The Influence of Air Quality on Solar Irradiances in most Air Polluted months in China

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Abstract: Solar energy, as a kind of clean and sustainable energy, is widely used in most countries, and the number of PV generators is increasing year by year in China. The solar energy generation directly depends on the amount of solar irradiance, which is easily affected by atmosphere situation. With the rapid development of urbanization and industrialization, the atmosphere situation in China become worse and worse, and the air is always heavily polluted in recent years, which will reduce the irradiance getting to the ground. In order to analyze the effect of air quality on the solar irradiance, we analyze three kinds of solar irradiance Direct Normal Irradiance (DNI), Global Horizontal Irradiance (GHI), and Diffuse Irradiance (DIF). The influence of the Air Quality Index (AQI) on DNI, GHI, DIF are analyzed from November to February in the most air polluted months in recent four years for Beijing, Harbin, Shanghai and Guangzhou. The date when the AQI was the local maximum(minimum), DNI and GHI were the local minimum(maximum), and DIF was also the local maximum(minimum) are selected. The results shows that DNI and GHI decrease, and DIF increases with the increase of AQI. The six-order polynomial is used to fit the difference of the three irradiance and the difference of AQI. The average fitting coefficient R² for GHI is 0.8855, DNI is 0.8529 and DIF is 0.8466, and the highest R² for GHI is 0.9748, DNI is 0.9794 and DIF is 0.9820.

1. Introduction
With the rapid development of world economy, the traditional energy cannot meet the energy demand. The storages of traditional energy (coal, oil, natural gas, etc.) are decreasing day by day. The global energy crisis has appeared, and about 2 billion people cannot get the normal energy supply. At the same time, the overuse of traditional energy sources has damaged the global environments. Therefore, all the countries are looking for renewable energy sources.

Solar energy is an inexhaustible renewable energy. It has the characteristics of cleaness, safety, long life, abundant resources and good economic benefits, which are of great significance in the long-term energy strategy. From the 1980s, the variety of solar cells and the applications of solar energy have been expanding. In 2011, the new installed capacity of PV was about 27.5GW worldwide, and increased by 52% from 18.1GW in 2010. Nearly 20GW of the world's total installed capacity was installed in the
European market, but the growth rate was relatively slow. The growth mainly happened in Italy and Germany, accounting for 55% of the world's total growth. While the market demand in the Asia-Pacific region represented by China, India and Japan increased by 129%. By the end of 2015, the installed PV capacity reached 43 GW in China, and China became the most installed country in the world. According to the National Energy Administration, China's PV power generation reached 106.9 billion kwh from January to November in 2017, increased by 72% compared with the same period of 2016, and it was the first time for the annual PV power generation exceeding 100 billion kwh. 106.9 billion kwh of PV power generation can replace 33 million tons of standard coal, which could reduce carbon dioxide emission by 93 million tons.

The amount of Solar irradiance getting to the earth surface can easily be influenced by atmosphere situation. The factors such as atmospheric cloud thickness, water vapor, temperature, and air quality have direct and indirect effects on the arriving irradiance. As we know, there are always heavy air pollution in China in recent years, and the application of solar energy must be influenced by the air quality. Wang Xinran discovered that the effect of the air pollution on radiation budget and meteorological elements over Beijing was significant, and the effect of air pollution must be considered in fine weather forecast[1]. Qi Yue found the surface solar radiation in Eastern China, Central China and the part of North China decreased more sharply than the west of China. The distribution of aerosol optical depth was similar to the downward trend of solar radiation and the aerosol pollution played an important role in the decline of surface solar irradiance [2]. Several research teams analyzed the influences of atmospheric transparency on the incoming direct solar irradiance[3][4][5]. Zheng Hongfei found the attenuation of solar irradiance caused by the atmospheric pollution was 15%~30%, and more serious in winter than in summer[6]. In Chen Xiaobo’s research paper, the average solar irradiance decreased with the increase of PM2.5 concentrations and showed an exponential relationship with PM2.5 concentrations[7]. Shao Zhenyan found that the total surface irradiance decreased with the increase of PM10 concentration[8].

