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Decomposing global solar radiation into its direct and diffuse components

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ABSTRACT

To assess the viability of proposed solar installations, knowledge of global solar radiation is not sufficient. For stationary photovoltaic plant, we require global radiation series, but also the contemporaneous diffuse radiation series. Alternatively, for concentrated solar thermal, we need global and direct normal solar radiation. In this paper, we investigate whether one can simply use a model for predicting diffuse radiation using multiple predictions derived by our research team, the Boland–Ridley–Lauret (BRL) model, to give delineations of both diffuse and direct or if we need to use another model for direct or develop a new direct normal statistical model.

Contents

1. Introduction

The evaluation of the performance of a solar collector such as a solar hot water heater or photovoltaic cell requires knowledge of the amount of solar radiation incident upon it. Solar radiation measurements are typically only for global radiation on a horizontal surface. They may be on various time scales, by minute, hour or day. Additionally, one can infer daily totals from satellite images. These global values comprise two components, the direct and the diffuse. DNI, “the direct normal irradiance, is the energy of the direct solar beam falling on a unit area perpendicular to the beam at the Earth's surface. To obtain the global irradiance the additional irradiance reflected from the clouds and the clear sky must be included” [1]. This additional irradiance is the diffuse component.

For various applications, one needs knowledge of diffuse solar radiation and for others, one needs to have measured or estimated values of direct solar radiation. For flat plate collectors and house energy analysis, we require global and diffuse radiation series but for concentrated solar thermal, we need global and direct solar radiation. If only global radiation on a horizontal surface is available through measured data or inferred from satellite images, one will need some type of model to estimate either the diffuse or direct from the global values. When research first began on this topic, the solar collectors in use were all flat plate, and so attention was focused on developing diffuse radiation models.

There is an added reason for computing values of the diffuse radiation. Typically solar collectors are not mounted on a horizontal surface but tilted at some angle to it. Thus it is necessary to calculate values of total solar radiation on a tilted surface given

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values for a horizontal surface. It is not possible to merely employ trigonometric relationships to calculate the solar radiation on a tilted collector. This is because the diffuse radiation is anisotropic over the sky dome and the "radiative configuration factor from the sky to the tilted solar collector is not only a function of the collector orientation, but is also sensitive to the assumed distribution of the diffuse solar radiation across the sky" [2]. There are two different approaches to calculating the diffuse radiation on a tilted surface; using analytic models, for example the Brunger approach [2] or empirical models such as the BRL model [3]. Each rely on knowledge of the diffuse radiation on a horizontal surface. The diffuse component is not generally measured. Consequently, a method must be derived to estimate the diffuse radiation on a horizontal surface based on the measured global radiation on that surface.

Numerous researchers have studied this problem and have been successful to varying degrees. Liu and Jordan [4] developed a relationship between daily diffuse and global radiation which has also been used to predict hourly diffuse values. The predictor typically used in studies is not precisely the global radiation but the "hourly clearness index k_t, the ratio of hourly global horizontal radiation to hourly extraterrestrial radiation" [5]. Orgill and Hollands [6] and Erbs et al. [7] correlate the hourly diffuse radiation with k_t, but Iqbal [8] extended the work of Bugler [9] to develop a model with two predictors, k_t and the solar altitude. Reindl et al. [5] use stepwise regression to "reduce a set of 28 potential predictor variables down to four significant predictors: the clearness index, solar altitude, ambient temperature and relative humidity." They further reduced the model to two predictor variables, k_t and the solar altitude, because the other two variables are not always readily available. Another possible reason was that some combinations of predictors may produce unreasonable values of the diffuse fraction, eg. greater than 1.0 [5]. Skartveit et al. [10] developed a model which in addition to using clearness index and solar altitude as predictors, also added a variability index. This is meant to add the influence of scattered clouds on the sky dome. As well, Gonzales and Calbo [11] stress the importance of including the altitude and the variability of the clearness index in any predictions of the diffuse fraction. Aguiar [12] fitted an exponential model to Mediterranean daily data using only the clearness index and found a consistency of fit amongst locations of similar climate.

