IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

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IOP Conf. Series: Earth and Environmental Science **585** (2020) 012012 doi:10.1088/1755-1315/585/1/012012

A method for predicting the solar photovoltaic (PV) potential in China

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Abstract: A reliable assessment of energy efficiency for photovoltaic system is of importance for the solar energy policy planning and industrial development. Despite extensive advances over past years, almost all economic analyses overlooked the effect of local environment on the photoelectric conversion efficiency of solar cells, therefore leading to a non-negligible error in the prediction of photovoltaic potential. In this work, we developed a unified model to evaluate the regional economics of photovoltaic system by incorporating the heat transfer in solar cell and associated environmental influences. This model significantly improves the prediction accuracy of photovoltaic potential by establishing a correlation between the regional meteorological data and solar energy generation. In particular, with a meteorological data reduction, we dramatically decrease the computational complexity for predicting the photovoltaic potential. Through a theoretical analysis with the unified model, we demonstrate that the existing price mechanism of PV electricity in China cannot fully eliminate the economic disparities in various areas owing to the neglect of environmental effect. This work not only offers new insight into the research of solar resource and related policy making, but also provides guidelines for the further development of solar power industry.

1. Introduction

As one of the most competitive renewable resources, the solar energy has the advantages of inexhaustible and environment friendly. The International Energy Agency predicts that the solar photovoltaic (PV) power generation will become the primary energy source, which accounts for 20 ~ 50% of the global power generation by 2050 [1]. As one of the countries with the highest solar potential, annual solar irradiation in China ranges from 1,000 kWh/m^2 to over 2,000 kWh/m^2 [2]. China increased more than 10.6 GW capacity and generated about 25 billion kWh of electricity from solar PV in 2014 [3, 4]. In 2015, with 77 GW in the installed solar photovoltaic capacity, by far the world's largest, China has been eager to stimulate the PV energy consumption instead of the device manufacturing[5]. In recent years, the Chinese government has rolled out policies concerning PV consumer (e.g., solar power stations and domestic PV users), in the hope to quickly expand the domestic market and balance between the consumption and production of the PV industry. However, owing to neglecting the environmental effects in the economic analysis, the present solar energy policy did not completely solve the complex financing problems with the risks in the access to power grids and uncertainties estimation in profitability in different regions of China [6]. Therefore, a reliable prediction technology of regional solar potential is desirable for future national energy planning and solar industry development.

Over the past decade, various theoretical models have been developed to estimate the real-time energy performance of photovoltaic device. In 1999, Hammer, et al. [7]first showed that the prediction accuracy of solar power generation was dramatically improved by introducing the meteorological data in the calculations. Similarly, Atsushi Y, et al. [8] developed a model to estimate the output power of photovoltaic array using the solar irradiation intensity. In recent years, based on the theoretical study of Mayer [9], the Munich Trade Fair Center established a forecasting system to precisely predict the real-time solar power output with the inversion data of satellite remote sensing. While, to date models can be directly applied in the regional economic analysis due to the complicated computation process with real-time weather data, especially in the calculation of PV potential in a large area [10].

In this work, we establish a theoretical modeling framework to investigate the environmental influence and associated thermal effects on the PV system. By studying the dependence of operating performance on environmental factors, we demonstrate that the data reduction of real-time meteorological statistics can significantly decrease the computational complexity without affecting the prediction accuracy of solar energy output. Particularly, by introducing a correlation between the solar energy conversion efficiency and averages of meteorological variables, we develop a unified prediction model compatible for the regional PV economic analysis. The unified model is further adopted to calculate the annual electricity generation in four representative regions of China (Zhangye, Sanya, Haikou and Beijing) within three price ranges. The results indicate that the current forecasting method based only on different regional solar resources in China causes a non-negligible error for estimating the PV potential. Therefore, the associated Chinese subsidy policy of PV power plant cannot completely balance the economic benefit due to the prediction inaccuracy. The outcome of our work not only provides a practical and accurate predicting method for regional economic analysis of solar industries, but also sheds new light on the solar energy policy formulation in China and other countries.

