



World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels

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ABSTRACT

This study provides estimates of photovoltaic (PV) panel optimal tilt angles for all countries worldwide. It then estimates the incident solar radiation normal to either tracked or optimally tilted panels relative to horizontal panels globally. Optimal tilts are derived from the National Renewable Energy Laboratory's PVWatts program. A simple 3rd-order polynomial fit of optimal tilt versus latitude is derived. The fit matches data better above 40° N latitude than do previous linear fits. Optimal tilts are then used in the global 3-D GATOR-GCMOM model to estimate annual ratios of incident radiation normal to optimally tilted, 1-axis vertically tracked (swiveling vertically around a horizontal axis), 1-axis horizontally tracked (at optimal tilt and swiveling horizontally around a vertical axis), and 2-axis tracked panels relative to horizontal panels in 2050. Globally- and annually-averaged, these ratios are ~1.19, ~1.22, ~1.35, and ~1.39, respectively. 1-axis horizontal tracking differs from 2-axis tracking, annually averaged, by only 1–3% at most all latitudes. 1-axis horizontal tracking provides much more output than 1-axis vertical tracking below 65° N and S, whereas output is similar elsewhere. Tracking provides little benefit over optimal tilting above 75° N and 60° S. Tilting and tracking benefits generally increase with increasing latitude. In fact, annually averaged, more sunlight reach tilted or tracked panels from 80 to 90° S than any other latitude. Tilting and tracking benefit cities of the same latitude with lesser aerosol and cloud cover. In sum, for optimal utility PV output, 1-axis horizontal tracking is recommended, except for the highest latitudes, where optimal tilting is sufficient. However, decisions about panel configuration also require knowing tracking equipment and land costs, which are not evaluated here. Installers should also calculate optimal tilt angles for their location for more accuracy. Models that ignore optimal tilting for rooftop PV and utility PV tracking may underestimate significantly country or world PV potential.

1. Introduction

Global solar photovoltaic (PV) installations on rooftops and in power plants are growing rapidly and will grow further as the world transitions from fossil fuels to clean, renewable energy (Jacobson et al., 2017). A critical parameter for installing fixed-tilt panels is the tilt angle, since PV panel output increases with increasing exposure to direct sunlight. Energy modelers also need to know the optimal tilt angle of a panel for calculating regional or global PV output in a given location or worldwide.

Another issue for installers and modelers is whether 1-axis vertical tracked PV panels (panels that face south or north and swivel vertically around a horizontal axis) receive more incident radiation than 1-axis horizontal tracked panels (panels at optimal tilt angle that swivel horizontally around a vertical axis), and the extent to which incident radiation to 1-axis- and 2-axis-tracked panels (which combine 1-axis vertical and horizontal tracking capabilities to follow the sun perfectly

during the day) exceeds that of optimally tilted panels. Finally, because global and regional weather and climate models almost all calculate radiative transfer assuming that radiation impinges on horizontal surfaces, energy modelers also need estimates of the ratio of incident solar radiation to panels that track the sun or are optimally-tilted to that of panels that are placed horizontally on a flat surface.

This study first provides estimates of optimal tilt angles derived from the NREL PVWatts program (NREL, 2017) at 1–4 sites in each country of the world. These optimal tilt angles are representative of assumed historic meteorological conditions near a given site, so are only approximate. Although installers would need to make more precise calculations at each site, the results provided here are still useful rough estimates. The study then provides convenient albeit rough polynomial fits to the PVWatts data of the optimal tilt angle as a function of latitude for both the Northern and Southern Hemispheres. The optimal tilt data by country and by latitude are then input into a global climate model, GATOR-GCMOM for year 2050 meteorological and air quality

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conditions, to provide ratios of incident solar radiation normal to an optimally tilted, 1-axis vertically-tracked, 1-axis horizontally-tracked, and 2-axis tracked PV panel relative to a horizontal panel.

The reasons for using GATOR-GCMOM rather than PVWatts for the global calculations are (1) GATOR-GCMOM covers the entire world, whereas PVWatts covers locations only near specific meteorological stations, (2) GATOR-GCMOM is used here to examine a future 2050 scenario, where aerosol, cloud, temperature, and wind speed properties differ from today, whereas PVWatts treats only past conditions, and (3) we want to use GATOR-GCMOM to calculate incident solar radiation for the two components of 1-axis horizontal tracking that, when combined, exactly comprise the components of 2-axis tracking, and this cannot be done with current PVWatts output. Specifically, one way for a panel to follow the sun exactly throughout the day (2-axis tracking), is for the panel to swivel horizontally around a vertical axis and, independently, swivel vertically around a horizontal axis. In this study, we calculate incident radiation for both cases – namely vertical tracking (swiveling vertically around a horizontal axis with the panel facing south or north) and horizontal tracking (swiveling horizontally around a vertical axis with the panel at optimal south-north tilt), and separately calculate incident radiation for 2-axis tracking. Whereas PVWatts calculates incident radiation for 2-axis tracking, it does not consider either of the above 1-axis options; instead, it invokes a third option, which is to swivel east-to-west around an axis parallel to a specified tilt, not necessarily the optimal tilt, of the panel. That option is not examined here, but the 1-axis horizontal tracking option treated here results in incident radiation within 1–3% of the 2-axis tilting option at most latitudes, thus may be close to optimal, if not optimal, for 1-axis tracking.

