Characteristics of surface solar radiation in Sino-Singapore Eco-city

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Abstract. Using solar observation and meteorological data of the Sino-Singapore Tianjin Eco-city from August 14\textsuperscript{th} 2014 to August 12\textsuperscript{th} 2015, characteristics of solar radiation of the eco-city and characteristics of solar radiation on a tilted surface under different weather conditions were analyzed and assessed. And the accuracy and error sources of isotropic and anisotropic calculation model for solar radiation on a tilted surface were studied. The results show that observed radiation on a horizontal and tilted surface is quite different at monthly, seasonal and annual time scales, so the estimated photovoltaic power generation based on the solar radiation on a horizontal surface is not accurate. Diurnal cycle of solar radiation is affected by different weather conditions and the power stations need to adjust generation strategies according to weather conditions. Accuracy of the two kinds of tilted radiation calculation models is similar and the overall calculation effect is reasonable. The uncertainty of the direct portion segment calculation function is the main cause of calculated errors.

1. Introduction

Sino-Singapore Tianjin Eco-city (eco-city for short, the same below) is located in the northern part of Binhai New Area. It is a major strategic cooperation project between China and Singapore governments to address global climate change, save resources and energy and build a harmonious society. Eco-city gives priority to develop renewable energy, and utilize wind, solar, geothermal and other green energy to reduce the impact of human activities on the environment. Solar energy is an important part of the eco-city construction for making full use of solar energy resources as a supplement to conventional energy sources [1-2]. Eco-city has completed 9.27 MW solar photovoltaic power stations and achieved parallel operation. Traditionally, photovoltaic power stations tilt solar panels to obtain more solar energy. However, the meteorological stations only carry out radiation observations on a horizontal surface, and the power stations are rarely equipped with tilted radiation observations consistent with solar panels inclination. Therefore, the effective radiation adopted by power plant in the actual operation needs to be calculated by the tilted radiation calculation models based on geometrical optics theory [3-14].

To assess solar energy resources in the eco-city, and to provide more accurate professional weather services and countermeasures for the photovoltaic power generation, Meteorological Bureau of Binhai New Area and Meteorological Bureau of Tianjin collaborate and launch experimental observation of eco-city solar energy resources, key prediction technology research of photovoltaic power generation,
assessment and services. In this paper, using eco-city solar observation experimental data, solar radiation characteristics and the impact of weather conditions on the solar radiation are analyzed in depth. Results and sources of error of solar radiation on a tilted surface calculated by different models are discussed as well.

2. Observation experiment and data processing

2.1. Site and equipment Introduction

Solar radiation stations are located in the eco-city sewage treatment plant roof surrounded by open space and there are no tall buildings and no white reflector around. Observation station equipped with two solar radiation sensors that one horizontal, one tilted (toward the south, inclination of 21.5°, the same as solar panels). Models are TBQ-2-B (Beijing Huantron Technology Co., Ltd), spectral range 300 ~ 3000 nm, the radiation range 0 ~ 2000 W / m², the degree of stability less than ±2%, cosine response ≤7% (when solar elevation angle of 10°), and sampling interval 1 min. To ensure the accuracy and consistency of the observed data, two sensors were calibrated and synchronized observation before install. During the observation, remove dust and wipe are periodically done to the sensor glass cover to avoid observational error caused by fouling.

2.2. Data processing and methods

2.2.1. Quality Control. Observation data used in this paper is solar irradiance on a horizontal and tilted surface for the period 14 August 2014 to 12 August 2015 by the hour from 9 to 16. Figure 1a shows scatter plot of irradiance on a horizontal and tilted surface. As a whole there is good agreement between the two, and most of the data points distribute in the vicinity of the fitting trend line. But there are still a fraction of data points deviated larger, so quality control to the observational data are needed.

Quality control methods used in this paper are that linear fit irradiance on a horizontal and tilted surface firstly, and then use fitting formula to calculate the corresponding tilted irradiance while the irradiance on a horizontal surface as independent variables. Furthermore difference between measured and calculated values and the mean range are given. Ultimately the difference 3 times greater than the mean range is eliminated. Figure 1b shows the scatter plot after quality control that it shows a very good agreement.