2. Existing issues in prediction of regional PV potential

In previous studies of forecasting the solar cell performance, various researchers demonstrated that the environment conditions considerably affected the operation of solar PV power generation system. To obtain an accurate prediction of solar energy efficiency, the meteorological data must be included in the model. Some classical theoretical models for calculating the PV efficiency are listed in Table 1. In 1986, Osterwald [11] and Green [12] developed a simple forecasting model without considering the environmental influences on the PV energy conversion. This theoretical model was usually used in the 1990s due to the lower computation cost, yet it inevitably resulted in a large error for predicting the associated regional PV potential. By taking into account the solar irradiation intensity in the model derivation, Yona [8] and Knowe [13] dramatically improved the calculation accuracy of PV power output. From 2000 to 2010, their model was widely adopted to estimate the real-time energy performance of small and medium PV power stations. In addition, Hammer [7] and Lorenz [14] provided a more accurate prediction model for the solar PV power system, yet this method has not been widely applied due to the excessive number of parameters in the model and the complicated computing process.

Table 1. models for photovoltaic power generation forecasting
(For the variables and parameters in the model, see the related references)

Method	*Models*	*Characteristics*
Osterwald [11]	$P = P_{m,STC} \dfrac{G}{G_{STC}} \left[1-\gamma\left(T_c - 25\right)\right]$	• *Environmental effects are excluded* • *Poor accuracy*

Green [12]	$P = P_m N_{mp} N_{cp} N_{ms} N_{cs}$	
Knowe [13]	$P = I \times E_f \left(A_p\right)$	• *Environmental effects are included* • *Computationally expensive* • *Improved accuracy*
Yona [8]	$P = \eta SI\left[1-\beta\left(T_c - 293\right)\right]$	
Hammer [7]	$P = c\sum_{i=1}^{V} G_{clear}\left(\vec{x_i}\right)\left(1-n\left(\vec{x_i}\right)\right)$	• *Computationally expensive* • *Abundant weather data* • *Highest accuracy*
Lorenz [14]	$P = \frac{\eta_{MPP}\left(I_t, T_m\right)}{\eta_{STC}} \times \frac{1}{1000\mathrm{W/m^2}} P_{nom}$	

To ensure the prediction accuracy, the theoretical models shown in Table. 1 require real-time meteorological datas to compute the solar power generation. Because of the difficulty in collecting the regional meteorological statistics, these models are limited to calculate the energy performance of individual solar power station located in a certain region. For assessing the PV potential across a wide area, however, the economic analysis still uses an inaccurate method to evaluate the annual electricity generation of PV system (e.g., 1,500kWh as an average electricity generation in one year), which ignored the environmental effect in energy conversion [15].

3. Environment-dependent photoelectric conversion

To reveal the dependence of various environment factors on the prediction of solar power generation, here we develop a unified modeling framework to precisely calculate the energy output of photovoltaic system by incorporating the varying environment conditions and associated thermal effect on a PV module. Generally, the power generation of solar cell is governed by the solar irradiation absorption and the temperature of PV panels. According to the energy balance in the photoelectric conversion process (thermal conduction and installation angle of the PV module are not considered), the temperature variations of one PV panel is given by,

$$\rho\delta C\frac{\mathrm{d}T_\mathrm{p}}{\mathrm{d}t} = G\alpha - P + (h_\mathrm{w} + h_\mathrm{r})(T_\mathrm{a} - T_\mathrm{p}) \quad \textbf{(1)}$$

where G is the solar irradiation intensity, t is the irradiation time. ρ, δ, C, α and T_p denote the density, thickness, specific heat capacity, absorptivity and temperature of the PV panel, respectively. In this work, ρ = 2,702 kg/m^3, δ = 0.002m, C = 903 J/(kg·k), α = 0.8. P is the electrical power generated from the PV panel, T_a is the temperature of ambient environment, h_w is the convective heat transfer coefficient at the exterior PV panel surface, and h_r is the overall irradiation heat transfer coefficient of the entire photovoltaic panel.

