Study on the optimum tilted angle of solar panels in Hainan tropical photovoltaic facility agricultural system

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Abstract. Photovoltaic facility agriculture system can effectively alleviate the contradiction between limited land and Photovoltaic power generation. It's flexible to create suitable environment for crop growth, and generate electricity over the same land at the same time. It's necessary to set appropriate solar panel angle to get more solar energy. Through detailed analysis and comparison, we chose the Hay's model as solar radiation model. Based on the official meteorological data got from Haikou Meteorological Bureau, and by comparing the amount of radiation obtained at different tilted angles per month, the optimal placement angle of PV panels at different seasons in Haikou was obtained through calculation, and the optimal placement angle from April to October was also obtained. Through optimized angle and arrangement of solar photovoltaic panels, we can get greater power efficiency.

1. Preface

PV facility agriculture system is a system which integrates solar photovoltaic power generation and modern high-tech planting. The system is supported by steel skeleton, and covered by solar photovoltaic panels, which ensures the solar photovoltaic power generation and lighting demands of the crops below at the same time. Reasonable inclination of solar panels can effectively improve the utilization rate of solar energy and increase the power generation efficiency. Hainan province is located in the tropics, the inclination angle of solar panels there is much different from that in mainland.

2. Factors affecting the inclination angle

2.1. Continuity

The total solar radiation in a year changes continuously, we can find out the total amount of radiation in each month from the meteorological data, the six consecutive months that have more horizontal radiation are called the summer half year, while the other six months called the winter half year. In the northern hemisphere, most of the summer months range from April to September, winter half year ranges from October to March in next year. The total amount of horizontal radiation in summer half year is always higher than that in winter half year [1].

2.2. Uniformity

In choosing the optimum titled angel, the reception of daily average radiation on the array should be uniform. That is, there should be little difference between summer half year and winter half year, which can avoid the waste of too much radiation in summer while the deficiency in winter[1].

2.3. Maximum

In choosing the optimum titled angel, the reception of daily average radiation on the array in winter half year should be maximum[1].

But these three practices are not necessarily applicable to Hainan.

3. Calculation of solar radiation

The total solar radiation on inclined plane surface called H_T consists of H_{bT} (direct solar radiation), H_{dT} (diffuse solar radiation from sky) , and H_{rT} (reflection radiation from the earth), that is,

$$H_T = H_{bT} + H_{dT} + H_{rT} \tag{1}$$

The relationship between H_{bT} and H_b (direct solar radiation from horizontal plane surface) is [1-4]:

$$H_{bT} = H_b \cdot R_b \tag{2}$$

$$R_b = \frac{\cos(\varphi-\beta)\cdot\cos\delta\cdot\sin\omega_{sT} + \frac{\pi}{180}\omega_{sT}\cdot\sin(\varphi-\beta)\cdot\sin\delta}{\cos\varphi\cdot\cos\delta\cdot\sin\omega_s + \frac{\pi}{180}\omega_s\cdot\sin\varphi\cdot\sin\delta} \tag{3}$$

In（3）， φ is local latitude， β is inclination angle，solar declination can approximately be：

$$\delta = 23.45\sin\left[\frac{360}{365}(284+n)\right] \tag{4}$$

The solar declination can be approximately expressed as,

$$\delta = 23.45\sin\left[\frac{360}{365}(284+n)\right] \tag{5}$$

Among them, *n* is the number of days counted from the New Year's day.

Horizontal sunset angle is[1-4]:

$$\omega_{sT} = \min\left\{\omega_s, \cos^{-1}\left[-\tan(\varphi-\beta)\cdot\tan\delta\right]\right\} \tag{6}$$

$$H_{dT} = H_d\left[\frac{H-H_d}{H_O}R_b + \frac{1}{2}(1+\cos\beta)\left(1-\frac{H-H_d}{H_O}\right)\right] \tag{7}$$

Among the above， H_d is diffuse solar radiation on the horizontal plane surface, H is total radiation on the horizontal plane surface, H_O is radiation on the horizontal plane surface outside the atmosphere which can be determined by the formula below[1-4]:

$$H_O = \frac{24}{\pi}I_{SC}\left[1+0.033\frac{360n}{365}\right]\left(\cos\varphi\cdot\cos\delta\cdot\sin\omega_s + \frac{\pi}{180}\omega_s\cdot\sin\varphi\cdot\sin\delta\right) \tag{8}$$

Among the above, I_{SC} is 1367W/m^2 called solar constant. The reflection radiation from the earth is：

$$H_{rT} = \frac{1}{2}\rho H(1-\cos\beta) \quad (9)$$

Among the above, ρ is called the ground reflectivity, normally $\rho = 0.2$.

