The virtual pyranometer: Development and results of early field applications.

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ABSTRACT

A method for evaluating the radiation received on a tilted photovoltaic (PV) array at an intermediate location based on global horizontal radiation measurements from a network of weather stations in the United Kingdom (UK) is presented. The objective of this method is to provide accurate estimates of solar radiation on any PV system in the UK at lower cost than using competing approaches. This will allow for weather corrected condition monitoring. While large PV systems can afford dedicated weather monitoring equipment, this is not economically feasible for smaller systems (<50 kWp). The use of a virtual pyranometer to augment the monitoring of such systems could allow the benefits of detailed radiation monitoring to be expanded to the >85% of UK PV capacity in systems of 10kW or less.

A three step process is described with spatial interpolation done using an inverse distance weighting method, diffuse and direct component separation done using two approaches; a logistic function of hourly clearness index, daily clearness index, solar altitude, apparent solar time a persistence factor for global radiation developed by Boland et al and a piecewise model dependent on solar altitude and hourly clearness index developed by Reindl et al. The third and final step is the transposition of the direct component using basic trigonometry and the Perez anisotropic model of the sky dome for the diffuse component.

The concept of the virtual pyranometer system is described and initial results of testing the elements of the virtual pyranometer model against real data are presented.

Keywords: Solar energy, irradiation, transposition, virtual pyranometer, condition monitoring

1. INTRODUCTION

Performance monitoring of PV systems is a key part of any operation and maintenance program. It is often a requirement to demonstrate the performance ratio of a PV system both at handover and on a continuing basis. Performance ratio measured at short time steps can help with rapid detection of even modest equipment problems. System owners risk losing a significant amount of generation without timely detection of faults. Since the great majority of UK PV systems are supported by the feed-in tariff regime, it is important to maximize their yield. Detailed condition monitoring of the kind described in this paper can facilitate this without the need to resort to the expense of high quality irradiance sensors on each system.

Performance ratio is a dimensionless quantity which expresses the overall losses from a PV system due to all possible factors (Marion, 2005).
Radiation monitoring stations measure global horizontal irradiance to enable comparison across sites. For the majority of applications such as agriculture or ecology, this horizontal irradiance data is sufficient however for PV monitoring it is necessary to have tilted irradiance (assuming the PV system in question is not mounted horizontally).

![Map of the UK showing the location of Met Office Radiation Network sites](image)

The UK has a very dense network of ground monitoring stations for radiation, with 82 stations across the country (Figure 1). As documented in Perez (1996) in many countries satellite data is more accurate than ground data, in the UK where station separation is small, the accuracy of interpolated ground data makes it possible to use this data as the basis of estimated in-plane radiation.

This paper describes the combination of techniques used to derive a virtual dataset of irradiance and presents results of on-site and virtual pyranometer based monitoring for a site in Perth, Scotland.

2. METHODS

The virtual pyranometer described in this paper comprises three key stages. The first stage is the interpolation of global horizontal irradiance data to the location of interest. The second stage is the estimation of the diffuse and direct components of the interpolated global horizontal irradiance. The final stage is the separate transposition of the two components into an arbitrarily tilted plane and recombination of the two components to give total in-plane irradiance. Each of these steps is described in this section.
2.1 Interpolation

Currently, the results presented are based on interpolation by inverse distance weighting. This uses a simple process of calculating the weights for each measurement point as the square of the distance to the target site. Figure 2 shows the locations of the weather stations used in the IDW interpolation and Table 1 the weightings used to estimate the global horizontal irradiance at a site in the City of Perth, Scotland where a PV system instrumented with an in-plane pyranometer is being monitored. This forms the basis of the complete virtual pyranometer process reported here.

![Figure 2](image.png)

**Figure 2** The white circles show the location of Met Office stations, the red circle shows the system location in Perth.

<table>
<thead>
<tr>
<th></th>
<th>Distance (km)</th>
<th>1/r²</th>
<th>Normalized weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strathallan</td>
<td>18.39</td>
<td>0.0544</td>
<td>14.05</td>
</tr>
<tr>
<td>Leuchars</td>
<td>38.42</td>
<td>0.0260</td>
<td>6.73</td>
</tr>
<tr>
<td>Braemar</td>
<td>65.26</td>
<td>0.0153</td>
<td>3.96</td>
</tr>
</tbody>
</table>

2.2 Decomposition

Techniques for separation of diffuse and direct irradiance components are generally based on the correlation of diffuse irradiance and clearness index, k, (the ratio of radiation received at the surface to radiation flux passing through a plane of the same orientation at the top of the atmosphere).

The simplest such model is that of Liu & Jordan (1960), which calculated the diffuse fraction of the global irradiance using a piece-wise first order fit of the clearness index. This work was extended to produce higher order equations relating k and diffuse fraction including those of Erbs (1982); Orgill & Hollands (1977) and Reindl et al (1990). These models retain the piece-wise approach, splitting the data into three bins based on clearness index. For the Reindl model used here, the thresholds are at a value of <0.3 corresponds to overcast skies, a value greater than 0.78 corresponds to a completely clear sky with the intermediate region covering all other conditions.

Recently Boland, Ridley & Lauret (2010) have developed a new diffuse fraction calculation which uses a logistic function of hourly clearness index, persistence factor, solar altitude and
daily clearness index to estimate the diffuse fraction using a single equation for all clearness indices.

Both the Reindl and BRL models have been applied to the interpolated global horizontal data for this work to evaluate the relative merit of the two component separation methods.