Since the instantaneous electrical conversion efficiency of the solar cell η highly depends on the temperature of the PV panel T_p, the power output P will decrease with the ascending temperature of PV panel [8, 16],

$$P = G\eta\left(T_\mathrm{p}\right) = G\eta_\mathrm{e}\left[1-\beta\left(T_\mathrm{p} - 293\right)\right] \quad \textbf{(2)}$$

where η_e is the electrical conversion efficiency at the reference temperature 293K, and β is the temperature coefficient of the solar cell, β = 0.0045.

The heat transfer coefficients associated with the external convection h_w and irradiation h_r of the PV panel can be calculated as [16, 17],

$$h_w = 3.8u + 5.7 \tag{3}$$

$$h_r = \varepsilon\sigma\left(T_p^2 + T_a^2\right)\left(T_p + T_a\right) \tag{4}$$

where u is the ambient wind velocity, ε is emissivity of the PV panel and ε = 0.8, σ is the Steve-Boltzmann's constant.

Integrating the generated power on the PV module, the total electricity generation Q is given,

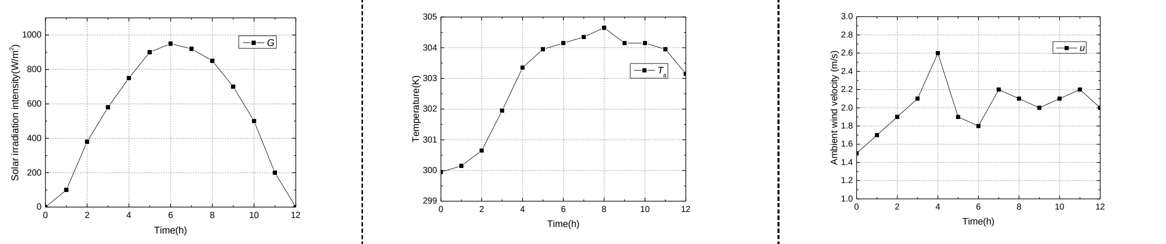
$$Q = \int_0^{t_r} P\mathrm{d}t = \int_0^{t_r} G\eta(T_p)\mathrm{d}t \tag{5}$$

where t_r is the duration time of irradiation. The equation (1) to (5) provides an accurate modeling framework to predict the operating curve of the PV system. A mass of real-time meteorological statistic, such as irradiation intensity, ambient temperature and wind velocity, must be collected for calculating the generated electricity Q as shown in equation (5). However, the difficulty in meteorological data acquisition greatly limits the application of such modeling framework in national economic analysis. Therefore, it is imperative to further simplify the model and reduce its dependence on real-time meteorological data.

4. Effects of meteorological variables

For analyzing the effects of the meteorological variables, an actual scenario of PV module operation was calculated with the real-time meteorological data as the benchmark. Figure 1a-c show the time evolution of solar irradiation intensity G, ambient temperature T_a, and wind velocity u in Hong Kong (data obtained from the Hong Kong Observatory, 04/09/2015). Compare to the result calculated by the ideal efficiency of the PV cell (Q = 1.035 kWh/m^2), the actual energy generation (Q = 0.723kWh/m^2) is 30% lower with considering the meteorological variable. This gap is especially relevant in the price sensitive market of PVs, where only few percent of PV energy output can render a project possible or uneconomical [18, 19].

The distinct degradation of solar energy conversion in actual scenario indicates that the environment effects cannot be neglected in the economic analysis and national policy formulation.

