Effect of Temperature on PV Potential in the World

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ABSTRACT: This work aims to identify the geographic distribution of photovoltaic (PV) energy potential considering the effect of temperature on PV system performance. A simple framework is developed that uses the JIS C 8907 Japanese industrial standard to evaluate the effects of irradiation and temperature on PV potential. The global distributions of PV potential and yearly performance ratio are obtained by this framework. Generally, the performance ratio decreases with latitude because of temperature. However, regions with high altitude have higher performance ratios due to low temperature. The southern Andes, the Himalaya region, and Antarctica have the largest PV potentials. Although PV modules with less sensitivity to temperature are preferable for the high temperature regions, PV modules that are more responsive to temperature may be more effective in the low temperature regions. The correlation between the estimates obtained by our framework and results from a more data-intensive method increases when the temperature effects are considered.

INTRODUCTION

Recently, as concern about climate change and nuclear power increases, interest in renewable energy is high. However, the geological dispersion of renewable energy sources around the world makes assessment of their potential difficult. A global map of renewable energy sources would help clarify regions with net energy supply or demand, e.g., for connecting the demand and supply of renewable energy sources across international borders.1

Photovoltaic (PV) electric power generation is a promising technology for generating renewable energy from solar irradiation. However, the output of PV is sensitive to its operating conditions, so estimating PV potential accurately is a complex problem. Furthermore, given the limited availability of data for the entire world, a method that achieves accurate estimates with available data is necessary.

Most estimates of PV potential use either the power rating method or the energy rating method.2 The power rating method integrates the instantaneous PV power generation over time, thereby accounting for the time-dependency of PV output.3 Huld et al. estimated the PV potential in Europe, using the framework of King et al. to account for ambient temperature and PV module type.4,5 The Photovoltaic Geographical Information System (PVGIS) used the method of Huld et al. to estimate the PV potential in Europe and Africa.6 The main problem of this method is its complexity and data requirements. Complete instantaneous weather data is not available globally, so no work has estimated the global PV potential by the power rating method.

The energy rating method estimates PV potential by multiplying the total solar irradiation during a specific period of time by a performance ratio. The simplicity of the energy rating method and the availability of global weather data7 has enabled researchers to estimate the PV potential for the world,8 and numerous countries.9–11 These studies use a constant performance ratio. However, the performance ratio actually changes under different operating conditions, especially ambient temperature,12,13 which limits the accuracy of these studies.

Our objective is to identify the areas of the world with the highest PV potential considering the spatial and temporal variation of temperature. JIS C 8907 is the Japanese industrial standard for estimating the performance ratio for PV energy generation as a function of a number of factors including ambient temperature.
temperature. Because ambient temperature generally has the largest effect on the performance ratio, we develop a modified energy rating method based on the JIS method that estimates the effect of ambient temperature on global PV potential. We use the method to generate a global map of PV potential and annual performance ratio. The results are verified using estimates from PVGIS.

**METHOD**

**Estimation of PV Potential.** We estimate the PV potential for PV systems mounted on a platform above ground and operated under direct connection to the grid without any kind of storage such as batteries. We assume that the PV systems consist of crystalline silicon PV (c-Si PV) modules: c-Si PV includes both multicrystalline silicon PV and single-crystalline silicon PV, which are the most popular modules in the present market.

The annual PV energy generation $E_{Py}$ (kWh) for each region is obtained by summing the monthly PV energy generation $E_{Pm}$ (kWh) in that region. Regions are obtained by gridridding the entire globe along 360° longitude and 180° latitude into 64 800 regions.

$$E_{Py} = \sum E_{Pm} \quad (1)$$

The monthly energy generation is obtained from eq 2.

$$E_{Pm} = \frac{P_{AS}KH_{Am}}{G_s} \quad (2)$$

Here, $K$ is the performance ratio, $P_{AS}$ is the nominal power of the PV array at standard test conditions in kW, $H_{Am}$ is the monthly total solar irradiation on the PV array in kWh/m², and $G_s$ is the solar irradiance at standard test conditions, which is 1 kW/m².

