PROGRESS TOWARD A VIRTUAL PYRANOMETER FOR LOW COST PERFORMANCE MONITORING OF PV SYSTEMS.

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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 technique developed combines well-established models for radiation transposition into a tilted plane with a geostatistical interpolation method. This method may offer a low cost route to accurate estimates of PV performance ratio in regions with a dense weather sensing network.

While large PV systems can afford dedicated weather monitoring equipment, this is not economically feasible for smaller systems (<50 kW_p). 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 much larger numbers of small systems helping to ensure that they operate as effectively as possible throughout their lifetimes.

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.

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 at handover as well as on an ongoing annual basis. Performance ratio over a shorter time step can provide an early indication of equipment problems. Since most PV systems are supported by a feed-in tariff regime, it is important to maximize their yield. Detailed monitoring of the kind described in this paper can facilitate this.

Performance ratio is a dimensionless quantity which expresses the overall losses from a PV system due to all possible factors (1).

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).

The UK has a very dense network of ground monitoring stations for radiation, with 82 stations across the country (figure 1). While in many countries satellite data is more accurate, 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.
Fig. 1 A Map of the UK showing the location of Met Office Radiation Network sites

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. Data from several different locations have been used to validate each of the model steps in turn and the overall model.

2.1 Interpolation

The interpolation of radiation will use the geostatistical technique of kriging. As with all interpolation techniques, this comprises the calculation of weights. In kriging, the covariance is used to determine the strength of the relationship between each pair of points provided and this is plotted against distance to give the variogram. A fit is made against the variogram in order to calculate the uncertainty associated with the interpolation of data.

The great strength of kriging is that unlike other interpolation techniques it can directly calculate the uncertainty associated with the interpolation of data.

A second advantage compared to more simple techniques is the introduction of shadowing. The influence of points that are further away from the location of interest in the same direction as another point automatically have their weights reduced accordingly.

An R package and associated web processing service, Intamap can be used to interpolate radiation data using a range of techniques. Provided with data at one set of points, Intamap will interpolate that data at a second set of points provided by the user. For the virtual pyranometer this second set of points will be either the coordinates of PV systems or a regular grid, depending on the number of systems being evaluated.

The package also contains provision for cross validation where a subset of the points is not used to run the interpolation and the interpolated values at these points are compared to measured data. The most accurate, and also most computationally intense form of cross validation is leave one out cross validation where a single point is left out of the interpolation input; this is performed for each point in the dataset in turn to provide a thorough analysis of the accuracy of the technique.

The Intamap (3) interpolation process used in this project is still under development. Hourly global horizontal irradiance data from all stations across the UK (2) for 2010 was consolidated into total monthly irradiation for each site. This was provided as the input data to the R Intamap package. The grid of interpolation points was created programmatically for the complete latitude and longitude range covered by the data at a resolution of 0.1 degrees. The results of this interpolation are reported here to give an indication of the potential of the technique.

The remaining results presented are based on an older version of the virtual pyranometer that used inverse distance weighting to calculate the global horizontal irradiance at a given location. This was done for two sites. The first was 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. The second was to cross-validate the inverse distance weighting technique at Kew, London based on data from five encircling stations. Details of the weightings used in each case are provided in tables 1 & 2.
TABLE 1: INVERSE DISTANCE WEIGHTING GROUND STATION WEIGHTS FOR PERTH

<table>
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<tr>
<th>Distance (km)</th>
<th>$1/r^2$</th>
<th>Normalized weights</th>
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<tr>
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<td></td>
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TABLE 2: INVERSE DISTANCE WEIGHTING GROUND STATION WEIGHTS FOR KEW

<table>
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<th>Distance (km)</th>
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<th>Normalized weights</th>
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2.2 Decomposition

Techniques for separation of diffuse and direct irradiance components are generally based on the correlation of diffuse irradiance and clearness index, $k_t$ (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 (4), 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 $k_t$ and diffuse fraction including those of Erbs and Orgill & Hollands (5, 6). In this paper the correlation used was the reduced form of that devised by Reindl et al (7), which is a piece-wise first order function of clearness index and solar altitude.

The performance of the Reindl model was verified using global and component horizontal radiation data from the weather station at the University of Reading. The global irradiance was separated according to the Reindl method and compared with the observed values of diffuse irradiance.

