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General method to obtain recommended tilt and azimuth angles for photovoltaic systems worldwide

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ABSTRACT

In this study, a general method to obtain the 95% generation bound for photovoltaic (PV) systems worldwide was developed using a clear-sky model and then validated using ground surface observations, satellite-derived data, and typical meteorological year (TMY) files. The 95% generation bound for plane-of-array (POA) irradiation is used to provide the recommended tilt and azimuth angles where the loss fraction of POA irradiation is limited to 5% of the maximum POA irradiation. It was found that the 95% generation bound by this method behaves almost the same as that under real weather conditions. Cooling season was proposed for the application of PV-powered air conditioners. When compared with the annual 95% generation bound, the cooling-season 95% generation bound in Hong Kong covered a smaller range of tilt angles but much larger range of azimuth angles. Diffuse ratio is one of the most important factors influencing the 95% generation bound, making it a comparable or conservative estimate when compared to the results obtained by local irradiance data. Latitude is another important factor that influences the 95% generation bound. At lower latitude, the 95% generation bound locates at lower tilt angles and has a flatter line due to the smaller value of solar zenith angle around solar noon. The distribution of accumulated direct normal irradiance (DNI) in the morning and afternoon hours also influences the 95% generation bound. The contour lines, as well as the 95% generation bounds (based on ground surface observations and TMY files), are shifted some degrees toward the east or west.

1. Introduction

The installation of photovoltaic (PV) systems has accelerated rapidly in recent years. It is reported (Sawin et al., 2017) that in 2016, 75 GW of new PV capacity was installed around the world. By the end of 2016, the total global PV capacity reached over 303 GW, and at least 17 countries had enough PV capacity to meet 2% or more of their electricity demand. The National Energy Administration (NEA, 2017) reported that in China, the new PV capacity installed in 2016 was 34.54 GW, the total PV capacity was 77.42 GW by the end of 2016. This means that PV power met 1% of the total national power generation in China.

When installing fixed PV system, the installation angles is often considered at the first stage for PV system design. The optimum installation angles for PV systems refer to the annual optimum tilt and azimuth angles, which are selected for yielding the maximum PV power output during the whole year. The general knowledge prevalent among professionals is that PV module surfaces should face towards the equator (i.e., face South in the North hemisphere and North in the South hemisphere), and be tilted at an angle around the site latitude (Portolan dos Santos and Rüther, 2014). However, this method makes it hard to choose tilt and azimuth angles when a PV system must be installed at angles deviating from the optimum. Some literature from studies of equatorial countries gives different results: PV arrays oriented eastward gain higher plane-of-array (POA) irradiation than those facing the equator (Khoo et al., 2014; Saber et al., 2014) and the effect of orientation for PV modules at low tilt angles can be negligible (Ng et al., 2014; Portolan dos Santos and Rüther, 2014; Saber et al., 2014). Lave and Kleissl (2011) found for most locations in the United States that the optimum installation angles varied by up to 10° from the rule of thumb of latitude tilt and due south azimuth, and that the sensitivity of annual POA irradiation to inclination is small near the optimum point. Little research has been conducted on PV power generation at non-optimum angles, especially for medium or high latitude sites.

Because of limitations imposed by specific buildings or landforms, PV systems sometimes cannot be installed at optimum tilt and azimuth angles. For example, the PV modules referred to in Ubertini and Desideri (2003) had to be mounted on a south-east facing rooftop with a

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Nomenclature

a_{cs}	terms to account for the incidence angle of the cone of circumsolar irradiance on POA
A_{clear}	quantities of tilt and azimuth angle combinations within the 95% generation bound by the clear-sky model
A_{int}	quantities of tilt and azimuth angle combinations that appear in the region defined by the intersection of the 95% generation bound by the clear-sky model and that under real weather conditions
A_m	constant
A_M	air mass
b_{cs}	terms to account for the incidence angle of the cone of circumsolar irradiance on horizontal
B_m	constant
B_s	defined by Eq. (11)
C_m	constant
f_{ij}	coefficient
F_1	circumsolar coefficient
F_2	horizon brightness coefficient
G	global horizontal irradiance, W m^{-2}
G_{0n}	extraterrestrial solar irradiance in its normal component, W m^{-2}
G_B	beam horizontal irradiance, W m^{-2}
G_{Bn}	direct normal irradiance, W m^{-2}
G_D	diffuse horizontal irradiance, W m^{-2}
G_{sc}	solar constant, equal to 1367 W m^{-2}
G_T	POA global irradiance, W m^{-2}
G_{TB}	POA beam irradiance, W m^{-2}
G_{TD}	POA diffuse irradiance, W m^{-2}
G_{TG}	POA ground-reflected irradiance, W m^{-2}
G_{Tcir}	POA circumsolar diffuse irradiance, W m^{-2}
G_{Thor}	POA horizon-brightening diffuse irradiance, W m^{-2}
G_{Tiso}	POA isotropic diffuse irradiance, W m^{-2}
IR	intersection ratio
R_B	ratio of beam irradiance on POA to that on horizontal
R_{Diff}	ratio of diffuse horizontal irradiation during a period to global horizontal irradiation
R_G	ratio of POA ground-reflected irradiance to GHI

