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Triplet Irradiance Measurements

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Introduction

Cloud properties including speed, direction, density, and thickness, govern the dynamic features of irradiance, and hence the dynamic features of power output from PV panels and arrays. For example, ramp rates are expected to be directly proportional to the cloud speed and related to the coincidence of cloud direction and array orientation.

With the rapid growth in solar PV installations, concerns have been raised regarding grid impacts from output power fluctuations caused by cloud motion [1]. Thus, there is a requirement for improved observation and simulation of the connection between cloud dynamics, irradiance, and PV power output, in order to support the further growth of solar PV and mitigate the negative impacts that it might cause to the grid.

Cloud speed and direction play an important role in siting, sizing, and layout of solar PV plants, forecasting and development of models that can be used to estimate ramp rates caused by clouds on solar PV [2-7]. Bosch et al. [6] indicated that ramp rates are directly proportional to the cloud speed.

A popular method is to detect transitions in shading over three or more irradiance sensors, as clouds obscure sunlight. Time delays between sensor pairs detecting the same cloud edge are calculated, and from the geometry of the sensor layout, cloud speed and direction are calculated. However, some authors report problems using the cross-correlation technique in linear cloud edge method to obtain time delays between the signal pairs and instead used maxima and minima points of the signals to calculate the cloud speed. It can be argued that use of minima or maxima points might not be accurate enough with the use of linear cloud edge method but the time delays between the ramping edges are more representative as they are directly caused by the cloud edges. Regarding the most correlated pair used by Fung et al. [4], Wang et al. [7] cast doubt on its accuracy and instead developed an improved method of linear cloud edge which plotted a cosine curve but suffered a limitation because it could only derive cloud speed that was at right angle to the cloud edge and underestimating it when it was at a different angle. Cloud properties can also be calculated from satellite imagery, but limitations arise from image frequency and image processing [6,8].

In this work, we demonstrate that cloud speed and direction can be reliably and accurately determined using a well-spaced triplet of silicon irradiance sensors logged at high frequency. Cross-correlation is used to calculate time delays of cloud edges detected from sensor pairs. Furthermore, a positive correlation between cloud speed and 10 m wind speed is found, with deflection consistent with ground friction and the Coriolis force.

Method

Data was initially recorded for 5 months from March 2016, near Leeds, UK. Further data will be recorded in 2018, near Kampala, Uganda.

Solar irradiance was recorded using a set of three silicon photodiode sensors, model SP-230 from Apogee Instruments Incorporation. This type of sensor features a high sensitivity of 0.2 mV W^{-1} m^{-2} and a spectral range of 360 to 1120 nm, matching the spectral response of solar PV. The voltage output of the sensors were then transmitted, amplified ten times, and filtered before being recorded by a logomatic V2 data logger in binary format at high-frequency (10.17Hz).

The sensors were set up in an open garden near Leeds with dimensions shown in figure 1. The positions of the sensors were dictated by suitable mounting points and to minimise shading. An approaching cloud edge is also illustrated. Note that the cloud direction, *Φ*, isn't assumed to be perpendicular to the cloud edge angle, θ, necessitating the use of four time delays to complete the calculation of *Φ*, θ_1, θ_2, and v (cloud speed). This is achieved by using two separate cloud edges with angles θ_1 and θ_2. The cloud direction and speed are assumed to remain constant within the two detected cloud edges, but angles θ_1 and θ_2 are not assumed identical.

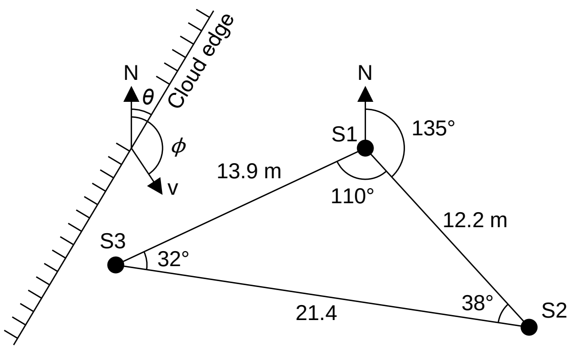

Figure 1. Sensor layout and cloud edge illustration. S1, S2 and S3 are the sensors.

The two cloud-edge technique developed by Bosch et al. [6] was used to derive cloud speed and direction, and the reader should refer to this article for details of equations used. Sensor pair S1 and S3 provide time delays TE1 and TE2, while sensor pair S1 and S2 provide time delays TF1 and TF2.