The Reindl paper describes two cases where combinations of $k_t$ and diffuse fraction produce “questionable” data. These cases correspond to (i) overcast conditions with an unreasonably large share of direct irradiance and (ii) clear skies with an unreasonably large share of diffuse irradiance. These points are removed from the fitting model. The data taken from the University of Reading also showed a third case with around 30% of intermediate conditions having unreasonably low levels of diffuse irradiance. These were also removed from our model using the equation \[ I_D / I < 2.0 k_t + 1.3. \]

2.3 Transposition

The methods for transposing 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 difficult 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 (8) model, which superimposes two regions about the Sun's position and the horizon which modify a uniform background field.

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

The Perez model will be tested for a site near Heathrow where PV on a zero carbon housing development is being monitored with both global horizontal and global in-plane irradiance data are collected. The Perez model also feeds into the overall virtual pyranometer being validated at the site in Perth, Scotland.

3. RESULTS

3.1 Kriging interpolation using Intamap

Figure 2 shows the input irradiation data for April 2010, the variogram and raster of the interpolated dataset. The final image shows the same raster generated using the web processing service and layered over a Google Earth image.
Fig. 2 Results of Intamap kriging for April 2010 (a) The experimental variogram, (b) the interpolated irradiance, (c) the interpolated irradiance overlain on Google Earth, (d) the input data

The key value from the variogram is the range, the distance over which there is significant correlation between irradiances. For April 2010, this value was 2.9 degrees which corresponds to a distance of approximately 250 – 300 km.

3.2 Inverse distance weighting interpolation

The measured and inverse distance weighted interpolated daily irradiance and mean bias error are shown in figure 3. It is clear from this chart that the inverse distance weighted irradiance provides a good estimate to measured global horizontal irradiance throughout the year.

Fig. 3 Measured and interpolated irradiance data and mean bias error at Kew

While generally good, the interpolation at Kew showed a small positive bias of 5.72% relative to the observed data. As figure 4 shows these were rarely greater than 10% from the mean bias.

Fig. 4 Distribution of mean bias error on interpolated irradiance at Kew

3.3 Decomposition

The decomposition of global horizontal irradiance into the diffuse and direct components required the introduction of an additional elimination case. Figure 5 shows (a) the unadjusted distribution of measured diffuse irradiances and (b) the modeled data. The distribution of measured diffuse values is skewed with a tail toward lower diffuse fractions. By contrast, the distribution of the modeled data is much more confined and matches quite well with the upper region of the measured range within each clearness index bin.
Modifying the measured diffuse data according to the criteria outlined in section 2.2, the modeled data fit the measurements well, with a residual sum of squares of 41, which is comparable to those reported in the original paper by Reindl et al.

Clearness index and mean bias error were plotted against time which gave a clear indication that there is a seasonality to both variables. Figure 6 shows a subset of this data for Summer 2011.

3.4 Transposition

The transposition model was compared to in-plane and horizontal irradiance measured at a site near Heathrow. The tilted plane was tilted at 18 degrees and oriented directly due south. The in-plane dataset was found to be suffering from a calibration problem with values well below the reported horizontal irradiance. The measurement of horizontal irradiance had some problems with data acquisition so instead, the global horizontal data for a Met Office site less than 5 km away was used for the horizontal data.

Although the in-plane pyranometer had a calibration issue, the profile of the variations in measured and modeled global in-plane irradiance were very similar suggesting that the Perez model is performing well.

3.5 The virtual pyranometer

The decomposition and interpolation elements of the virtual pyranometer method have been validated by comparing calculated in-plane irradiance data with radiation measured in-plane at a zero carbon home development near Heathrow. Data for summer 2011 was analyzed. It was immediately clear from a comparison of the on-site measurement of horizontal irradiance with the in-plane that the in-plane pyranometer was miscalibrated leading to in-plane irradiance often being lower than horizontal irradiance.

Global horizontal irradiance from the Met Office station at Eton Dorney, 4.5km from the development was separated into diffuse and direct components and...
transposed into the plane of the array. Although there is a large mismatch in the absolute values of modeled and measured tilted irradiance, when plotted on independent vertical axes as in figure 7, it is clear that the profile of the two sets of in plane irradiance data are very similar.