In this paper, the relations between the Air Quality Index (AQI) and three types of surface solar irradiance are analyzed. The AQI is determined by several main pollutants: fine particles (PM2.5), inhalable particulate matter (PM10), sulfur dioxide (SO2), nitrogen dioxide (NO), ozone (O3), and carbon monoxide (CO). AQI is divided into six categories, different categories represent different polluted levels and have different influence to people’s health. The details are shown in Table 1. The three types of surface irradiance are the global horizontal irradiance (GHI), the direct normal irradiance (DNI) and the diffuse irradiance (DIF), which will directly affect the photovoltaic and photothermal utilization of the solar energy. We analyze the influence of AQI on the three types of solar irradiance in four typical cities: Beijing, Harbin, Shanghai and Guangzhou. Beijing and Harbin are northern cities and always have the most serious air pollution. Shanghai is the most developed city in China and it is in the middle east. Guangzhou is a southern city and has light air pollution. This analysis is done from November to February in recent four consecutive years.

| Air Quality Index | Levels of Health Concern | Detail description |
|-------------------|--------------------------|--------------------|
| 0-50              | Good                     | Air quality is considered satisfactory, and air pollution poses little or no risk |
| 51-100            | Moderate                 | Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people. |
| 101-150           | Unhealthy for Sensitive Groups | People with lung disease, older adults and children are at a greater risk from exposure to ozone and from the presence of |
particles in the air.

| 151-200 | Unhealthy | Everyone may begin to experience some adverse health effects, and members of the sensitive groups may experience more serious effects. |
|---------|-----------|----------------------------------------------------------------------------------------------------------------------------------|
| 201-300 | Very Unhealthy | This would trigger a health alert signifying that everyone may experience more serious health effects. |
| 301-500 | Hazardous | This would trigger a health warnings of emergency conditions. The entire population is more likely to be affected. |

2. Data analysis

2.1 Analysis of solar irradiance and air pollution

In China, heavy air pollution always happens in winter. We analyze the winter’s situation. We took Beijing as an example, and analyzed the relationship between the solar irradiance (GHI, DNI and DIF) and the air pollution index AQI from November 2013 to February 2014. The irradiance data used in this paper are provided by China Meteorological Data Service Center, and the AQI data are from China National Environmental Monitoring Centre. Figure 1 to figure 4 show the changes of the four variations in November and December 2013 and in January and February 2014. The solid lines are their changes with the date, and the dotted lines are their linear fittings.

In November, as the linear trend of the air pollution index AQI gradually decreased, DIF also decreased, while DNI and GHI increased gradually. The same situation appeared in December. In January 2014, as the AQI increased, DNI and GHI went down, while DIF increased too. Figure 4 shows the same trend in February.

On November 3rd, 4th, 7th, 10th and 15th in Fig.1, on December 8th in Fig.2, on January 2nd, 3rd, 4th, 11th, 12th, 16th, 19th, 30th in Fig.3, and on February 3rd, 19th, 27th in Fig.4, When the air pollution index AQI was the local maximum (minimum), the corresponding DIF also was the local maximum (minimum), while the DNI and the GHI were the local minimum (maximum). The reason for this phenomenon is that when the air pollution become worse, there will be more air pollution particles and the diffuse irradiance component of the light becomes larger (that is, the DIF becomes larger) and the direct irradiance received by the ground will decrease. When the air quality becomes better (that is, the AQI becomes small), the diffuse irradiance component of the light is smaller (DIF becomes smaller), the direct irradiance value and the total amount of irradiance arriving at the ground become larger. Therefore, the amount of solar irradiance received by the ground is largely affected by the degree of air pollution.
Figure 1. The four variations (GHI, DNI, DIF and AQI) in Nov. 2013 in Beijing