The cross-correlation technique was used to derive the time delays between solar irradiance signals from the two sensor pairs. Before carrying out the cross-correlation, a 3051 sample moving average, which was equivalent to a 5-minute smoothing, was subtracted from the normalised signals to bring the signals pairs to a common average zero-level. Cloud speed values below 2 ms^{-1} and above 50 ms^{-1} were discarded as they were considered unrealistic and could have been generated by noise. Cloud directions and speeds obtained within a given hour were averaged. It is worth noting that it was not possible to derive cloud direction and speed during overcast conditions due to lack of valid cloud edges.

Ramp rates were determined by deriving the gradients of the ramps generated by the cloud edges. In this case, one signal from a single sensor was sufficient and sensor S3 was used. Front and trailing cloud edges generated negative and positive ramp rates respectively. However, the maximum absolute ramp rate occurring within a given hour was picked. The signal was subjected to filtering using Savitzky-Golay filter with a weighting vector of five with a length of 23 samples to reduce noise. All signal processing and cross-correlation were performed using MATLAB on a standard PC.

Results and analysis

From the 2016 data, minimum cloud speeds of 4 ms-1 and a maximum of 40 ms-1 were obtained while dominant direction was found to be from the west-northwest. Comparison was then made to hourly wind speed and direction data recorded at 10 m above the ground level from the Bingley SAMOS weather station which is located 4 km away from the triplet of irradiance sensors. Cloud speed is invariably higher than the 10 m wind speed, on account of friction between air and the earth's surface. This well-known effect is quantified using

$$\mathrm{U(z)}=\mathrm{U}_{10}\,\frac{ln(Z/Z_o)}{ln(10/Z_o)}$$

where U(z) is the wind speed, z is height, and z_0 is surface roughness length. Consistent with this relationship, we report a linear relationship between cloud speed and 10 m wind speed, with a correlation coefficient, R, of 0.9.

Comparing cloud direction with wind direction, a deflection of 22.50° in the cloud direction clockwise of the 10 m wind direction was observed. The dominant 10 m wind direction was found to be from the west, while the dominant direction of the clouds was found to be from the west-northwest.

Ramp rates were determined and compared with 10 m wind speeds. A low to moderate positive correlation were observed with a minimum and maximum correlation coefficient, R, of 0.20 and 0.44 in June and April respectively. These correlations are understood to have been diminished because of noise and solar irradiance reflected and focused onto the sensors by various cloud sides.

Overall, it was observed that all the computed cloud speeds were higher than the respective recorded 10 m wind speeds throughout the period of the study. It should be noted that hourly recorded 10 m wind speeds were selected and compared with the cloud speeds only when there were cloud speed results, meaning partial cloud conditions. Strong positive correlation was observed in the comparison between 10 m wind speed and the cloud speed. The comparison was carried out using three different approaches.

In the first approach, selecting results obtained in March 2016 for the analysis, a scatter plot of daily averaged cloud speeds against wind speeds is shown in figure 2.

In the second approach, a scatter plot was drawn between the hourly cloud speeds and the hourly recorded 10 m wind speeds for five months (from March to July 2016). The results are not shown here, but it is noticeable that a similar trend was maintained as in figure 2. However, there is a wide range of different cloud speeds within a given recorded 10 m wind speed. One of the reasons for this was considered to be as a result of different cloud types and layers that were located at different altitudes moving at different speeds as reported by Janeiro et al. [8].

In the third approach, a scatter plot of the average of the cloud speeds that occurred in a given 10 m wind speed for the period of five months (from March to July 2016) was plotted against the 10 m wind speeds and the result is shown in figure 3. The correlation coefficient, R, was found to be 0.95, but only when the relationship is allowed to be linear but not proportional. This is because low correlation is observed at low wind speed.

A sensor triplet has also been installed as part of a solar irradiance measuring station at the Centre for Research in Energy and Energy Conservation (CREEC) in Kampala, Uganda. In common with many developing nations, Uganda's demand for electricity is projected to increase rapidly driven by electrification of rural communities.

