Sensitivity of Shading Calculations to Horizon Measurement Accuracy

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ABSTRACT

Residential or small scale commercial solar installations require site surveys in the planning stage to evaluate obstacles that may block light access to a planned array or collector. This can be done by remote sensing techniques and later refined by on-site evaluations. A variety of tools exist to perform these evaluations. Techniques are available in literature for calculating the effect of this known horizon profile on the expected irradiation available to the collector. In this paper, we evaluated the sensitivity of the irradiation to uncertainty in the horizon profile measurement using software written in Python. Uncertainty in both the azimuth and altitude of the horizon can originate from several sources depending on the tool being employed. The uncertainties in measurement couple with the various approximations made in the use of conventional tools such as System Advisor Model (SAM), to produce a cumulative uncertainty. In order to estimate the sensitivity, a set of hypothetical horizon profiles were generated and annual and monthly irradiation were estimated based on TMY3 solar resource data. Estimates of the impact of the horizon profile on the solar resource were made using shading calculation techniques from literature. Variations in the altitude and azimuth of the horizon profile were introduced and the resulting impact on the estimated irradiation is reported. This data may guide interpretation of site survey measurements and future tool development.

1. INTRODUCTION

A common first step in evaluating a potential solar installation is performing a site analysis. This process requires analysis of the local solar resource based on available or inferred meterological data, and investigation of the solar access. Any obstructions to the sun must be identified and their impact on the potential resource availability must be considered.

Several methods exist for obtaining information about potential shading sources. Simple methods can be performed by manually sighting obstacles and marking their azimuth and altitude on a sun chart. Several more sophisticated methods exist that take advantage of digital hardware. A review of these was conducted by Duluk *et al.* [1], who identify several areas for improvement in the state-of-the-art.

Any type of horizon measurement introduces uncertainties in both the azimuth and altitude of the obstacle positions. These uncertainties will influence subsequent calculation of the solar resource on the tilted surface, as they are included in the form of a shading algorithm. In selecting an appropriate site analysis method, or in creating new methods, it is important to be aware of the role that these uncertainties play. In this paper we perform computations of the solar resource with variable horizon profiles to determine the sensitivity to variability in the profile location.

2. ANALYTICAL METHODS

In order to evaluate the impact of shading on the solar resource, a model must be chosen to produce estimates of the resource on a tilted surface. This paper follows closely the approach used in other work by the authors and co-workers [2]. For detailed descriptions of the rationale for the methodology, readers are referred to the paper cited; however, a synopsis of the method is provided here for convenience. All calculations used here were based on Typical Meteorological Year (TMY3) data [3].

2.1. Tilted Surface Irradiance Model

Hourly values of the plane-of-array irradiance are obtained using the model developed by Muneer [4]. This model is similar to the common Perez *et al.* model [5], in that it considers an anisotropic sky for the diffuse irradiance calculation. While developed initially with European data, this model was used by Lave and Kleissl [6] to compute optimum orientations for locations throughout the United States. The Muneer approach requires inputs of two-out-of-three of: the Global Horizontal Irradiance, Direct Normal Irradiance and Diffuse Horizontal Irradiance. In keeping with the default approach used by System Advisor Model (SAM) software [7], we select Direct Normal Irradiance and Diffuse Horizontal Irradiance, obtaining the Global Horizontal Irradiance from a combination thereof. This methodology produces a prediction of the hour-by-hour irradiance on a tilted planar surface (plane-of-array irradiance) based on the sun altitude and azimuth (α_s and γ_s, respectively) and the collector tilt and azimuth (β and γ_c, respectively)

The equations that produce plane-of-array irradiance using the Muneer [4] model are as follows. Beam irradiance on the tilted surface ($G_{b,t}$) is computed from the Direct Normal Irradiance ($G_{b,n}$) using the incidence angle between the sun and the collector (θ_i):

$$G_{b,t} = G_{b,n} * \cos\theta_i$$

The diffuse irradiance on the tilted surface ($G_{d,t}$) requires several intermediate calculations. First a beam clearness index (K_b) is computed as follows:

$$K_b = \frac{G_{b,n}}{\epsilon * 1361\, W/m^2}$$

The correction ϵ accounts for the eccentricity of the earth's orbit. This term is applied in an empirical function, *f*, based on the tilt of the panel. The correlation used here is obtained for Southern Europe, following the choice by Lave and Kleissl:

$$f = \cos^2\left(\frac{\beta}{2}\right) + (0.00263 - 0.7120\, K_b - 0.6883\, K_b^2) * \left[\sin\beta - \beta\cos\beta - \pi\sin^2\left(\frac{\beta}{2}\right)\right]$$