$H_{Am}$ is obtained by multiplying the number of days in the month by the average daily irradiance over the course of the month on equator-pointed surfaces tilted at the latitude angle, which are obtained from the NASA Surface meteorology and Solar Energy database. $K$ is obtained from eq 3.

$$K = K_HK_PK_BK_C \quad (3)$$

Here, $K_H$, $K_P$, $K_B$, and $K_C$ are parameters for irradiation/energy losses on the PV array surface, in the PV module, in the battery circuit, and in the power conditioner circuit, respectively. We use the JIS recommended value of 0.97 for $K_H$. Although shading on the PV array surface would affect this value, we ignore that effect here. We set the value of $K_B$ to be 1 because we have assumed grid-connected operation. We use the recommended value of power conditioners, 0.90, for $K_C$.

The effect of ambient temperature on the PV module is included in $K_P$, by a correction term $K_{PT}$.

$$K_P = K_{PD}K_{PT}K_PAK_PM \quad (4)$$

Here, $K_{PD}$, $K_{PA}$, and $K_PM$ are coefficients showing losses by time-dependent module function, array circuit, and array load, respectively. Staining and dust on the PV array surface would affect $K_{PD}$, but we ignore those effects here. We use the value recommended for c-Si PV modules of 0.95 for $K_{PD}$, the generally recommended value of 0.97 for $K_{PA}$, and the recommended value for grid-connected PV modules of 0.94 for $K_PM$. $K_{PT}$ is given by eq 5.

$$K_{PT} = 1 + \alpha_{Pmax}(T_{Am} + \Delta T - 25) \quad (5)$$

Here, $\alpha_{Pmax}$ is the maximum power temperature coefficient, which is $-0.0041\, ^\circ C^{-1}$ for c-Si PV modules; $T_{Am}$ is the 24 h ambient temperature profile averaged over month $m$; and $\Delta T$ is the weighted average of module temperature annual increase. We obtained a value of 18.4 °C for $\Delta T$ of PV systems mounted on platforms. This value was confirmed to be valid between 20 and 40 °C for 64 Japanese residential PV systems. Although regional differences in factors such as wind and humidity might also affect the value, we believe that it should be valid within ±0.1 °C. The calculated value of $K_{PT}$ was verified to be within ±3% of the measured value for the PV systems. The value of $T_{Am}$ for each region is obtained from the NASA database.

All parameters except for $K_{PT}$ are assumed to be constant in order to focus on the effect of temperature on the PV potential. Then, $K$ is given as follows.

$$K = K' \times K_{PT} \quad (6)$$

$$K' = K_HC_{PD}C_PAK_PMK_BC \quad (7)$$

In this work, we set the design factor $K'$ to 0.75 based on the recommended values shown above.

The annual PV potential per nominal power is obtained using the results from eqs 1, 2, and 6:

$$Y_{Py} = \frac{E_{Py}}{P_{AS}} = \frac{K'}{G_S} \sum_{m=1}^{12} \{1 + \alpha_{Pmax}(T_{Am} + \Delta T - 25)\}H_{Am} \quad (8)$$

The yearly performance ratio is obtained from eq 9:

$$K_y = \frac{Y_{Py}G_S}{H_{Ny}} = \frac{\sum_{m=1}^{12} \{1 + \alpha_{Pmax}(T_{Am} + \Delta T - 25)\}H_{Am}}{\sum_{m=1}^{12} H_{Am}} \quad (9)$$