![Figure 1. Scatter plot of radiation on a horizontal and tilted surface before (a) and after (b) filtering.](image)

After the quality control, irradiance will be converted to radiation exposure hourly, the total cumulative radiation exposure from 9:00 to 16:00 act as Daily radiation exposure. And then the monthly average radiation, the seasonal radiation exposure and the annual radiation exposure are calculated. In order to reflect the physics regulation and seasonal characteristics of solar radiation better, vernal equinox, summer solstice, autumnal equinox and the winter solstice are used as
boundary nodes, namely spring form March 22 to June 22, Summer from June 23 to September 22, fall from September 23 to December 22, winter from December 23 to March 21.

2.2.2. Tilted solar radiation model. Solar radiation on a tilted surface include direct radiation, scattered radiation and reflected radiation which tilted surface received, wherein the calculation method of direct radiation and reflected radiation is relatively simple. But for scattered radiation, calculation model is different because of isotropic and anisotropic difference in the sky. One model used here is isotropic model Klein [9] proposed, another is anisotropic model Hay [10] proposed.

1) Isotropic model, the solar radiation on a tilted surface is calculated as follows

$$H_b = H_o R_o + \frac{(H - H_o)(1 + \cos \theta)}{2} + \frac{H \rho(1 - \cos \theta)}{2}$$

where $H_b$ is solar radiation on a tilted surface, $H_o$ is direct radiation on a horizontal surface, $R_o$ is ratio of direct radiation on a tilted surface to direct radiation on a horizontal surface, $H$ is solar radiation on a horizontal surface, $\theta$ is tilted angle, $\rho$ is ground reflectance. $R_o$ is calculated by

$$R_o = \left[ \left( \cos \theta \sin W \sin h \right) \frac{\pi}{180} (k_{ss} - k_{sr}) - \left( \sin W \cos h \sin \theta \cos V \right) \frac{\pi}{180} (k_{ss} - k_{sr}) + \right.$$ 

$$\left. \left( \cos h \cos W \cos \theta \right) \left( \sin k_{ss} - \sin k_{sr} \right) + \left( \cos W \cos V \sin h \sin \theta \right) \left( \sin k_{ss} - \sin k_{sr} \right) - \right.$$ 

$$\left. \left( \cos W \sin \theta \sin V \right) \left( \cos k_{ss} - \cos k_{sr} \right) \right]^{-1}$$

where $W$ is solar declination, $h$ is geographic latitude, $k_{sr}$ is sunrise hour angle on a tilted surface, $k_{ss}$ is sunset hour angle on a tilted surface, $V$ is azimuth on a tilted surface, $k_s$ is sunset hour angle on a horizontal surface. $k_{sr}$ and $k_{ss}$ are calculated by

$$k_{sr} = -\min \left\{ k_s \left( -\frac{a}{D} \right) + \sin^{-1}\left( \frac{c}{D} \right) \right\}$$

$$k_{ss} = \min \left\{ k_s \left( -\frac{a}{D} \right) + \sin^{-1}\left( \frac{c}{D} \right) \right\}$$

where $k_s = \cos^{-1}\left( \frac{1}{\tan h \tan W} \right)$, $a = \sin W \left( \sin h \cos \theta - \cos h \sin \theta \cos V \right)$, $b = \cos W \left( \cos h \cos \theta + \sin h \sin \theta \cos V \right)$, $c = \cos W \sin \theta \sin V$, $D = \left( b^2 + c^2 \right)^{1/2}$,

$W = 23.45 \times \sin(360 \times \frac{284 + d}{365})$, $d$ is the number of calendar days of the date from January 1.

2) Anisotropic model, the tilted solar radiation is calculated as follows

$$H_b = H_o R_o + \frac{H \rho(1 - \cos \theta)}{2} + \left( \frac{H - H_o}{H_o} \right) \left[ R_o \left( \frac{1 - H_o}{H_o} \right) \left( 1 + \cos \theta \right) \right]$$

where $H_o$ is astronomical radiation in the top of the atmosphere.

