Impacts of air pollution and meteorological conditions on the generation efficiency of photovoltaic system in Xi’an, China

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Abstract. In recent years, as a renewable resource, solar energy has been widely used and has bright prospects. Studies have shown that air pollution has a certain impact on photovoltaic power generation, but the quantitively influence of the impact factors is not clear. Though the analysis of experimental records of various air pollutants and meteorological factors, and calculation results of extinction coefficient and power generation efficiency, the main factors affecting photovoltaic power generation are determined quantitively.

1. Introduction

Solar energy, as a renewable new energy, has the advantages of clean, environmental-friendly and sustainable. It has become an important choice to deal with the problems like energy shortage, climate change, energy conservation and emission reduction. In regions with abundant solar energy resources in China, the average annual solar radiation can reach 5,850-6,680 MJm-2. At present, the utilization of solar energy in China mainly has two aspects: 1. Use the photothermal effect to convert solar radiant energy into heat energy; 2. Use the photovoltaic effect to convert solar energy into electric energy. In 2016, the Chinese National Energy Department proposed that during the 13th five-year plan period (2016~2020), the average annual growth rate of solar energy holdings will reach 16.8 percent. In terms of photovoltaic power generation, China has increased from 100,000 kW in 2007 to 77.42 million kW in 2016, an increase of more than 700 times, with an average annual growth rate of 103%. Solar energy, which has broad prospects of application, is highly concerned by all countries in energy domain. But in recent years, the study has found that the air pollution, especially the haze has great impact on the solar radiation because atmospheric aerosols will absorb and scatter solar radiation. Aerosol pollution made solar power generation capacity decrease 1.5 kWh per square meter a day in northern and eastern China, or as high as 35% (Li et al, 2017).

This study focuses on the influence of the efficiency of photovoltaic power generation in Xi’an, which is the largest and most developed city in northwest China. As one of the most polluted cities in China, the annual PM2.5 concentration of Xi’an is 62 μg m-3 in 2018, which is 77% higher than the WHO Period-I standard. When in the process of haze episodes, the combined action of pollutant emission and meteorological conditions lead to the diurnal variation of atmospheric extinction coefficient, and the solar radiation intensity decreased significantly compared with the clean weather (Song et al., 2013; Zhao et al., 2013; Tao et al., 2015).
In this study, hourly data of various meteorological and air pollution were recorded and normalized to analyze the correlation between the efficiency of photovoltaic power generation and various factors.

2. Principles and analysis

2.1. The influence of atmospheric aerosols on solar power generation
Solar radiation received at the earth's surface is attenuated by atmospheric conditions, primarily due to atmospheric scattering by air molecules, water vapour, and dust, and atmospheric absorption by ozone, water vapour, and carbon dioxide. At noon on a cloudless summer day, about 70 percent of the sun's radiation passes through the atmosphere directly to the earth's surface. Another 7% or so of solar radiation is scattered by atmospheric molecules and particles and eventually reaches the ground. The remaining is absorbed by the atmosphere or scattered back into space. Therefore, the solar radiation received is closely related to the concentration of atmospheric suspended aerosols and nitrogen dioxide, which will absorb and reflect sunlight. This phenomenon leads to the reduction of the power generation produced by photovoltaic power stations. Meanwhile, if haze events occur frequently and continuously, the amounts of fine particles on the surface of photovoltaic panel will keep accumulating and forming a dust layer that is difficult to clean. Dust accumulation on the surface of the panel will reflect, scatter and absorb solar radiation, reducing the solar transmittance, decreasing the solar radiation received by the panel and thus lessen the power generation produced by the photovoltaic system. In addition, the efficiency of photovoltaic panel will also be reduced by the warming effect of absorbing radiation of dust layer.

2.2. Experimental devices and principles
In this study, the main devices include photovoltaic panel (100W, MOGESOLAR), meteorological station (EDS AS-2000), actinometer (KIMO SL200), power meter, power source (220V), data logger and cement resistor. The study was implemented in an open terrain of the roof (5 meters high) in the Weishui campus of Chang’an university, which is located near the northern third ring road in Xi’an. The photovoltaic panel, power meter, data logger and cement resistor formed a closed loop to test the efficiency of photovoltaic system with the interval of 5 minutes from March 10th to 28th, 2019. Meanwhile, various meteorological data, such as temperature, wind speed, relative humidity (RH), wind direction and wind speed are measured by the meteorological station. The interval of meteorological data was also 5 minutes.

3. Data analysis

3.1. The calculation of extinction coefficient

\[ b_{ext} = b_{sp} + b_{ap} + b_{ag} + b_{sg} \]  

The revised IMPROVE chemical extinction equation (Pitchford et al., 2007) is:

\[ b_{ext} \approx 2.2 f_s (RH) \cdot [\text{Small Sulfate}] + 4.8 f_l (RH) \cdot [\text{Large Sulfate}] + 2.4 f_s (RH) \cdot [\text{Small Nitrate}] + 5.1 f_l (RH) \cdot [\text{Large Nitrate}] + 2.8 f_s [\text{Small Organic Mass}] + 6.1 f_l [\text{Large Organic Mass}] + 10 f_s [\text{Elemental Carbon}] + 1 f_s [\text{Soil Dust}] + 1.7 f_s [\text{Sea Salt}] + 0.6 [\text{Coarse Mass}] + \text{Rayleigh Scattering} + 0.33 [\text{NO}_2] \cdot (\text{ppb}) \]  