Plane-of-array diffuse irradiance is then calculated using the diffuse horizontal irradiance, $G_{d,h}$.

$$\frac{G_{d,t}}{G_{d,h}} = f * (1 - K_b) + K_b\frac{\cos\theta_i}{\sin\alpha_s}$$

Solar altitudes below 5.7° are treated as a special case and follow the following equation, as described by Page [8]:

$$\frac{G_{d,t}}{G_{d,h}} = \cos^2\left(\frac{\beta}{2}\right) * \left[1 + K_b * \sin^3\left(\frac{\beta}{2}\right)\right] * [1 + K_b * \cos^2\theta_i * \sin^3(90 - \alpha_s)]$$

A term representing the ground reflected irradiance $G_{r,t}$ is computed using a constant ground albedo of $\rho_g = 0.2$ in the following equation:

$$G_{r.t} = \frac{1-\cos\beta}{2}\rho_g(G_{b,n}\sin\alpha_s + G_{d,h})$$

The three terms (Beam, Diffuse Sky and Ground Reflected) are summed to produce to total irradiance on a tilted surface:

$$G_{g,t} = G_{b,t} + G_{d,t} + G_{r,t}$$

2.2. Estimating the Effect of Shade on Irradiance

The approach used for determining the amount of irradiance obstructed by a shadow is similar to that used by SAM. The approach assumes that when an obstruction is present, the beam component of the irradiance is completely obstructed, while other components are left alone. As a result, errors in the position of the horizon create hourly variability in the irradiance, which has an impact on optimum orientations. For the purposes of this study, a point-in-polygon method was adapted to provide determination of whether a given solar position was shaded by the horizon. The finite size of the sun was not considered.

SAM also includes the ability to specify a constant scalar by which the diffuse irradiance can be reduced. This is essentially a correction for the effective sky view factor. In the current study, we have neglected diffuse irradiance scaling, due to the fact that as it is determined as a constant value, it is unlikely to suffer from large effects of uncertainty in the horizon measurement. Additionally, since this affects all hours uniformly, it would not be expected to impact the ultimate optimal azimuth and tilt for a collector.

A more detailed approach to shading is proposed by Drif *et al.*[9], who recommend that the circumsolar portion of the diffuse irradiance be modified when the collector is shaded. At the time of writing, data including this modification was unavailable, however, it should be considered as part of continued work in this area.

2.3. Simulated Horizon Profiles

The horizon profiles used in this study were simulated, that is, analytical profiles that were easily reproducible by computer software. Two shapes were considered, a rectangular obstruction and a parabolic obstruction. Both were characterized by a peak altitude, a central azimuth and a width in azimuth space. In the case of the parabolic profile, the width is the width at the focus of the parabola, and doesn't represent a concrete value in the graph shown. A sample profile is shown in Fig. 1, with the hourly effects of shading highlighted.

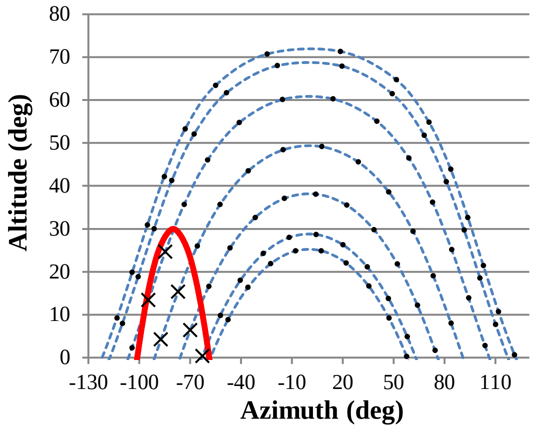

Fig. 1: Sample sun chart. Parabolic profile has parameters (peak = 30°, center = -80°, width = 30°). Dots indicate unshaded hourly position, crosses are shaded.

3. RESULTS AND DISCUSSION

An in-depth discussion is provided for TMY3 data acquired at the closest location to the authors, namely State College, Pennsylvania. A more general discussion using a wider set of locations will follow. Given the caveats about use of TMY3 data for instantaneous solar resource modelling [3], we choose aggregate measures of the solar resource as the most appropriate metrics for this study. The comparison variables chosen were the annual irradiance on a fixed collector and the computed optimum collector orientation.

3.1. Obstruction Central Azimuth Errors

Parabolic profiles of different peaks and widths were applied at central azimuths varying from -180° to +180°. The impacts of this on annual irradiance are shown in Fig. 2. The derivative of this irradiance with respect to azimuthal variation, normalized by the unshaded irradiance, is shown in Fig. 3. Due to the variability of the irradiation data throughout the day, particularly for non-clear sky days, the morning/afternoon impacts are not necessarily symmetric. Increases in variation errors per unit azimuth observed for taller, wider obstructions. The peak variation in annual irradiation caused by a 1° shift in shading profile position is seen to be approximately 0.6% of the unshaded annual irradiation.