Using the measured data of tilted surface of eco-city, the accuracy of two models is assessed. But radiation on a horizontal surface needs to be "direct-diffuse separation" due to the lack of observations of direct radiation and diffuse radiation. So the "direct ratio" method Erbs [15] proposed is used to achieve "direct-diffuse separation" of the total radiation.
3) "direct-diffuse separation" method

Direct ratio is defined as the proportion of direct radiation in the total radiation, which is calculated as follows

\[ A = \frac{H_b}{H} \]  \hspace{1cm} (6)

where \( A \) is direct ratio. Direct ratio can represent atmospheric transparency coefficient. And the atmospheric transparency coefficient refers to the ratio of the observed total radiation and astronomical radiation in the top of the atmosphere. Its relationship with the direct ratio as follows

\[
\begin{align*}
A &= a_0 k_T & k_T < b_0 \\
A &= c_0 + c_1 k_T - c_2 k_T + c_3 k_T^2 - c_4 k_T^4 & b_0 \leq k_T \leq b_1 \\
A &= a_1 & k_T > b_1
\end{align*}
\]  \hspace{1cm} (7)

where \( k_T \) is atmospheric transparency coefficient, \( a_0, a_1, c_0 - c_4 \) are fitting coefficients of regression equations, dimensionless, \( a_0 = 0.09, a_1 = 0.835, c_0 = 0.0489, c_1 = 0.1604, c_2 = 4.388, c_3 = 16.638, c_4 = 12.366 \), \( b_0, b_1 \) are divided interval coefficients of subsection simulation curve, dimensionless, \( b_0 = 0.22, b_1 = 0.80 \).

3. Results and analysis

3.1. Characteristics of the solar radiation eco-city

Figure 2 presents the seasonal cycle of radiation on a horizontal and tilted surface in eco-city. It indicates that radiation on a horizontal and tilted surface both feature unimodal distribution: the maximum radiation appears in May, and the minimum radiation occurs in January. Both radiations on a horizontal and tilted surface are relative deficit in June, which is possible as the relative humidity is relative high during this season. The radiation on a horizontal and tilted surface is equal in March and October; from April to September, however, the solar radiation is higher than radiation on a tilted surface. The radiation on a tilted surface is higher than that on a horizontal surface for the rest months. Therefore, using observed total radiation on a horizontal surface to evaluate monthly power generation is not accurate. In addition, the annual mean total radiation on a horizontal surface exceeds the total radiation on a tilted surface by 124.2 MJ m\(^{-2}\) (Table 1). Seasonally, the total radiation reaches peak in spring, and then declines in summer; it continues to decrease in autumn and with slight increase in winter. It suggests that the total radiation on a horizontal surface is higher than radiation on a tilted surface in spring and summer, and vice versa. Taken together, there is large discrepancy between observed radiation on a horizontal and tilted surface on monthly, seasonal and annual time scales. Using observed radiation on a horizontal and tilted surface to evaluate and estimate the monthly, seasonal and annual power generation will result in ineligible bias. Therefore, in order to accurately assess the solar resource and photovoltaic power generation, we suggest to conduct the radiation observation on a tilted surface parallel to the solar panel for at least one year.

| Year    | Radiant exposure on a horizontal surface( MJ·m\(^{-2}\)) | Radiant exposure on a tilted surface( MJ·m\(^{-2}\)) |
|---------|--------------------------------------------------------|---------------------------------------------------|
| Year    | 5142.0                                                 | 5017.8                                            |
| Spring  | 1744.5                                                 | 1540.1                                            |
| Summer  | 1536.4                                                 | 1337.8                                            |
| Autumn  | 849.0                                                  | 968.7                                             |
| Winter  | 906.0                                                  | 1064.4                                            |
Figure 2. Changes of radiation on a horizontal and tilted surface across the year in eco-city.