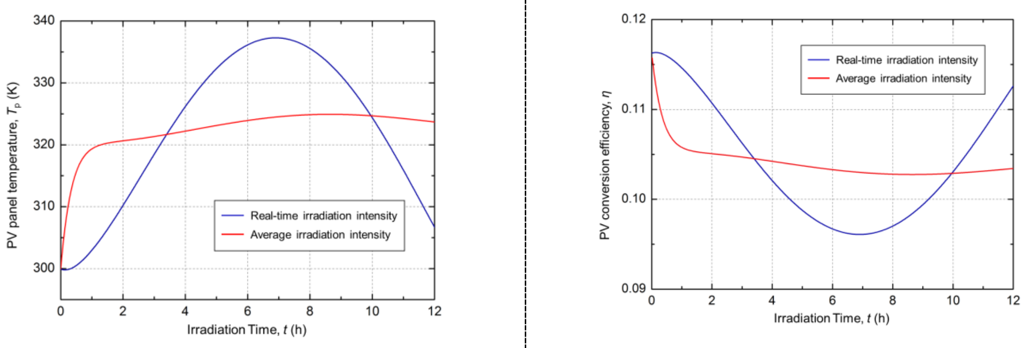


(a) **(b)** **(c)**

Figure 1. Real-time weather data in HK (04/09/2015)

4.1. Meteorological data reduction

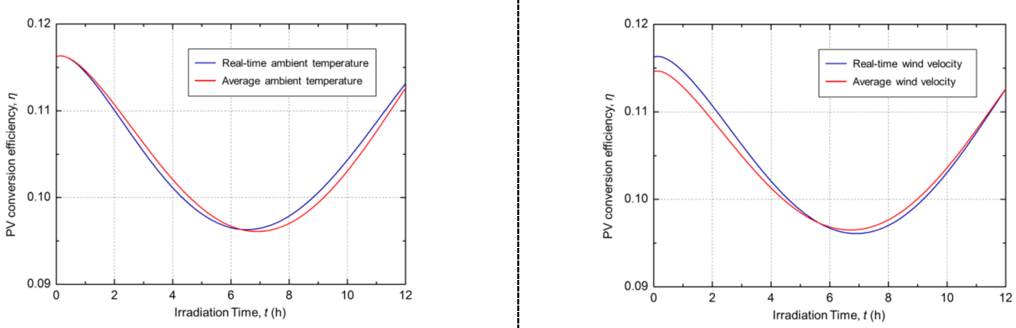
To concurrently satisfy the convenience and accuracy in the prediction of solar power generation, it is imperative to simplify the meteorological data and investigate the induced deviation in the theoretical calculation. With the control variate method, we separately analyzed the dependence of energy output on the data averaging for the irradiation intensity G, ambient temperature T_a and wind velocity u. Figure 2a-b show the theoretical calculation results of PV panel temperature and PV conversion efficiency by substituting the average solar irradiation intensity (G_{avg} = 580W/m^2) into the model. By contrast to the actual scenario, with the constant solar irradiance, the temperature of PV panel sharply increases at the beginning and flattens after one hour in a rapid manner. Such temperature variation enables the PV conversion efficiency and generated power tend to be stable for most of the day. Although the operating curves of PV module, under invariant solar irradiation, differs from the actual scenario, the total electrical energy output of two cases are quite close. For the constant irradiation intensity, the daily electricity generation (Q = 0.724 kWh/m^2) is only ~0.1% higher than that of the benchmark calculation, where the forecasting error is negligible for the PV potential economic analysis.



(a) **(b)**

Figure 2. Transient efficiency of a PV cell in different cases of G

Similarly, we average the real-time data of ambient temperature and wind velocity, and calculated the operation performance of PV module by substituting the average ambient temperature (T_{avg} = 303K) and wind velocity (u_{avg} = 2m/s) into the model. The calculation results in Figure 3a and b show that the data reduction of ambient temperature and wind velocity has little effect on the energy conversion efficiency on the PV module. For these two cases with average ambient temperature and wind velocity, the predictions of daily electricity generation Q are both ~0.3% lower than that of the actual scenario.