Figure 2. The four variations (GHI, DNI, DIF and AQI) in Dec. 2013 in Beijing
Figure 3. The four variations (GHI, DNI, DIF and AQI) in Jan. 2014 in Beijing
2.2 Analysis of the influence of air pollution on solar irradiance

In order to make further study on the relationship between DIF, DNI, GHI and AQI, we chose typical extremum data for analysis. We chose the date when AQI was the local maximum(minimum), DNI and GHI were the local minimum(maximum), and DIF was also the local maximum(minimum). The reason for the selection is that the irradiances received by the ground are affected by a number of factors. When the irradiances and AQI are the extremum on the same day, the main factor may be the air quality. Table 2 gives the chosen data from November 2013 to February 2014 for Beijing. For instance, on November 3rd 2013, AQI was the local minimum, DIF was also the local minimum, while DNI and GHI were the local maximum, which could be seen in figure 1. On January 11th 2015, AQI was the local maximum, DIF was also the local maximum, while DNI and GHI were the local minimum, which could be seen in figure 3. The differences of GHI, DNI, DIF and AQI between two adjacent extreme points were calculated, then the relation of the differences of the three irradiances and the differences of AQI were fitted by the sixth-order polynomial, as showed in figure 5 to figure 7.

Table 2. The chosen date and data for Beijing from 2013.11 to 2014.2

| Year | Month | Date | GHI (W/m²) | DNI (W/m²) | DIF (W/m²) | AQI |
|------|-------|------|------------|------------|------------|-----|
| 2013 | 11    | 3    | 1063       | 2378       | 222        | 80  |
| 2013 | 11    | 4    | 974        | 2217       | 244        | 57  |
| 2013 | 11    | 7    | 986        | 2178       | 225        | 59  |
| 2013 | 11    | 10   | 1037       | 2431       | 196        | 53  |
| 2013 | 11    | 25   | 848        | 2081       | 173        | 59  |
| 2013 | 12    | 8    | 47         | 150        | 423        | 341 |
| 2014 | 1     | 2    | 404        | 938        | 313        | 117 |
| 2014 | 1     | 3    | 706        | 1857       | 213        | 80  |
Figure 5 shows the fitting curve for GHI difference and AQI difference. These two variables fitted well with the sixth-order polynomial fitting curve. The coefficient $R^2$ was used to evaluate the goodness of the fitting. The value of $R^2$ ranges from 0 to 1. The closer $R^2$ is to 1, the better the fitting is. On the contrary, the smaller the $R^2$ is, the worse the fitting is. In Figure 5, the $R^2$ is 0.84, which means that the observed data fit the fitting curve very well. The $R^2$ for DNI and AQI fitting is 0.8468 in Figure 6, and for DIF and AQI fitting is 0.9085 in Figure 7. The high $R^2$ values mean that the three types of solar irradiance were influenced by the air quality and had strong relationship between them when they were at extremums at the same time.

![Fitting curve](image_url)

Figure 5. The fitting curve of GHI difference and AQI difference from 2013/11 to 2014/2 for Beijing.

| Year | Month | Day | GHI Difference (W/m²) | AQI Difference |
|------|-------|-----|-----------------------|----------------|
| 2014 | 1     | 4   | 168                   | 434            |
| 2014 | 1     | 11  | 389                   | 985            |
| 2014 | 1     | 12  | 807                   | 1910           |
| 2014 | 1     | 16  | 160                   | 413            |
| 2014 | 1     | 19  | 105                   | 243            |
| 2014 | 1     | 30  | 915                   | 2168           |
| 2014 | 2     | 3   | 1085                  | 2412           |
| 2014 | 2     | 19  | 1104                  | 2118           |
| 2014 | 2     | 27  | 1373                  | 2674           |
We use the same method to analyze the data in winter of 2014, 2015 and 2016 for Beijing, and in winter of 2013, 2014, 2015, 2016 for other three cities Harbin, Shanghai and Guangzhou. The fitting coefficient $R^2$ values are showed in Table 3, Table 4 and Table 5. Most of the $R^2$ values are above 0.8. Therefore, whether in the northern cities Beijing and Harbin with heavy air pollution, or the middle and southern cities with lighter air pollution, the air quality really infects the irradiances amount getting to the ground. They have the strong relation which can be fitted by the polynomial.