Many studies have provided equations that allow for the theoretical calculation of the optimal tilt angle over time of a solar collector based on Earth-sun geometry (e.g., Kern and Harris, 1975; Koronakis, 1986; Lewis, 1987; Gunerhan and Hepbash, 2009; Chang, 2009; Talebizadeh et al., 2011; Yadav and Chandel, 2013). Some of these studies have derived simple linear expressions of optimal tilt angle versus latitude (Chang, 2009; Talebizadeh et al., 2011). However, optimal tilt depends not only on latitude but also on weather conditions, including cloud cover (Kern and Harris, 1975) and the altitude above sea level (Yadav and Chandel, 2013). Because of the difficulty in determining optimal tilt angle as a function of cloud cover and weather conditions, calculators such as PVWatts (NREL, 2017), are often used to estimate optimal tilt angles at specific locations (Yadav and Chandel, 2013). Here, we first use PVWatts to estimate 1–4 optimal tilt angles for each country of the world.

Breyer and Schmid (2010a) combined satellite data with geometric and radiative equations to map global estimates of optimal tilt angles for solar PV. Similarly, Breyer and Schmid (2010a, 2010b), Breyer (2012), Bogdanov and Breyer (2016), Kilickaplan et al. (2017), Breyer et al. (2017a, 2017b), Sadiqa et al. (2018) have applied tilting, single-axis, and/or 2-axis tracking equations to regionally- or globally-gridded solar radiation satellite datasets for energy analysis. However, it appears that no 3-D global or regional climate, weather, or air pollution model has included tilting, 1-axis horizontal tracking, 1-axis vertical tracking, or 2-axis tracking interactively within it. Pelland et al. (2011) used horizontal-plate solar radiation output from a downscaled climate model to estimate PV output from fixed-tilt panels. However, the calculation was done offline (after the 3-D model simulation was performed) rather than online (interactive within the 3-D model), thus it could not examine the effects of, for example, instantaneous temperature and wind speed, on panel performance. This study offers the opportunity to estimate global PV output anywhere in the world with tilted or tracked panels relative to horizontal panels using consistent meteorology and accounting for temperature and wind speed on panel performance.

The ideal tracking or tilting option depends not only on the incident solar radiation relative to a horizontal surface but also on the land or roof area needed to avoid shading, and the cost of tracking versus

tilting. For example, 2-axis tracking in a utility PV plant requires more land area to avoid shading panels behind the front row than do 1-axis tracking or optimal tilting, and 2-axis equipment is more expensive than is 1-axis equipment or optimal tilting. Shading depends not only on panel tilting, but also on the height that panels are placed relative to each other. For example, panels that track the sun placed on a south-facing hillside will likely see less shading than will panels on uniformly elevated ground. Shading further depends on the number of panels placed on each single platform that tracks the sun. In sum, the decision about what type of tracking or tilting option is best ultimately depends not only on the incident radiation received normal to each panel, but also on the land or roof area required to avoid shading and on the cost. In this study, we examine only the ratios of incident radiation with different tilting and tracking options relative to horizontal panels. We do not consider areas required or costs. However, these topics are discussed at length in Breyer (2012).

2. Methodology for determining optimal tilt angles

We first use PVWatts (NREL, 2017), which combines solar resource data from a specific location with 30 years of historic temperature and wind speed data from a nearby meteorological station, characteristics of a solar panel, and orientation of the panel relative to the sun. PVWatts uses ‘typical year’ meteorology from each station, which is relevant, since the data have considerable inter-annual variability. For example, in the U.S., solar output during the lowest 10th percentile solar output meteorological year is on average, 4.8% less than that during the 50th percentile year (Ryberg et al., 2015). PVWatts uses solar data from the National Solar Radiation Database 1961–1990 for the U.S., the Canadian Weather for Energy Calculations database for Canada, and both ASHRAE International Weather for Energy Calculations Version 1.1 data and Solar and Wind Energy Resource Assessment Program data for all other countries. “Typical year” solar radiation values from these databases are updated by PVWatts to account for the reduction in sunlight due to clouds and air pollution at each site. Panel altitude, latitude, longitude, and angle relative to the sun are used to estimate exposure of the panel to sunlight. Air temperature and wind speed data are used to estimate panel temperature.

Here, PVWatts is used to estimate annually averaged solar output in all countries of the world assuming tilted panels. The optimal tilt angle in each location is found by calculating panel output with different tilt angles until the tilt angle giving the maximum output is found. That tilt angle is the optimal tilt angle. In most countries, an optimal tilt angle is estimated for only one location. For several large countries, estimates are obtained for 2–4 locations (Table 1). The optimal tilt angles calculated here are not necessarily the most cost-effective fixed tilt angles because they do not account for the additional land needed to minimize shading between panels (Section 3.2 of Breyer (2012)).

The main assumptions for the calculations with PVWatts include the following: 10 kW of premium panels with a temperature coefficient of $-0.0035/\text{K}$ and 10% efficiency losses. Such losses include soiling (2%), wiring (2%), connections (0.5%), mismatch (2%), light-induced degradation (1.5%), nameplate rating (1%), shading (0.5%), and availability (0.5%). All panels are assumed to face due south in the Northern Hemisphere (180° azimuth angle) or due north in the Southern hemisphere (0° azimuth angle), with the exception of Nairobi, Kenya, which is slightly in the Southern Hemisphere (-1.32° S), but has an optimal tilt angle calculated to face 4° southward.

3. Optimal tilt angle results

Table 1 provides all optimal tilt angle results from PVWatts. Fig. 1 shows the resulting optimal tilt angles versus latitude for each location in each country of the world in Table 1. The results are approximate for each location, so installers would need to make more exact calculations at their location of interest. 3rd-order polynomials are fit through the

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