**Weather Conditions in the World.** Figure 1 shows the global distribution of annual total irradiation on equator-pointed tilted surfaces obtained by summing the monthly total solar irradiation values in the NASA database, which are averages of 22 years of data from 1983 to 2005. These irradiation values include the effects of cloud cover and contain both direct and indirect solar irradiance, both of which can be used by PV systems. Generally, irradiation is largest near the equator and at high altitudes. Regions with irradiation values greater than 2000 kWh/m² include the southwest region in North America, the Southern Andes region in South America, central and south Africa, midwest Asia, the Himalaya region in Asia, the northwest region of Australia, and Antarctica. Irradiation values in countries having large amounts of installed PV systems, such as Germany and Japan, are relatively small.
Figure 2 shows the global distribution of annual average ambient temperature. Generally, irradiation and temperature are correlated except in Antarctica. However, the annual average ambient temperatures in the Himalaya and Southern Andes regions are much lower than that in other regions with the same latitude due to high altitudes. Temperature decreases with increasing altitude at a rate of about $-9.8 \, ^\circ C/km$ to $-4.0 \, ^\circ C/km$. The altitudes in the Himalaya and Southern Andes regions reach over 5000 m. Therefore, the temperatures in those regions could be up to $50 \, ^\circ C$ lower than regions at sea level with the same latitude. Irradiation also increases with increasing altitude as shown in Figure 1.

**RESULTS AND DISCUSSION**

Figure 3 shows the global map of annual energy generation potential by c-Si PV systems. The regions with the largest irradiation values have large PV potentials. In particular, the Himalaya and Southern Andes regions have energy potentials of more than 1800 kWh/kW PV, due to the combination of large irradiation values and low temperatures. The Himalayan region is especially attractive because it is near regions with large future energy demands, such as China and India.

Installation of $1.2 \times 10^9 \, km^2$ of c-Si PV arrays rated at 1800 kWh/kW PV and 0.14 kW/m$^2$ in this region could meet the total electricity consumption in China of about 3.1 trillion kWh in 2007. This area is less than 4% of the area of the Himalaya region having a PV potential greater than 1800 kWh/kW. Moreover, because CO$_2$ emissions per unit electricity in China and India are larger than those in the developed countries, using PV energy in these regions could have a large mitigation effect on climate change. Of course, many problems must be addressed when installing PV systems in high altitude regions, such as transporting the PV system and increased need for maintenance due to the severe environmental conditions. Several high-altitude PV plants are currently in operation.

Antarctica also has large PV potential because of its high irradiation and low temperature. However, due to the large seasonal variance of PV energy generation, with essentially no energy generation from April to September, together with the
lack of significant energy demand in this region and the difficulty of maintaining the PV system, the feasibility for utilizing the PV potential in this region is low. If such disadvantages can be overcome, or if some way can be developed to store the generated energy, e.g., in the form of hydrogen or refined metals, then it may be possible to utilize the large potential in this region in the future.

Figure 4 shows the global potential map of PV energy generation without considering the temperature effect. Comparing this figure with Figure 3, the effect of temperature on the PV potential is clear. At an ambient temperature of 40°C, the loss of energy due to temperature is almost 13% for a conventional c-Si PV module. The loss can be reduced by using PV modules having an $\alpha_{P_{\text{max}}}$ greater than $-0.0041 \, ^{\circ}\text{C}^{-1}$, such as amorphous Si or CdTe PV modules. This would increase the PV potential in regions with large temperature, such as Africa, Middle East Asia, and Australia. Conversely, the PV potential decreases for larger values of $\alpha_{P_{\text{max}}}$ in regions where the monthly average temperature is less than 6.6°C, such as Antarctica, the Himalayans, and the southern Andes, because $T_{\text{Am}} + \Delta T - 25$ becomes negative for $\Delta T$ equal to 18.4°C in eq 5. Those regions should use PV modules, whose performance increases at less than 6.6°C, such as c-Si or CIS PV modules.

Figure 5 shows the yearly performance ratio $K_y$ obtained by eq 9. Temperature differences cause the performance ratio to vary from 0.65 to 0.90.