Results for flat-top shading obstacles are similar to those seen for the parabolic profiles in Fig. 2. The total reductions in annual irradiation caused by flat top profiles are greater, however. This is intuitive given the greater solid angle obstructed by a flat-top profile with the same parameters. The maximum variation per azimuthal degree remains around 0.6% of the unshaded irradiation.

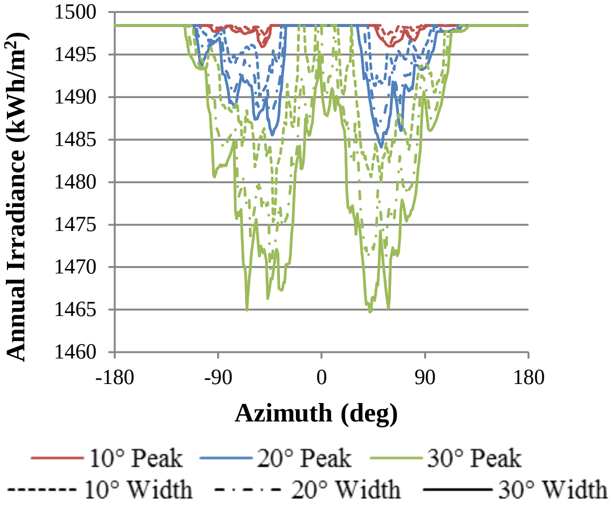

Fig. 2: Annual irradiation with varying parabolic shade profile.

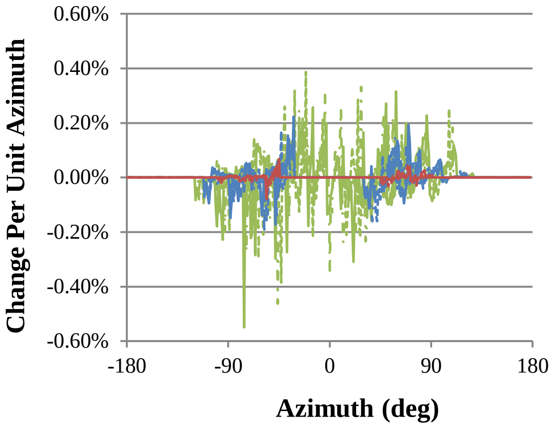

Fig. 3: Percent variation in annual irradiation per degree central azimuth variation. Same legend as seen in Fig. 2.

Due to the computational demand of the optimization calculation, a full complement of optimum calculations could not be performed. Rather, optimum variation was computed for obstacles that moved +/- 10° azimuth from the worst case observed in the data described above. The maximum optimum angle error within the 10° azimuth window was 2.1° in azimuth and 0.4° in tilt. Assuming a 10° azimuthal error in obstacle measurement occurred, and the collector were incorrectly aligned by this amount, the annual irradiation reduction is 215 Wh/year, or 0.014% of the true optimum annual irradiation.

3.2. Obstruction Altitude Errors

The variation caused by fine changes in the peak altitude of the obstruction is shown in Fig. 4. The rate of change of irradiation with respect to peak altitude variation is shown in Fig. 5. Both of these figures highlight results for parabolic obstructions. Flat top obstructions were also tested with similar outcomes. Once again, all results shown are for TMY3 data from State College, PA.

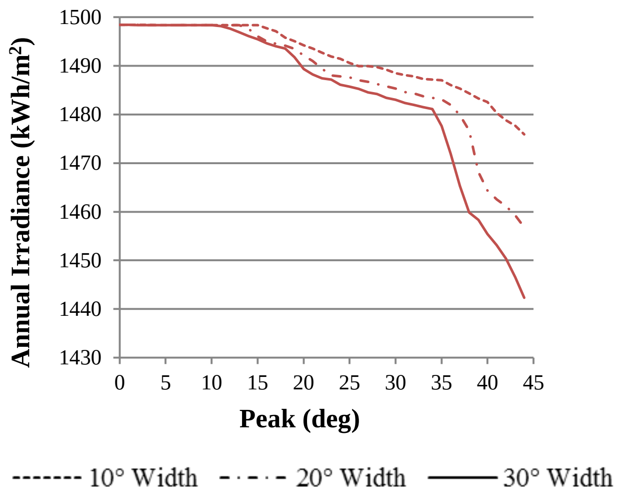

Fig. 4: Variation in annual irradiation due to obstruction altitude error, for parabolic obstruction with a center of $\gamma = -80°$. Collector orientation is $\beta = 20°$ and $\gamma_c = 0°$.

