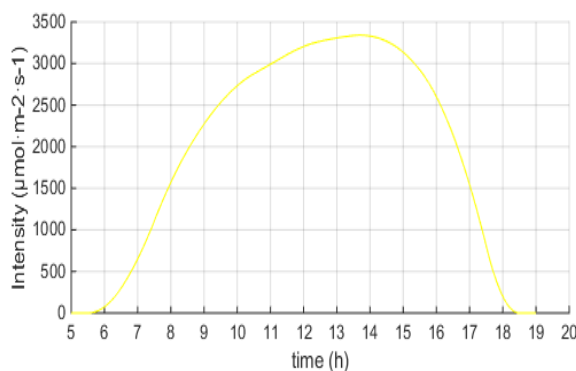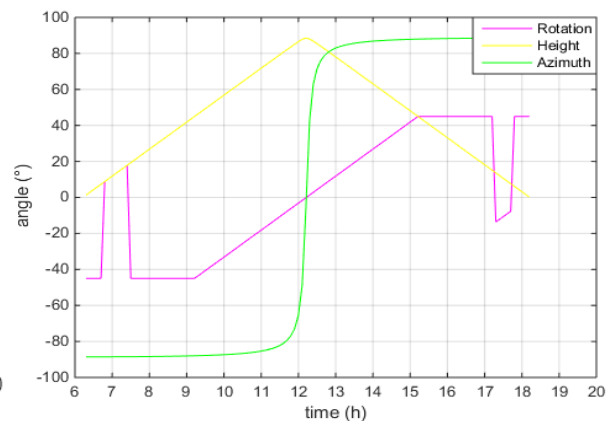

Figure 7. Solar radiation curve in September 25th   **Figure 8.** New shading control algorithm

3.3. *Optimized light environment*

Take a short time period to analyze the optimized solar radiation distribution effect. Choose one day from 7: 00 to 8: 00 in September as an example. Substract the unoptimized solar radiation distribution from the optimized one, the difference can be obtained. Figure 9 shows the PAR discrepancy under the two circumstances during this time period, Fig. 10 shows the sunshine hours distribution discrepancy. It is obvious that the two graphs have similar distribution. After optimization, in the bright yellow areaes, PAR increases by about 0.2 $MJ/m^2 \cdot d$ and sunshine hours increases for almost one hour.
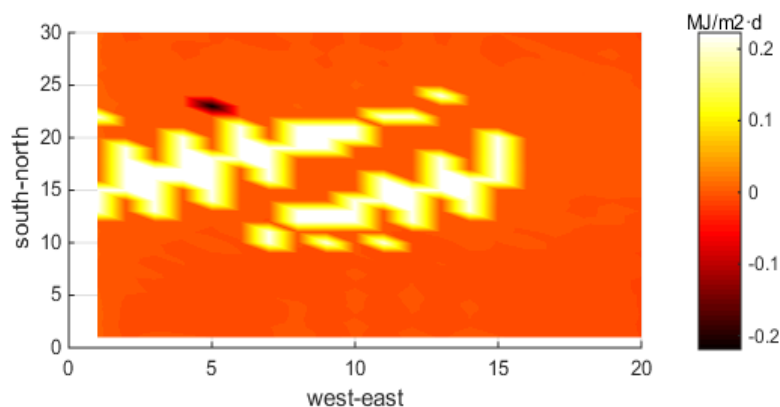

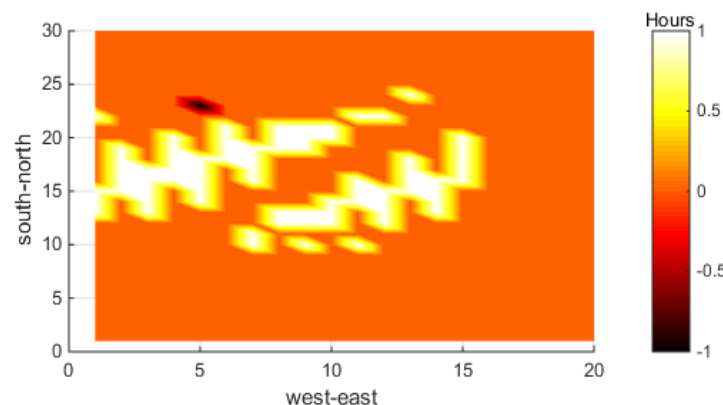**Figure 9.** PAR difference during 7:00 to 8:00

Figure 10. Sunshine hours difference during 7:00 to 8:00

4. Conclusion

By studying the tracking law of oblique single-axis AV system, it can be found that in the higher latitude, variations in rotation angle are approximately similar during every day of the growth period of plants. An approximate method is used to analyze the solar radiation distribution of this system. Daily mean distribution of PAR and sunshine hours have the same distribution rule. LAP and required solar radiation time length of crops can be regarded as two indexes to select the right crop. In order to optimize the solar radiation distribution for the specific crop, select 50% and 100% of LSP as references to improve the tracking algorithm. The new algorithm can adjust the shading area according to the reference points. When the solar radiation exceeds LSP or is less than 50% of LSP, the system can maximizes the shading area. Conversely, when the solar radis bation ietween 50% of LSP and LSP, the system can minimizes the shade area. At the same time, power generation is guaranteed. Futher research should be undertaken to investigate the optimal equilibrium point of the two.

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