Boland et al. [13] presented the use of a decaying logistic function to estimate the diffuse fraction from knowledge of the clearness index. Subsequently, the lead author of that paper combined with other researchers to provide a theoretical basis for selecting that form of the model [14]. This concept was further developed by adding more predictor variables to enhance the fit, resulting in the Boland–Ridley–Lauret (BRL) model [3]. The modelling effort in these three studies can be classified as from a frequentist approach to statistical modelling. This refers to the classical least squares estimation procedure that was used to perform the parameter estimation. In related work [15,16], the problem was undertaken using an alternative statistical starting proposition, Bayesian model building and parameter estimation. It was reassuring that using two separate modelling approaches, the same predictor variables were found to be significant and the parameter estimates proved to be very similar.

In recent years, there has been increasing interest in both concentrating solar thermal (CSP) and concentrating solar photovoltaic (CPV) installations, and as a consequence, an increasing interest in reliable estimation of direct normal radiation. So, we now have the situation where for some applications, we need to estimate diffuse radiation from global radiation, and for others, direct normal radiation (DNI) from global radiation. As testimony to this, Perez–Higueras et al. [17] have developed a simplified model to predict direct normal from global. Additionally, the latest version of Meteonorm software [18] includes two models in this area, one statistically based model, the BRL model [3] for estimating diffuse from global, and one physically based model, the Perez model [19], to estimate DNI from global.

The question that comes immediately to mind is whether we need a plethora of models, specifically do we need a "best" model for estimating diffuse from global and a "best" model for estimating DNI from global? Or, can one model suffice, wherein estimation of the diffuse from global is performed, for instance, and then the DNI is calculated from the other two components? In this paper, we will provide evidence that using the BRL model [3] to estimate diffuse solar fraction, and from it calculate DNI performs as well as any present model specifically designed to estimate the DNI from knowledge of the global. The implication is that we do not need another complex model to model direct solar radiation, because the direct solar radiation coming from the modelling of diffuse solar radiation is sufficient.

The paper is organized as follows. Section 2 describes the development of the logistic function model of hourly direct normal solar radiation with multiple predictors. Comparison of the logistic function model with other models and error analysis is given in Section 3. How direct normal solar radiation is calculated from the BRL model for modelling diffuse solar fraction with multiple predictors and comparison of this procedure with other models is described in Section 4. The final section is devoted to conclusions.

2. Historical development of the diffuse fraction model

The original approach to diffuse fraction estimation from the clearness index relied on a basic assumption that there are three separate regions in the scatterplot – Fig. 1, reflecting differing processes. Lanini [20] discusses this with using the Reindl model [5] to as an example. The model is given below:

$$d=\eta_1+\gamma_1 k_t+\delta_1 \sin\alpha \quad 0\le k_t\le 0.3 \quad d\le 1.0$$
$$d=\eta_2+\gamma_2 k_t+\delta_2 \sin\alpha \quad 0.3<k_t<0.78 \quad 0.1\le d\le 0.97$$
$$d=\eta_3+\gamma_3 k_t+\delta_3 \sin\alpha \quad k_t\ge 0.78 \quad 0.1\le d$$

Lanini shows that for an example data set, the diffuse fraction varies in the middle sub-interval of $0.3\le k_t\le 0.78$, with solar altitude α but has very little variation in the end ranges $k_t<0.3$ and $k_t>0.78$. This is then used as the justification for breaking the interval for k_t into three segments and using separate models in each sub-interval. Reindl may well have been guided by earlier work where a similar splitting was done. Many of the earlier approaches, such as that of Orgill and Hollands [6], used piecewise

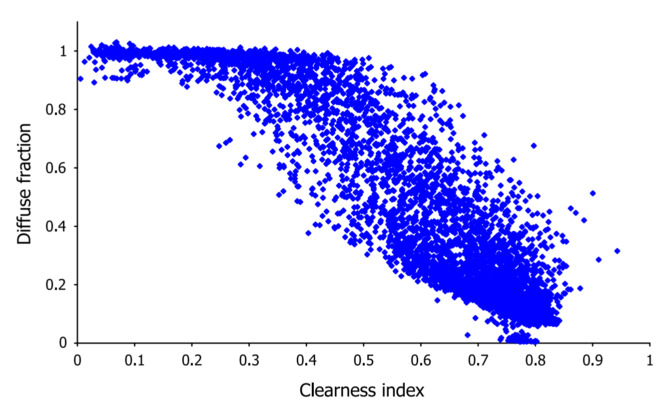

Fig. 1. Diffuse fraction versus clearness index for Adelaide.