Curves in Figure 3 show the diurnal variations of irradiance on a tilted surface on sunny, partly cloudy, cloudy, overcast and rainy days. Sunny day indicates day with no special weather phenomenon, less than thirty percent of daily average total cloud cover, greater than 15 km visibility. Thirty to fifty, sixty to ninety, and greater than ninety percents of daily average total cloud cover signify partly cloudy, cloudy, overcast sky, correspondingly. Rainy day is defined when there is persistent rainfall. It can be found that, on the sunny and partly cloudy days, the irradiance are maintained at a higher level throughout the day with the maximum value at 12 pm and minimum value at 16 pm. The diurnal curve of the irradiance is just like a parabola, which means sufficient solar radiation and large utilization rate because of the small impact to the grid during grid-connected power generation. Under the cloudy and overcast sky, the irradiance is small than it under the sunny and cloudy conditions and its curve is like a zigzag pattern with large fluctuation. In this case, grid-connected power generation has significant impact on the grid. There is smallest irradiance (small than 200 W/m²) on the rainy day without diurnal cycle. It indicates that utilization rate of solar energy is low. The power station needs to adjust the power supply plan and carry out the maintenance of power grids. In a word, the diurnal variation of the solar radiation has certain randomness and volatility. These features have an effect on the stability of power system. Therefore, the power generation plan needs to be adjusted according to different weather conditions in time. Plans of conventional energy generation and photovoltaic power generation also need to be made. Reduce standby rotation capacity, keep the power system stability, and reduce the waste of resources.

Figure 3. Diurnal cycle of radiation on a tilted surface in eco-city under typical weather conditions.

3.2. Assessment of the tilted solar radiation calculation models
The former analyses suggest that there is discrepancy between radiation on a horizontal and tilted surface on monthly, seasonal and annual time scales, and that it is more reasonable to evaluate power generation using radiation on a tilted surface. Before the power station was founded, however, long-term radiation observation on a tilted surface was lacking in the evaluation of solar radiation and
power generation. Previous evaluations were carried out via combining the solar radiation on a horizontal surface from local meteorological institutes with isotropic or anisotropic tilted radiation calculation models. The evaluations using this approach rely on the accuracy of the two models. This study analyzes one-year observations of total radiation on a horizontal and tilted surface in Eco-city, evaluates the accuracy of the two models, and explores the possible causes of errors.

Table 2 presents the correlation coefficients, mean deviation, root mean square error [16-19], and t-statistic [20] between the calculated radiations on a tilted surface from two models and observed radiations. It suggests that the two models have similar correlation coefficients and root mean square error, but the anisotropic model features smaller absolute value of mean deviation and t-statistic. The implication is that the overall effects of the two models are equal, while the anisotropic model shows higher accuracy. Compared with observations, however, both models present large error (Figure 4). For the anisotropic model, although the relative error of 90% results are less than 30%, the partition of results which show less than 10% relative error is only 28%. In addition, 10% results present more than 30% relative error. For the calculated values based on statistics, the absolute difference ranges from -271 W/m² to 137 W/m².

Table 2. Statistical analysis of tilted radiation calculated values in two models.

|                | Correlation coefficient | Mean variation(W·m⁻²) | root-mean-square error (W·m⁻²) | t-statistics |
|----------------|-------------------------|------------------------|-------------------------------|--------------|
| Isotropic model | 0.96                    | -1.63                  | 77.45                         | 1.09         |
| Anisotropic model | 0.96                   | -0.05                  | 77.61                         | 0.04         |

Figure 4. Relative error of the isotropic calculation model (white column) and anisotropic calculation model (black column).