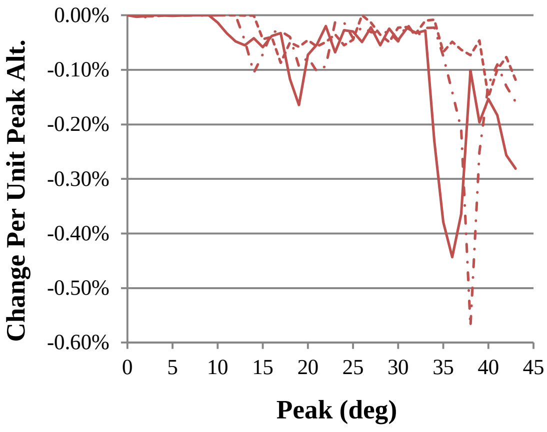

Fig. 5: Rate of change of annual irradiation per unit change in obstruction peak altitude.

These results indicate that taller obstructions are more significantly affected by error in the obstruction altitude than are shorter ones. The maximum error observed (around 0.6% annual irradiation per degree of obstruction altitude) is comparable to that seen in the central azimuth variation discussion.

A general relationship could be described between central azimuth and peak altitude obstruction position errors. From the data shown, it appears that when shading has a larger impact on the annual irradiation, errors in the position of the obstruction are more likely to result in larger errors in the irradiation estimate.

3.3. Errors in Optimum Orientation

Induced error in optimum orientation was discussed briefly in Section 3.1. Expanding upon the previous results, we tested the impact of the shading profile uncertainty on the optimum orientation for a five different test locations: Orlando, FL; Dallas, TX; Phoenix, AZ; Los Angeles, CA; and St. Louis, MO. A base case of a parabolic obstruction with peak of 30°, width of 30° and central azimuth of -80° was chosen. The central azimuth was both increased and decreased by 40° and the central peak altitude was increased and decreased by 10°. The differential choice here reflects the fact that in general, the altitude of an obstacle has one-quarter the maximum range of azimuth. Variation in optimum orientation was observed along with the reduction in annual irradiation caused by the incorrect orientation of the collector.

The maximum absolute errors in optimum collector orientation were 9.3° in azimuth and 1.7° in collector tilt (note that the maximum tilt and azimuth errors did not occur in the same test). The maximum irradiation loss caused by this orientation error was around 0.21% of the annual irradiation, amounting to an annual reduction of approximately 5.0 kWh/m^2. This value represents the irradiation seen by a collector aligned to an incorrect optimum, with the incorrect optimum influenced by errors in the horizon measurement. This error is quite small. In part, the insensitivity of annual irradiation to collector orientation is due to the cosine dependence of incidence angle errors [10].

While the error in actual available irradiation was observed to be very small, errors in predicted annual irradiation were somewhat larger. The reported optimum irradiation varied by as much as 3.7% of the annual irradiation, or roughly 87 kWh/m^2 annually. This indicates that it is more difficult to predict the actual available irradiation than to optimally orient a collector. That is, predictions of the available irradiation are much more sensitive to horizon measurement errors.

4. CONCLUSIONS

The breadth of location data available and the computational complexity of this analysis makes truly general analysis of this problem difficult. As a result, most of the data presented here is somewhat anecdotal in nature. However, some generalizable interpretation is possible.

The annual irradiation predicted for a collector was in general more sensitive to errors in measurement of larger obstacles versus smaller obstacles. Errors in both the altitude and azimuth of the obstruction produced similar “worst case” impacts, but obstructions with peak altitudes less than around 30° had relatively less influence. The optimum angle predicted for a collector was also influenced by errors in the horizon profile measurement, but not substantially. Optimum orientations remained within 10° in azimuth and tilt, even with errors as large as 40° in the obstacle azimuth. The “incorrect” optimum orientations induced by horizon measurement uncertainty had a negligible impact on the actual available irradiation. On the other hand, the impact of the uncertain shading profile on *predictions* of the available irradiation was greater, approaching a worst-case 4% percent of the true value in the cases tested.

These preliminary investigations show that horizon measurement uncertainty has a minimal impact on determining a suitable orientation for a solar collector, because the available irradiation was insensitive to the obstruction errors. Predictive capability was affected in a more significant way, but was still under 5% in all the cases tested. Though these conclusions are made with a variety of qualifications, it appears based on preliminary study that tools for measuring shading impacts on solar installations need not achieve a high degree of precision in order to produce inputs to first-order predictions of the solar resource. Additional investigation is warranted, especially geared toward understanding the impacts of practical horizon profiles and utilizing more complex methodologies for accounting for the reduction of irradiance due to shading.

5. REFERENCES

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