Table 3. The goodness of fit in winter 2014, 2015 and 2016 for Beijing

| Year/Month | DIF difference with AQI difference | GHI difference with AQI difference | DNI difference with AQI difference |
|------------|------------------------------------|-----------------------------------|-----------------------------------|
| 2014/11-2015/2 | 0.8596                              | 0.81                              | 0.8375                            |
| 2015/11-2016/2 | 0.6836                              | 0.8574                            | 0.9214                            |
| 2016/11-2017/2 | 0.9252                              | 0.9748                            | 0.9794                            |
### Table 4. The goodness of fit in winter 2013, 2014, 2015 and 2016 for Harbin

| Year/Month       | $R^2$ | DIF difference with AQI difference | GHI difference with AQI difference | DNI difference with AQI difference |
|------------------|-------|------------------------------------|-----------------------------------|-----------------------------------|
| 2013/11-2014/2   | 0.8781| 0.8294                             | 0.9239                            |
| 2014/11-2015/2   | 0.9211| 0.8921                             | 0.9352                            |
| 2015/11-2016/2   | 0.6610| 0.8921                             | 0.9065                            |
| 2016/11-2017/2   | 0.9386| 0.9529                             | 0.9681                            |

### Table 5. The goodness of fit in winter 2013, 2014, 2015 and 2016 for Shanghai

| Year/Month       | $R^2$ | DIF difference with AQI difference | GHI difference with AQI difference | DNI difference with AQI difference |
|------------------|-------|------------------------------------|-----------------------------------|-----------------------------------|
| 2013/11-2014/2   | 0.7572| 0.9227                             | 0.8864                            |
| 2014/11-2015/2   | 0.8235| 0.7617                             | 0.8732                            |
| 2015/11-2016/2   | 0.9030| 0.9464                             | 0.9477                            |
| 2016/11-2017/2   | 0.8783| 0.8049                             | 0.8268                            |

### Table 6. The goodness of fit in winter 2013, 2014, 2015 and 2016 for Zhengzhou

| Year/Month       | $R^2$ | DIF difference with AQI difference | GHI difference with AQI difference | DNI difference with AQI difference |
|------------------|-------|------------------------------------|-----------------------------------|-----------------------------------|
| 2013/11-2014/2   | 0.6514| 0.9202                             | 0.8694                            |
| 2014/11-2015/2   | 0.8844| 0.8532                             | 0.8653                            |
| 2015/11-2016/2   | 0.8901| 0.9212                             | 0.9239                            |
| 2016/11-2017/2   | 0.9820| 0.9891                             | 0.9819                            |

### 3. Conclusions

In this paper, we made study on the influence of Air Quality Index on solar irradiance in the past four years’ most air polluted months. The amount of solar irradiance received by the ground is largely affected by the severity of atmospheric pollution. When the air pollution index decreases, the diffuse irradiance decreases, and the direct normal irradiance and global horizontal irradiance increase. When air quality index increases, the diffuse irradiance increases, and the direct normal irradiance and global horizontal irradiance decrease. In order to excluding the other influence factors, the data that reached the local extreme points at the same time were selected to analyze the relationship between the differences of solar irradiances and the differences of the AQI. It was found that the fitting correlation coefficients were very high and close to 1. Therefore, improvement of air quality can further improve the utilization of solar energy.

Now, the governments and all the people realize the importance of alleviating air pollution to human’s physical health, and we have taken many actions to improve the air quality, for example, closing heavy polluting enterprises and encouraging new energy use. The air quality is getting better slowly, but it is still not good enough. The task is still very hard. These measures not only improve atmospheric air quality, but also improve the use of clean energy, which will create a sustainable cycle.
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