(a) **(b)**

Figure 3. Transient efficiency of a 1 m^2 PV cell in different cases of T_{avg} and u_{avg}

Figure 4 presents the calculated operating curves of PV module when averaging all the three meteorological data simultaneously in the computation. After the data reduction, the prediction of daily electricity generation is 0.722 kWh/m^2, which is ~0.1% lower than that of the actual situation. It is important to note that, for the invariant meteorological variables, the PV conversion efficiency can be described as constant when the PV system reach a steady state (see Fig. 4b). The result indicates that, for evaluating the solar energy output in a long period of operation, equation (5) can be further simplified as,

$$Q = \int_0^{t_r} G\eta(T_p)\mathrm{d}t = \eta_{avg}\int_0^{t_r} G\mathrm{d}t = \eta_{avg} \cdot \mathrm{TSI} \quad \textbf{(6)}$$

where η_{avg} is the average PV conversion efficiency, which is determined by G_{avg}, T_{avg} and u_{avg}. This deduction takes into account the environment effects on the solar energy conversion, while also avoiding the complicated computation process with the ever-changing solar irradiation intensity.

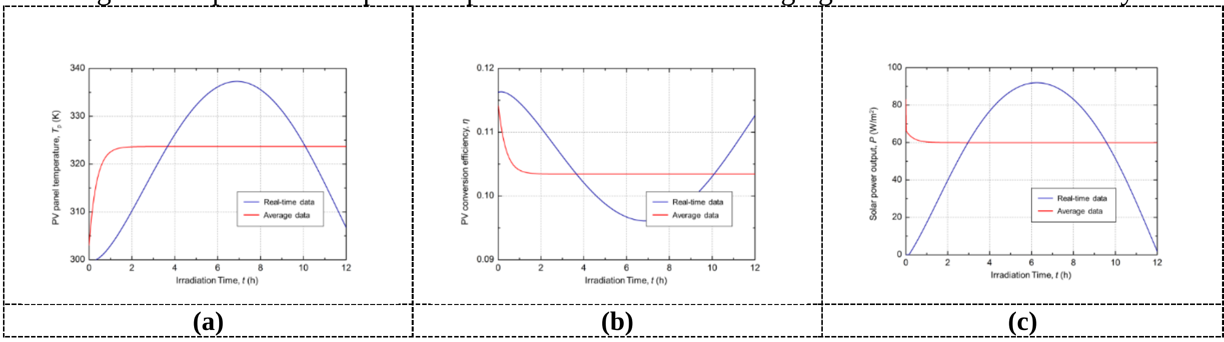


Figure 4. Different performance between actual weather data and average weather data

4.2. Unified model of regional solar energy output

The theoretical analysis reveals that the meteorological data reduction has little effect on the calculation result of daily electricity generation. Meanwhile, there is no interaction among the meteorological variables (G, T_a, u). Therefore, we can further develop a correlation between the average PV conversion efficiency η_{avg} and the meteorological variables by using the multiple regression,

$$Q = \eta_{avg} \cdot \text{TSI} = \left(\gamma + f(G_{avg}) + f(T_{avg}) + f(u_{avg})\right) \cdot \text{TSI} \quad \textbf{(7)}$$

where $f(G_{avg})$, $f(T_{avg})$ and $f(u_{avg})$ represent the functions of independent meteorological variables in regression analysis, and γ is the constant in mathematical derivation. The average PV conversion efficiency η_{avg} is consequently expressed as a regression function of average meteorological data. To figure out the composition of the regression function in equation (6), we analyze the variation of generated electrical energy Q with each independent meteorological variable by fixing the other two parameters.