Greek symbol

β	tilt angle of PV modules from horizontal (0° = horizontal, 90° = vertical), degrees
γ	azimuth angle of PV modules (in the Northern Hemisphere, the angle between true south and the projection on a horizontal plane of the normal to the surface, −90° = east, +90° = west; in the Southern Hemisphere, −90° = west, 0° = north, +90° = east), degrees
Δ	sky brightness
δ	solar declination, degrees
ε	sky clearness
θ_b	incidence angle of POA beam irradiance, degrees
θ_{int}	calculated angular intervals of tilt and azimuth angles, degrees
θ_z	solar zenith angle, degrees
ρ_g	ground reflectance
φ	latitude, degrees
ω	hour angle, degrees

Abbreviations

BSRN	Baseline Surface Radiation Network
DHI	diffuse horizontal irradiance
DNI	direct normal irradiance
GHI	global horizontal irradiance
POA	plane-of-array
PV	photovoltaic
TMY	typical meteorological year

20° tilt angle, instead of the optimum positioning. This was the best compromise available between maximum solar radiation, greatest available surface, and minimum costs. Thus, it is essential to study the POA irradiation over a larger range of installation angles for places worldwide and to provide recommended combinations of tilt and azimuth angles with acceptable percentages of energy loss (e.g., 3% or 5%). Although focused on discussions of optimum installation angles, some literature (Christensen and Barker, 2001; Hartner et al., 2015; Le Roux, 2016; Portolan dos Santos and Rüther, 2014) has given contour maps of annual POA irradiation as a function of tilt and azimuth angles to show different percentages of local energy gains. However, research on the recommended tilt and azimuth angles for sites all around the world are not found in the literature. In this paper, a 95% generation bound is proposed to provide the recommended tilt and azimuth angles for PV systems worldwide, where the loss fraction of POA irradiation is limited to 5% of the maximum POA irradiation available at a specific site.

Irradiance data is required to obtain the 95% generation bound for locations worldwide. Usually, the simulation of PV power output or POA irradiation should be based on local irradiance data (Christensen and Barker, 2001; Lave et al., 2015; Lave and Kleissl, 2011; Le Roux, 2016; Portolan dos Santos and Rüther, 2014), such as provided by ground surface observations, satellite-derived data, and typical meteorological year (TMY) files. For many places in the world, the local irradiance data for at least an entire year is not available, leading to difficulties in simulation or errors in results. In fact, accurate local irradiance data is not a must to calculate the recommended tilt and azimuth angles worldwide and PV systems are often installed at sites with good solar radiation. The clear-sky model was utilized in this study to generate the direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) at a specific latitude, which would offer much greater convenience for PV system design. The variations in diurnal cloud patterns were not taken into account for the 95% generation bound. This simplified assumption is based on the fact that the average variation of cloud patterns during a long period (e.g., one year) has relatively uniform influences on different tilt and azimuth angle combinations within the 95% generation bound, as the validations indicated in the section of Results and discussion. Obviously, this method may introduce large errors when used for a short period (e.g., one day or one week). Another limitation is that the site-specific PV power outputs cannot be obtained by the clear-sky model. The 95% generation bound by this method provides a wide range of tilt and azimuth angles conveniently, which can offer a broad and generalized guidance to solar energy developers, particularly for distributed PV systems in urban areas, or be used to support analyses of global solar energy potential.

The objective of this study was to develop a general method to harness the 95% generation bound at any specific location, which enlarges the installation angles available and makes PV installation more flexible. The clear-sky model (i.e., the ASHRAE (1972) model) was used to estimate solar irradiance worldwide instead of using local irradiance data. Due to the fact that PV systems for PV-powered air conditioners is an important application, the 95% generation bound for the cooling