We examine the accuracy of the JIS method by comparing the estimates with and without considering temperature of the PV potentials with estimates for capital cities in Europe and Africa obtained from the PVGIS Web site for tilt angle equal to latitude, c-Si PV modules, and system loss of 0.25 (see Figure 6). The regression line for the JIS results without considering temperature overestimates the PV potential by nearly 15% in locations with large PV potential, irradiation, and temperature are often correlated, so the PV potentials in locations having large irradiations could be overestimated if the temperature effect is neglected.

The differences between the results from the JIS and PVGIS methods are large in locations such as Reykjavik, Oslo, Douglas in Europe and Asmara, Nouakchott, and Harare in Africa even
when considering temperature. All of these cities are surrounded by mountains, ocean, or desert. The resultant steep gradients in geographical features cause sharp weather data variations that cannot be captured accurately by low resolution weather data, especially in Africa. The resolution of the NASA database is 1 degree, and that of PVGIS is 1.5 arc-minutes. Therefore, our results are likely to be less accurate for those cities.

Table 1 shows the $p$-values for linear regressions of $H_{py}$, $K_y$, and $Y_{py}$ obtained by the JIS method with consideration of temperature ($T$) and without consideration of temperature (NT) against the values obtained by the PVGIS method. The $p$-values are all below 0.01 except for $K_y$ calculated without considering temperature, especially in Africa. Neglecting the effect of temperature could result in overestimation of the performance ratio in high temperature regions. In addition, $K_y$ is also affected by both differences of weather data sources and differences between the JIS and PVGIS estimation methods. The NASA and PVGIS weather data differ by geological resolution. However, previous research indicates that the accuracy of PV energy generation increases when the hourly variation of the weather data is considered, which the PVGIS method does but the JIS method does not. These differences reduce the correlation of the performance ratio, but not $H_{py}$ and $Y_{py}$ when temperature is not considered.

The framework we have presented can be used to link PV specifications with the variation of PV potential, e.g., to show what type of PV module is suitable for different regions. These findings could help stakeholders to evaluate the potential for PV energy generation considering temperature in addition to

Figure 5. Global map of PV performance ratio for c-Si PV system.

Figure 6. Comparison of the PV potential estimation results of PVGIS and JIS.
irradiation. For example, we identified a large PV potential in the Himalayan region that is close to large future energy consumers such as China and India. Although we have focused on temperature, other factors could be included in JIS framework. For example, one could consider the snowfall effect in $K_{10}$, the cooling effect by wind by modifying eq S, and the staining of the PV modules by wind-borne particles in $K_{10}$. We hope that this work will provide a first step to investigate the most suitable locations for PV energy generation in the world.

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### REFERENCES

(1) Feresin E. Europe looks to draw power from Africa. *Nature*, 2007, 450, pp 595; DOI 10.1038/twas08.9a.
(2) Kroposki B; Emery K; Myers D; Mrg L. A. comparison of photovoltaic module performance evaluation methodologies for energy ratings. 1995; NREL/TP-411 7426.
(3) Ransome, S; Funtan, P. Why hourly averaged measurement data is insufficient to model PV system performance accuracy. *Proc. 29th PVSEC 2005*.
(6) PVGIS Website; http://re.jrc.ec.europa.eu/pvgis/.
(7) NASA Website; http://eosweb.larc.nasa.gov/sse/.
(23) AIST-LCA ver.5, National Institute of Advanced Industrial Science and Technology.

| Table 1. p-Values for the correlation between the estimates given by PVGIS and JIS |
|---------------------------------|-------------------|-------------------|
|                                 | $K_y$ [-]         | $Y_p$ [kWh/kW]    |
| $H_{sp}$ [kWh/m2]              | $T$   | NT | $T$   | NT |
| Total                          | <0.01 | 0.99 | <0.01 | 0.01 |
| Europe                         | <0.01 | 0.80 | <0.01 | 0.01 |
| Africa                         | <0.01 | 1.00 | <0.01 | 0.01 |