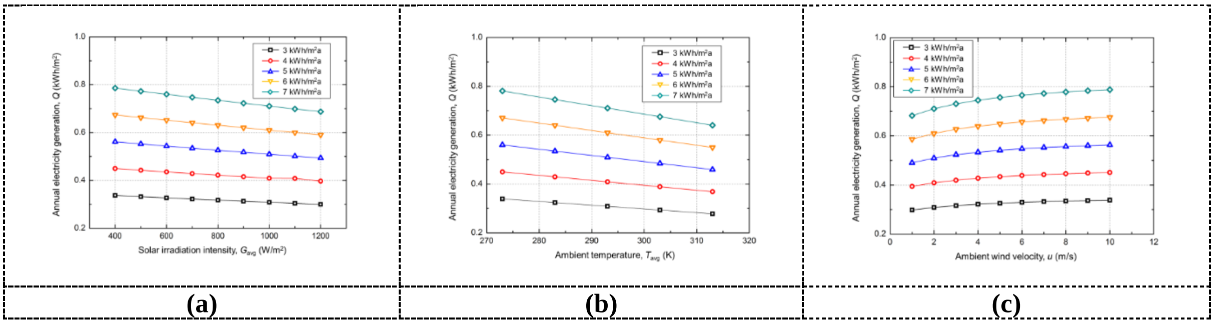


Figure 5. The relationship between G_{avg} (T_{avg} and u_{avg}) and Q under different TSI

In Figure 5a-c, we plot the daily electricity generation as functions of average solar irradiation intensity, ambient temperature, and wind velocity, for different total solar irradiations. To simplify the modeling for practical applications, the dependence of electricity generation on the meteorological variables was regarded as linear. Thus, the model in equation (6) can be expressed with a multiple linear regression (MLR),

$$Q = \left(a_1 G_{avg} + a_2 T_{avg} + a_3 u_{avg} + 0.263\right) \times \text{TSI} \quad \textbf{(8)}$$

where a_1 = -0.017x10^{-3} m^2/W, a_2 = -5.05x10^{-4} K^{-1}, a_3 = 1.53x10^{-3} s/m. The square of the corresponding correlation coefficient R2 of the developed MLR function is 0.97, implying that the MLR-based model derivation can be considered reasonable. Compared with the complicated computation with real-time meteorological data, this unified model provides a much more convenient prediction method for regional PV potential without sacrificing the calculation accuracy. Substituting the average meteorological data of Hong Kong in equation (7), the predicted daily electricity generation is 0.723kWh/m^2, which is as same as the actual scenario.

5. Economic assessment of PV potential in China

The existing method for forecasting the regional PV potential in China is based on the assumption of unchanged PV conversion efficiency, that is, the practical efficiency in electricity generation is regarded to be 80% of the ideal efficiency of installed PV panels [20]. Though this traditional method can roughly estimate the disparity of solar energy output through a simple calculation with total solar irradiation, it fails to determine the variation of PV conversion efficiency caused by the environmental difference in irradiation intensity, ambient temperature, and wind velocity. Using the unified model in equation (7), we evaluate the energy output and economy of solar photovoltaic panels installed in several representative regions in China. Table 2 shows the average meteorological parameters and predicted electricity generation Q using the unified model in equation (7). The calculation results demonstrate that the different irradiation intensity, ambient temperature, and wind velocity bring about an apparent discrepancy of the generated electricity in various regions, even if the total solar irradiation is similar.

Table 2. Meteorological data in four representative regions of China*

Regions	TSI (kWh/m^{2}a)	t_r （h/a）	G_{avg} =TSI/t_r (W/m^2)	T_{avg} （K）	u_{avg} （m/s）	η_{avg} (%)	Q (kWh/m^{2}a)
Zhangye	1,710	3,163	543	279.92	5.00	12.11	207.14
Sanya	1,720	2,491	690	302.60	3.20	10.42	179.28
Haikou	1,443	1,888	764	295.69	2.70	10.57	152.51
Beijing	1,410	2,520	560	286.25	2.10	11.28	159.01

* Data source: http://www.data.AC.CN/index.asp

As a representative region with abundant solar energy, Zhangye has the most favorable environmental conditions for efficient PV conversion process. The lower solar irradiation intensity and ambient temperature, as well as the higher ambient wind velocity ensure a lower operation temperature of the PV panel, therefore leading to a higher electricity output than the other regions with comparable total solar irradiation. Compared with Zhangye, the annual total solar irradiation at Sanya (10 kWh/m^{2}a) is 5% higher, yet the lower latitude results in a much higher ambient temperature and irradiation intensity. These environmental factors dramatically degrade the PV conversion efficiency and thus decrease the annular electricity generation by 13% than that of Zhangye. The similar results can also be found between Beijing and Haikou due to the environmental effects.

