Solar Energy 144 (2017) 399–410

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Sensitivity of shading calculations to horizon uncertainty

Joseph Ranalli [a,*], Robert Vitagliano [b], Mauro Notaro [b], David J. Starling [b]

[a] *Penn State Hazleton, 76 University Dr., Hazleton, PA 18202, United States*
[b] *Penn State Hazleton, United States*

ARTICLE INFO

Article history:
Received 21 September 2016
Received in revised form 7 December 2016
Accepted 9 January 2017

Keywords:
Shading
Horizon measurement
Irradiance uncertainty

ABSTRACT

Planning for solar power installations requires assessment of potential shading by nearby obstacles on the horizon. A degree of uncertainty exists in measurements of the horizon from the point-of-view of the proposed solar collector. This uncertainty takes the form of errors in the measurement of the azimuth and altitude of obstacles that may cause shading. We modeled irradiance reductions due to shading simulated horizon position measurement uncertainty. Results indicate that the sensitivity of solar simulations to horizon measurements is relatively low (around 2% per degree error for the most sensitive case observed). Beam and diffuse irradiance showed similar sensitivity to horizon measurement errors, and experienced similar trends in sensitivity relative to azimuth and altitude errors. For all cases, sensitivity to altitude errors was observed to be greater than sensitivity to azimuth errors. Conservative estimates of uncertainty in predicted irradiance based upon an existing measurement technique were around 3%.

1. Introduction

In December 2015, the United Nations Framework Convention on Climate Change recognized the "urgent and potentially irreversible threat to human societies and the planet" posed by climate change (United Nations, 2015). Exploitation of renewable energy resources is an important response to the worldwide call for action aimed at reversing the climate change trend. Solar photovoltaics (PV) represent one technology market with room for growth relative to this sustainable energy need. The International Energy Agency reports that in 2014, there were a cumulative 177 GW of solar capacity installed worldwide (accounting for roughly 1% of global demand), with around 40 GW having been installed in that year (International Energy Agency, 2015). The IEA also reports that three countries (Italy, Greece, Germany) produce more than 7% of their electricity demand via PV.

When it comes to economics, renewable energy technologies are typically characterized by high initial equipment costs, with low (in some cases, negligible) operating costs as compared to traditional, fuel-based energy production. As a result, life-cycle cost analysis methods must usually be used to demonstrate the practical economic case for these installations. To support the proliferation of solar development, design level tools have been developed to assist in prediction of the lifetime energy production, costs and savings associated with a proposed PV installation. Due to the long-term nature of the payback, these predictions usually consist of twenty year, or longer, simulations of the proposed system. The ability to accurately and reliably predict the inputs to these simulations, specifically the solar resource during the timespan, is viewed as one of the primary risks from the perspective of those who provide financing for solar installations (Vignola et al., 2012). Vignola et al. propose a methodology by which "bankable" resource data can be obtained, resulting in predictions with higher confidence levels that reduce the risk of uncertainty in the resource.

Solar resource datasets are based upon satellite or ground based observations of the irradiance over time. In general, these datasets are thus unable to account for obstructions that may impede the direct sunlight from reaching the collector on a site-by-site basis. The topography of the proposed site, which serves as the origin for shading of the collector, therefore presents an additional factor in PV output predictions. This shading is of special importance for PV technologies, because the electrical characteristics of PV result in a nonlinear response to shading; a small fraction of a PV panel being shaded may result in a dramatic reduction in the power output. Hanson et al. (2014) report that on a sample of 542 arrays, an average of 8.3% loss due to shading was observed. Approaches exist to model shading of PV arrays. One approach involves the measurement of obstructions from the point of view of the collector, which we term the local horizon, for each proposed solar installation site (Goss et al., 2014). This process is commonly known as a

* Corresponding author.
E-mail address: jar339@psu.edu (J. Ranalli).

http://dx.doi.org/10.1016/j.solener.2017.01.017
0038-092X/

Nomenclature

Symbols

f	shading factor (beam or diffuse)
G	irradiance (see subscripts below)
θ	angle of incidence between sun and collector surface normal
α_s	solar altitude angle
γ_s	solar azimuth angle
γ_c	collector azimuth angle
α_h	altitude angle of a point in the horizon list
γ_h	azimuth angle of a point in the horizon list
β	collector tilt angle
σ	standard deviation (uncertainty)
φ_c	obstacle central azimuth
φ_h	obstacle angular height
φ_w	obstacle azimuthal width

Subscripts for irradiance, G

x_b	beam component
x_d	diffuse component
x_g	ground reflected component
x_t	irradiance on tilted surface
x_{sh}	shaded irradiance (otherwise assumed to be unshaded)

site evaluation or site survey (Galli and Hoberg, 2009). Several technical and practical limitations may prohibit highly detailed site survey measurements from being made, introducing potential uncertainties into the horizon observation. MacAlpine and Deline (2015), in validating a model for PV performance based upon shading inputs, specifically identify the uncertainty of obstacle identification as a key area for future work, stating: "slight mistakes in obstacle sizing or placement may have a large impact on annual performance prediction." In this paper, we will describe a methodology that was employed to investigate the impact of these horizon measurement uncertainties on calculations of the predicted output of a photovoltaic installation.