There are several conditions under which the decomposition models give unrealistic results. Chiefly when the measured diffuse component is either excessive at intermediate clearness index due to misaligned shading geometry or too low at low clearness index due to extremely low sun angles and consequent air-mass issues. The third set of conditions when relative errors can become large is at very low irradiance. The input data have been filtered according to the same criteria as outlined by Padovan & del Col (2010) to remove these unreliable data.

2.3 Transposition

The methods for transposing each of the two separated components of the horizontal irradiance are very different. Direct horizontal irradiance is transposed by multiplying by the cosine of the angle of incidence of the sun on the tilted plane. Diffuse irradiance transposition is more challenging as it requires a model of the distribution of diffuse radiation across the sky dome.

The transposition of diffuse horizontal irradiance into the plane of the array uses the Perez (1990) model, which superimposes two regions about the Sun’s position and the horizon which modify a uniform background field. This is described visually in Figure 3.

The third component of irradiance on a tilted plane, ground-reflected irradiance, has not been addressed in this work.

3. RESULTS
A Kipp & Zonen CMP3 pyranometer has been installed in-plane as part of a suite of weather sensors on a 35 kWp PV system in Perth, Scotland. The system is installed in the plane of the roof at a pitch of 10° and oriented 30° east of due south.

Performance ratios have been calculated at the site using irradiance data from both the on-site and virtual pyranometer. The virtual pyranometer has been calculated on an hourly basis however the hourly virtual data is extremely noisy relative to the on-site measurements. In order to smooth the effect of this noise, the results presented in this paper are aggregated to a three-day time step.

The performance ratios calculated are extremely high, averaging well over 90% over the study period. While the system has several factors which could lead to a high performance ratio, such as short dc cable runs, highly efficient inverters and low ambient temperatures, these values remain subject to verification.

Figure 4 shows the on-site and interpolated irradiance data. While there is generally a good agreement between the modelled and measured datasets, it appears that over the sunniest periods the virtual pyranometer is overestimating the irradiance relative to the measured performance.

The performance ratio calculated using the virtual pyranometer is in reasonably close agreement with the on-site measurements for the period from April to October before the virtual data starts to diverge toward higher performance ratios. During the April-October period the Reindl decomposition method has given results which match more closely the measured performance ratio.
Figure 5 shows the performance ratio (PR) calculated using the on-site Kipp & Zonen pyranometer and the virtual pyranometer. While the points do not match perfectly, the virtual pyranometer has captured the general trend in PR; a similar chart for PR over a longer time-step would show much of the variability cancelled out.

![Figure 5 PR for Perth calculated using on-site (K&Z) and virtual pyranometer (IDW)](image)

Figure 6 shows the average diurnal variation in PR over the entire monitoring period. The trend in the chart is for PR to be relatively stable over most of the day but with lower PR in the morning and higher PR in the evening. When monthly diurnal variation is evaluated, the skew in the data swings from modest early morning overestimates for April – June to increasingly severe overestimates in the evening from July onwards. The time-base mismatch causing this problem was identified and remedied in December of 2011. When new data becomes available, the inaccuracy of the virtual data should be diminished.

![Figure 6 Daily profile of performance ratio](image)
4. DISCUSSION

While Inverse distance weighting is a computationally simple interpolation technique, it does not easily allow for the calculation of statistics on the accuracy of the interpolated data. The geostatistical technique of kriging is being investigated as an improved technique for this step of the process.

As reported by Padovan & del Col, the methods available for diffuse fraction estimation are currently not satisfactory. At the same time as this finding was reported, the BRL model was published elsewhere. The BRL model presents a compelling conceptualisation with a single function covering the full range of clearness indices however when assessed it is apparent that the model substantially underestimates the diffuse fraction at high clearness index (typically this corresponds to high irradiances and hence, high PV production). By contrast, the Reindl model slightly overestimates the diffuse irradiance at high clearness indices.

Both the BRL and the Reindl model fail to adequately capture the variability in the intermediate region.

An unavoidable effect of interpolating data rather than using on-site measurements of radiation is to smear out variation so when conditions change rapidly, the virtual pyranometer data will be smoother than the on-site values. A similar effect can be observed on a temporal scale with smoother radiation profiles on a longer timescale (e.g. minute vs. day). It is possible that this pseudo-temporal smoothing due to spatial interpolation may make the virtual pyranometer more accurate over longer time periods where spatial sensitivity of the solar radiation distribution is weaker. In order to accurately transpose irradiance from horizontal to in-plane, at least hourly data is required though as shown by this work, it is possible to aggregate data once hourly virtual pyranometer data has been generated. The relationship between time-step and accuracy of the virtual pyranometer is one of several potential areas for future study.

5. CONCLUSIONS

Progress toward a virtual pyranometer consisting of a three stage process of interpolation, decomposition and transposition of global horizontal irradiance to provide data on in-plane irradiance based on a network of global horizontal pyranometer has been presented.

The overall method is reasonably effective though further refinement is necessary before the data generated is of a standard suitable for commercial application. Once the virtual pyranometer has attained this level of reliability, it will be important to define the relationship between virtual pyranometer uncertainty and time-step.

Of the three model stages, the interpolation stage is being upgraded to make use of automated geostatistical methods. The decomposition stage appears to be the stage with the greatest uncertainty and further work is needed to identify the causes and remedy them. Filtering out clear sky conditions and adding additional explanatory variables such as aerosol loading are likely to be the most useful additions to the model. The Perez transposition model appears to be accurately transposing the diffuse irradiance.
REFERENCES


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