The Large and Small Sulfate in equation 2 indicate formation through dry and aqueous mechanisms and are defined by the IMPROVE equation as (Cao et al., 2010):
\[ \text{[Large Sulfate]} = \frac{[\text{Total Sulfate}]}{20}, \text{ for } [\text{Total Sulfate}] < 20 \mu g m^{-3} \]
\[ \text{[Large Sulfate]} = [\text{Total Sulfate}], \text{ for } [\text{Total Sulfate}] \geq 20 \mu g m^{-3} \]
\[ \text{[Small Sulfate]} = [\text{Total Sulfate}] - [\text{Large Sulfate}] \]

3.2. Normalization processing

Because of the diurnal variation of solar radiation, the effect of various air pollutants and meteorological factors on the efficiency of photovoltaic panel would change at different time. Therefore, it is necessary to normalize the data such as PM$_{2.5}$, PM$_{10}$, NO$_2$, O$_3$, RH, cloud extinction coefficient and the efficiency of photovoltaic system. Average each hour’s radiation proportion of several typical sunny days as the standard coefficient shown in Figure 1. The number of all meteorological and the concentration of air pollutants data are multiplied by the standard coefficient to obtain the valid normalized data.

![Figure 1. The diurnal variation of average solar radiation during the experiment.](image)

4. Result and discussion

The data of generation efficiency of photovoltaic system and some main influencing factors are shown in Table 1. The air quality during the monitoring period is often above the national standard, especially the PM2.5 concentration with an average of 42 $\mu$g/m$^3$. The persistent low-humidity condition during the monitoring period (<50%) would benefit the solar radiation and the generation efficiency of photovoltaic system.

| Time | PM2.5(μg/m$^3$) | PM10(μg/m$^3$) | Relative humidity(%) | Cloudage(%) | Power efficiency(%) |
|------|----------------|----------------|----------------------|-------------|---------------------|
| 3/10 | 46.0           | 113.0          | 54.53                | 77.17       | 3.71                |
| 3/11 | 26.4           | 78.3           | 21.06                | 87.45       | 34.59               |
| 3/12 | 33.1           | 82.1           | 22.13                | 35.85       | 39.35               |
| 3/13 | 38.8           | 84.8           | 24.08                | 95.63       | 15.20               |
| 3/14 | 27.4           | 56.1           | 15.24                | 74.06       | 38.28               |
| 3/15 | 33.1           | 83.6           | 16.83                | 78.97       | 28.01               |
| 3/16 | 56.9           | 118.8          | 24.66                | 32.73       | 27.15               |
| 3/17 | 59.4           | 124.2          | 35.67                | 95.00       | 14.56               |
| 3/18 | 27.3           | 63.4           | 19.19                | 0.55        | 42.24               |
| 3/19 | 38.3           | 102.6          | 39.10                | 95.00       | 4.17                |
| 3/20 | 35.7           | 90.6           | 19.20                | 21.67       | 9.99                |
Despite under the relatively low-humidity condition, the average efficiency of solar energy was only 24.2%, with a maximum efficiency of 42.2% and a minimum efficiency of 3.7%. It’s obvious that the day of maximum efficiency of electricity generating was accompanied with the lowest concentration of air pollutants during the monitoring period. While the day of minimum efficiency was accompanied with the PM pollution. It was found that the correlation coefficient between the PM$_{2.5}$ and extinction coefficient is as high as 0.80 (shown in Figure 2a), which indicated that the atmospheric particulate pollution would benefit the extinction of solar radiation directly and reduce the solar radiation on photovoltaic panel’s surface. Meanwhile, the correlation analysis also showed that the efficiency of photovoltaic system is dominated by the intensity of solar radiation with the correlation coefficient of 0.92, which is shown in Figure 2b. Besides, meteorological conditions, especially the RH and clouage were also significant factors affecting the generation efficiency of photovoltaic system. Compared with the above factors, the influence of NO$_2$, SO$_2$ and O$_3$ was negligible during the monitoring period in Xi’an.

| Date | PM$_{2.5}$ | PM$_{10}$ | SO$_2$ | NO$_2$ | O$_3$ |
|------|-----------|-----------|-------|--------|-------|
| 3/21 | 29.4      | 142.2     | 41.65 | 100.00 | 6.73  |
| 3/22 | 38.8      | 123.5     | 25.16 | 95.00  | 20.34 |
| 3/23 | 41.7      | 114.9     | 18.00 | 95.00  | 35.55 |
| 3/24 | 54.5      | 129.3     | 26.02 | 50.29  | 31.76 |
| 3/25 | 49.0      | 121.3     | 37.00 | 0.00   | 36.20 |
| 3/26 | 66.5      | 157.0     | 37.68 | 57.44  | 34.85 |
| 3/27 | 41.8      | 108.9     | 46.44 | 98.82  | 3.75  |
| 3/28 | 45.2      | 135.9     | 25.67 | 45.49  | 32.58 |

5. Conclusions
This study quantitively evaluates the influence of atmospheric pollutants such as PM$_{2.5}$, PM$_{10}$, NO$_2$ and O$_3$, and meteorological factors such as radiation, cloud cover and relative humidity on the generation efficiency of photovoltaic system in Xi’an. The clouage and relative humidity are the most important influencing factors and there are remarkable significant negative correlations between the two meteorological factors and the generation efficiency. The concentrations of PM$_{2.5}$ and PM$_{10}$ will determine the extinction coefficient and solar radiation directly, therefore PM pollution reduce the generation efficiency. The results of this study indicate that improving the air quality is of great
significance to the generation efficiency of the photovoltaic industry in Xi’an and even northwest China, where has the most abundant photovoltaic resources.

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