2. Background

2.1. Modelling of the shaded irradiance

Modelling the impact of shading on a solar panel typically is performed in a two-step process (Goss et al., 2014). The impact of obstructions on available irradiance is determined via geometric calculations related to the horizon, the sun position and the collector field of view. Irradiance reduction may be considered for an entire module, with approximations used to consider its spatial distribution or on a cell-by-cell basis (Goss et al., 2014; Quaschning and Hanitsch, 1995). Models exist for computing an adjusted irradiance based upon the shading at each point (Drif et al., 2008). The adjusted irradiance results can then be used as an input to an electrical model that simulates the PV module performance in terms of the electrical performance of each cell under variable irradiance (Bai et al., 2015; Bishop, 1988; Ishaque et al., 2011), aggregated by modelling connections between cells and strings. This paper deals primarily with the first part of the process: determination of the reduced irradiance.

Models of solar irradiance on a tilted collector consider the solar resource to be the sum of beam, diffuse and reflected-diffuse components (Muneer, 2004; Perez et al., 1990):

$$G_t = G_{bt} + G_{dt} + G_{gt} \tag{1}$$

Further, the diffuse irradiance may at times be considered to include isotropic, circumsolar (i.e. beam-like) and near-horizon components.

$$G_{dt} = G_{d,iso} + G_{d,cir} + G_{d,hor} \tag{2}$$

Shading affects both direct and diffuse irradiance components, but may be expected to influence the different components of the resource in different ways. The most common approach to analyze the differential shading effects is to determine separate beam and diffuse shading factors (Drif et al., 2008; Quaschning and Hanitsch, 1995) which vary between zero (shaded) and one (unshaded). The generic definition of a shade factor is the ratio between shaded and unshaded irradiance:

$$f = \frac{G_{sh}}{G} \tag{3}$$

As stated, separate shading factors may be used to describe the effect of shading on the beam and diffuse irradiance. The beam shading factor (f_b) represents the direct obstruction of the sun by an obstacle. As a result, it depends heavily on the sun position and must usually be calculated in a time dependent fashion. One method for calculation of the beam shading factor is by testing sun positions to determine whether they are located above or below a known horizon. On the other hand, the diffuse shading factor represents the reduction in the view factor between the sky and the collector caused by the horizon. That is, the hemispheric blue sky diffuse irradiance must be reduced to account for obstructions that hide portions of the sky dome. As a result, for a stationary collector, the diffuse shading factor can essentially be considered as constant with respect to time, as it is independent of the sun position. It may be computed using the following integral, considering all diffuse irradiance to be isotropic, adapted from literature (Quaschning and Hanitsch, 1995):

$$f_d = \frac{\iint S(\gamma, \alpha) \cos\theta \cos\alpha d\alpha d\gamma}{\pi(1 + \cos\beta)/2} \tag{4}$$

In this equation, the terms α and γ are the altitude and azimuth, respectively, for a patch of sky. The factor $S(\gamma, \alpha)$ represents the shading function, which takes a value of zero or unity, describing whether or not a patch of sky is shaded on an azimuth and altitude basis. The incidence angle, θ, is computed between the patch of sky at α and γ and the collector (oriented at a tilt of β and an azimuth of γ_c).

Multiple approaches exist for applying the shading factors and computing their influence on the irradiance. The primary differences between approaches occur in the interpretation of the beam shading factor: whether the beam shading factor is considered to be binary or allowed to take fractional values, and whether the beam shading factor is considered to apply only to the beam irradiance or to both the beam and circumsolar diffuse components.

Allowing the beam shading factor to take only binary values implies an infinitesimal (i.e. single point) collector for which the sun is either completely obstructed or not for the entire time period. The possibility of fractional values could be used to model a variety of physical phenomena: partial obstruction of the sunlight, shading for only a portion of the time step, or shading of only part of the collector. As to the second difference, some approaches only consider the beam shading factor to reduce the beam (direct) irradiance, but approaches have been proposed in which the diffuse