For adjusting the deployment of PV system, the Chinese government set different prices for the electricity generated from solar power stations [21]. The electricity price in Type I (Zhangye), Type II (Beijing) and Type III (Sanya and Haikou) regions are 0.85, 0.88 and 0.98 RMB/kWh, respectively. Based on the accurate prediction of PV electricity generation, we can obtain the PV income of these four regions. Figure 6a and b show the comparisons of daily electricity generation and associated income in the four regions. The black bars in Figure 6 denote the results estimated by the existing method used in China (80% of the ideal energy output of PV panel), and the red bars denote the prediction of the unified model in equation (7).

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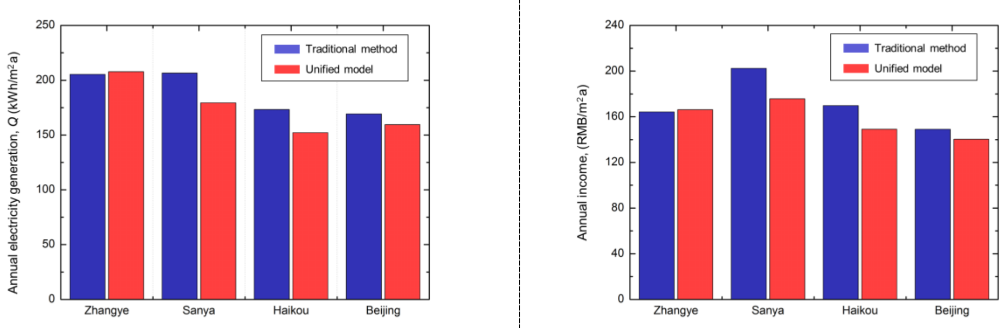

(a) **(b)**

Figure 6. Results calculated by two methods

As shown in Figure 6, the estimation error of regional PV potential using traditional method cannot be simply neglected or corrected in the economic analysis since the deviation is irregular. Compared with the calculation results with the unified model, the energy output in Zhangye is underestimated by 1%, while Sanya, Haikou and Beijing are overestimated by 6% ~ 15% without considering the environmental effects. We should note that the overestimated electricity generation in Sanya and higher price bring about the overrated prospective earnings for the investors (see Figure 6b). Such inaccurate information will stimulate an unreasonable development of solar industry in Sanya or other similar areas. By contrast, through a simple computation with average meteorological data, our model achieves a much more precise prediction of the regional PV potential, thus can offer an accurate guidance for the investors and national policy planning in the solar energy industries.

6. Conclusions and recommendations

With the aim of providing a reliable prediction method for regional solar photovoltaic potential, a unified model of PV energy conversion is developed in this study. Unlike previous work, the developed model not only takes into account the environment effect on the PV conversion efficiency, but also avoids the complicated calculation with real-time meteorological data. Our theoretical analysis reveals that the meteorological data reduction has little effect on the prediction of daily electricity generation. By developing a correlation between the average PV conversion efficiency and meteorological variables, the unified model offers an accurate estimation of solar energy output. In particular, the prediction error of daily electricity generation is less than 1.5% as compared to the calculation result with real-time weather information, which is negligible for the economic analysis.

Subsequently, the model is used to assess the economic potential of solar power generation in four representative regions of China. Through a comparison with the traditional forecasting method, the results suggest that the current economic analysis of PV potential in China is inaccurate owing to the neglect of variation in the PV conversion efficiency. Specifically, using the unified model, we demonstrated that the economic benefit of PV system in Sanya is overestimated by 15% because the higher ambient temperature significantly degrades the PV electricity generation. The theoretical investigations in this work underscore the importance of environment conditions for the PV economic analysis, and also provide a reliable prediction model for the rational solar energy policy planning in China or other countries to maximize the energy generation and profit of PV industry.

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