Substituting (2), (7)and(9) into (1),we can get the formula for total solar radiation in the inclined plane surface：

$$H_T = H_b \cdot R_b + H_d\left[\frac{H-H_d}{H_O}R_b + \frac{1}{2}(1+\cos\beta)\left(1-\frac{H-H_d}{H_O}\right)\right] + \frac{1}{2}\rho H(1-\cos\beta) \quad (10)$$

If we know the data of the horizontal solar radiation in different months, we can calculate the amount of solar radiation on different slopes.

Table 1 is the amount of sunny days from April to October, 2014 in Haikou, Hainan Province. Table 2 is monthly total radiation from April to October based on the information from Haikou Meteorological Bureau. It can be calculated that the direct solar radiation and diffuse solar radiation in the horizontal plane surface from April to October,2014 in Haikou, Hainan Province according to table 2[5].

Table1. Amounts of Sunny Days from April to October

Month / Days / Weather	April	May	June	July	August	September	October
Sunny	21	19	19	22	18	21	17
Cloudy/Rainy	9	12	11	9	13	9	14

Table2. Solar Radiation in the Horizontal Plane Surface from April to October

Month / Radiation	April	May	June	July	August	September	October
Total Radiation （MJ/m^2）	423.5	540.3	508.5	628.7	526.1	448.7	381.4
Direct Solar Radiation （MJ/m^2）	251.98	281.48	273.74	379.25	259.66	266.98	177.78
Diffuse Solar Radiation （MJ/m^2）	171.52	258.82	234.76	249.45	266.44	181.72	203.62

As for Photovoltaic array, angle β normally changes from （$\varphi-5$） to （$\varphi+25$） every 5°, δ and ω_s can be calculated by those seven angels. The radiations on inclined plane surface at different angles are shown in Table 4.

Table 3. δ, ω_s and H_o

n	δ （degrees）	ω_s （degrees）	H_o （W/m^2）
April 3rd（93）	4.81	91.76	41294.60
May 15th（135）	18.79	97.11	60244.13
June 15th（166）	23.31	99.02	72631.88
July 15th（196）	21.52	98.25	83250.54
August 15th（227）	13.78	95.12	91477.41
September15th（258）	2.22	90.81	94199.37
October15th（288）	-9.6	86.47	90859.76

According to Table 4, in Haikou, the optimum titled angle of Photovoltaic array is 15°in summer half year and it is 25° in winter half year.

4. Conclusion

Through detailed analysis and comparison, we choose the Hay's model as the solar radiation model. The model has the advantages of simple expression and high accuracy.Based on meteorological data, and the official data got from Haikou Meteorological Bureau, according to different seasons, the optimal placement angle of PV panels in Haikou is obtained by calculation.

Table 4. Radiation （MJ/m^2） on Different Inclined Plane Surfaces in Haikou

Month \ Degree（°）	15	20	25	30	35	40	45
April	427.86	424.71	419.23	411.68	402.08	390.19	376.53
May	515.99	503.28	488.35	471.20	452.15	431.21	408.72
June	476.86	461.95	445.46	427.14	407.02	385.66	362.82
July	590.47	572.13	551.45	528.44	502.74	475.52	446.42
August	512.43	503.03	491.05	477.59	461.59	443.53	423.69
September	458.64	456.91	452.98	446.32	437.49	426.50	413.10
October	404.72	408.93	410.20	409.96	407.52	403.08	399.34

Photovoltaic facility agriculture system can effectively alleviate the contradiction between people and land, promoting economic and social sustainable development. It's flexible to create suitable environment for different crops to grow, and generate electricity to meet the agricultural demand. Through optimized arrangement of photovoltaic panels, we can get greater power efficiency. It can also be developed into a kind of sightseeing agriculture. All in all, photovoltaic facility agriculture system has important significance for supply-side structural reform of energy and agricultural industry.

Acknowledgments

Thanks for the funding of Hainan province natural science foundation (Grant Number 20165198).

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