Now we explore the causes of errors in the models, and propose methods to improve the models. This study employs the concept of direct ratio to “direct-diffuse separation” of total radiation on a horizontal surface. As the direct radiation and scatter radiation are not available, we follow Erbs [15] to calculate direct ratio based on the empirical equation of direct ratio and coefficient of atmospheric transmission, and fitted empirical coefficient. The universality and accuracy of this method need further test due to following reasons: (1) the method itself is a conceptual model based on statistical theory; (2) the data sample is small; (3) the time period is short. Table 3 shows the calculated error of the anisotropic model in different seasons and under different atmospheric transmission. It indicates that when 𝑘𝑇 is smaller than 0.22, the coefficients among the four seasons is higher than 0.99, while the mean deviation, root mean square error and t-statistic are smallest when 𝑘𝑇 is larger than 0.22, suggesting that the accuracy of the model is very high, and the empirical equation of direct ratio is universal. When 𝑘𝑇 is between 0.22 and 0.8, the correlation coefficients for all seasons decline, and the root mean square error is 80 W/m². Note that the squared error in spring and summer is opposite to that in autumn and winter: spring and summer present positive deviation, indicating that the model overestimates the radiation during these seasons; autumn and winter present negative deviation,
indicating that the model underestimate the radiation in these seasons. Therefore, the universality of the model is poor when \( k_T \) is between 0.22 and 0.8. To achieve calculated results with higher accuracy, we need to correct the parameters of the direct ratio calculation models for each season. The situation when \( k_T \) is higher than 0.8 is similar to that when \( k_T \) is between 0.22 and 0.8. Also, when \( k_T \) is higher than 0.8, the mean deviation and root mean square error in autumn and winter is higher than other conditions. Taken together, the direct portion segment calculation function and its coefficients in our calculation model are not universal and accurate for different seasons and atmospheric transmission. In the practical application of power stations, it is suggested to assess the universality of the calculation models besides conducting the radiation observation on a horizontal and tilted surface. In addition, adjustments and corrections of calculation coefficients are needed to gain more accurate calculated results of radiation on a tilted surface.

### Table 3. Statistical analysis of anisotropic calculation model under different conditions.

| Season      | Range of \( k_T \) | Correlation coefficient | Mean variation (W m\(^{-2}\)) | Root-mean-square error (W m\(^{-2}\)) | \( t \)-statistics |
|-------------|---------------------|--------------------------|---------------------------------|---------------------------------------|-------------------|
| Spring      | <0.22               | 0.99                     | 19.21                           | 21.85                                 | 16.72             |
|             | 0.22~0.8            | 0.98                     | 68.95                           | 79.09                                 | 35.22             |
|             | >0.8                | 0.93                     | 55.04                           | 67.45                                 | 17.18             |
|             | <0.22               | 0.99                     | 20.59                           | 22.47                                 | 21.36             |
| Summer      | 0.22~0.8            | 0.99                     | 69.39                           | 75.11                                 | 50.28             |
|             | >0.8                | 0.92                     | 46.20                           | 62.53                                 | 12.11             |
|             | <0.22               | 0.99                     | 15.93                           | 17.41                                 | 20.15             |
| Autumn      | 0.22~0.8            | 0.96                     | -54.15                          | 83.26                                 | 20.12             |
|             | >0.8                | 0.95                     | -116.04                         | 125.57                                | 19.04             |
|             | <0.22               | 0.99                     | 14.52                           | 15.96                                 | 15.04             |
| Winter      | 0.22~0.8            | 0.94                     | -56.97                          | 86.12                                 | 20.42             |
|             | >0.8                | 0.98                     | -98.65                          | 102.78                                | 30.59             |

### 4. Conclusion

Using solar observation and meteorological data over the Sino-Singapore Tianjin Eco-city from 14 August 2014 to 12 August 2015, this study summarizes the characteristics of solar radiation on a horizontal and tilted surface, and explores the tilted radiation calculation models. The conclusions include:

a. Discrepancy between solar radiation on a horizontal and tilted surface in eco-city exists on monthly, seasonal and annual time scales. The radiation observation on a horizontal surface is not accurate enough to evaluate solar resources, and we suggest to conduct radiation observation on a tilted surface parallel to solar panel for at least one year.

b. The characteristics of solar radiation differ under various synoptic conditions. It is suggested to adjust power generation strategies in response to different weathers, especially for cloudy weather which are attributable to the irregularity and instability of power generation.

c. The accuracy of the two radiation calculation models is equivalent, and the calculation effects are acceptable. Error, however, still exists. The universality of the empirical equation of direct radiation ratio and correlation coefficients needs improvement. Besides conducting solar radiation observations on a horizontal and tilted surface, we suggest to assess the universality of tilted calculation models during the practical applications of power stations, and adjust and correct calculation coefficients based on realistic situations.

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