This suggests that the separation of horizontal irradiance components and their respective transposition processes have given a good estimate of the tilted irradiance however the calibration error makes the calculation of mean bias error meaningless.

Fig. 7 In-plane pyranometer and virtual pyranometer tilted irradiance

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 degrees and oriented 30 degrees east of due south.

Daily performance ratios have been calculated at the site using irradiance data from both the on-site and virtual pyranometer and the results presented in this paper are presented for weekly performance ratio for clarity. 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, these values are still subject to verification.

The important point to draw from figure 8 is the similarity of the on-site and interpolated irradiance data.

Fig. 8 Weekly tilted irradiance measured on site (K&Z, SMA) and using the virtual pyranometer (IDW)

Fig. 9 Weekly PR for Perth calculated using on-site (K&Z) and virtual pyranometer (IDW)

Figure 9 shows the weekly 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 monthly PR would show much of the variability cancelled out.

Fig. 10 Daily profile of performance ratio
Figure 10 shows the variation in PR over the day. 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. This is an artifact of a mismatch in the time bases of the yield and irradiance data which has since been identified and corrected.

4. DISCUSSION

The Intamap interpolation process seems to offer many advantages over the inverse distance weighting approach. The potential for automating the cross validation of data and interpolating to multiple sites simultaneously and in close to real time represent clear opportunities to improve the robustness and usefulness of the virtual pyranometer. The initial results presented in this paper do not make use of the cross validation function. It is important to perform this analysis to confirm that the interpolation process is valid.

As horizontal irradiance was unavailable at the Perth site, an interpolated dataset was created for the Met Office station at Kew and compared to the global horizontal irradiance data measured there. The interpolated readings were typically 6% above the measured irradiance. The likely cause of this is the increase in air pollution prevailing at Kew, much closer to central London than the interpolation stations located on the periphery of London. Although the method has produced positive results here, it is important to further test the interpolation process by leave-one out validation at other locations.

The inverse distance weighting process has not been analyzed to find conditions for which accuracy is particularly poor; for example, low irradiance or sun-angle could lead to small absolute errors translating into large relative errors. The calculations should be performed using datasets which have been filtered to remove these conditions to understand their impact on overall model performance.

The Reindl decomposition model seems to represent the least satisfactory element of the virtual pyranometer at this point. For a high clearness index, the model makes a reasonably good prediction of direct and diffuse irradiance.

A large proportion of the original data was eliminated by the application of the three cases for “questionable” values of diffuse fraction and clearness index. In addition, there were very few data points where the diffuse fraction was greater than the Reindl model values for a given clearness index, however, there were large numbers well below the modeled values.

This suggests that there is some identifiable set of conditions which are not being adequately captured by a model which is reliant on only clearness index and solar altitude. The evidence for increased error over summer is an indicator which should be pursued.

An alternative explanation is that there are problems with the measurement of the diffuse irradiance which manifest themselves as an unreasonably low diffuse fraction. If this were the case, it could be reasonably expected that the issue would result in a common effect across all data, but this is not what is observed in the data. If the raw data is re-checked and proves reliable, the creation of a new diffuse radiation correlation based on the observed values that can be carried out using only minimal equipment (i.e. measurement of global horizontal irradiance) may be necessary.

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 temporal smoothing may make the virtual pyranometer more accurate over longer time periods. In order to accurately transpose irradiance from horizontal to in-plane, at least hourly data is required though it would be possible to aggregate data once hourly virtual pyranometer data has been generated. The relationship between time-step and accuracy of the virtual pyranometer would be a worthwhile area for future study.

5. CONCLUSION

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.

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. The Perez transposition model appears to be accurately transposing the diffuse irradiance.
6. ACKNOWLEDGEMENTS

The authors would like to thank Will Usher of UCL Energy Institute and Helen Greatrex of University of Reading Department of Meteorology for their assistance with kriging and R.

This research was funded by the EPSRC and SSE.

7. REFERENCES


(3) Pebesma, G. et al, INTAMAP: the design and implementation of an interoperable automated interpolation web service, Computers & Geosciences, International Association for Mathematical Geology, 2011