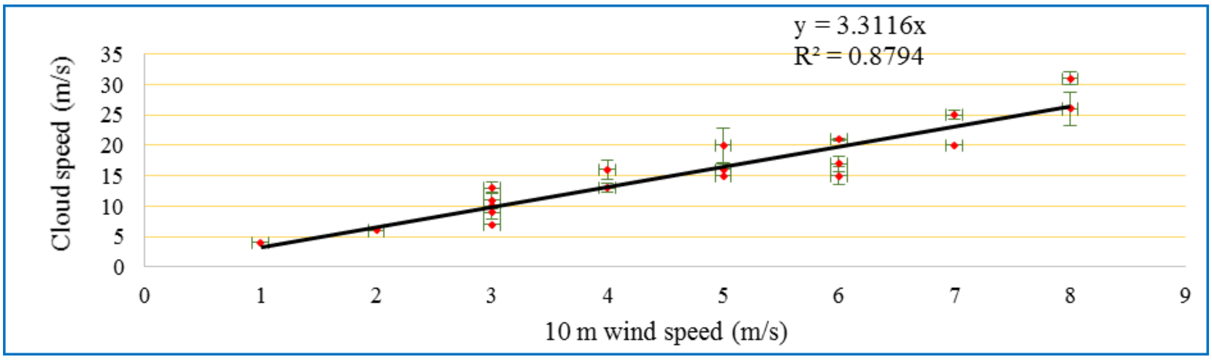

Figure 2. Scatter plot between daily average of cloud speeds and 10 m wind speeds in March.

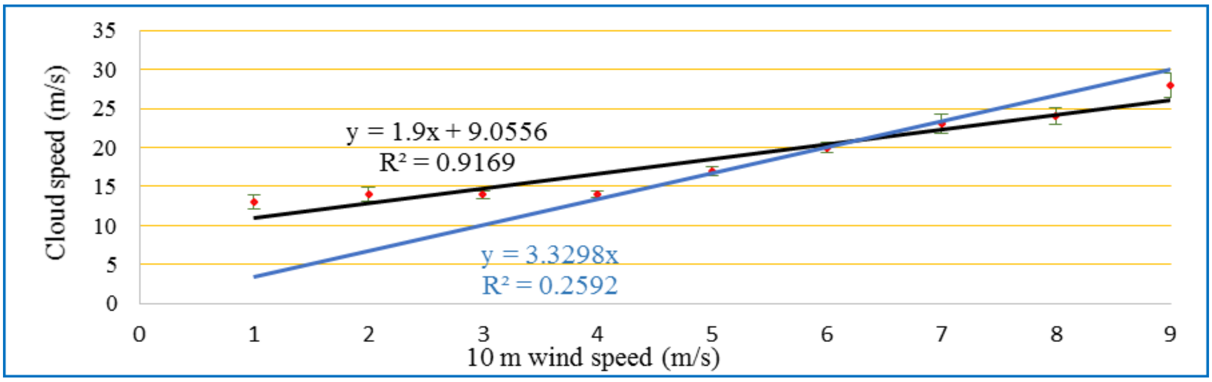

Figure 3. Scatter plot between averaged cloud speed at a given 10 m wind speeds for 5 months (from March to July 2016). Linear and proportional best fit lines are shown.

There is significant potential to provide the generation from PV, exploiting a very high solar resource. For comparison, the average annual global horizontal irradiation in Kampala is 2100 kWh m^{-2}, while it is 950 kWh m^{-2} in Leeds. The weather in Kampala is strongly influenced by Lake Victoria, with partial cloud common at some times during the year.

The sensors were secured into place on top of the roof of CREEC approximately 6 m apart. The roof of the CREEC building was the only feasible location due to challenges such as shading, theft and safety during installation. Data will be collected once a week from the data logger secured inside the building. This experiment will provide a contrasting dataset to that obtained in Leeds, supporting research in robust PV-biofuel microgrids and aid modelling of a wider scoped project for solar-driven biomass processing.

Discussion and conclusion

Cloud speed and direction were derived successfully using solar irradiance data recorded by a triplet of silicon photodiode sensors using cross-correlation to detect time delays between sensors. A minimum of 4 ms^{-1} and a maximum of 40 ms^{-1} of cloud speeds were obtained. Investigation into the relationship between cloud speed and 10 m wind speed showed a strong positive correlation which was considered to be linear, however, the relationship was suspected to be maintained only up to the gradient height as above this the geostrophic wind flows at a constant speed. In addition, very low wind speeds showed a low correlation. A clockwise deflection of cloud direction to the wind direction was observed. Dominant 10 m wind direction was found to be from the west while dominant cloud direction was from west-northwest. The deflection was attributed to a decrease in influence of surface friction and increase in the influence of Coriolis force with increase in height. Previous authors had reported a direct proportionality between cloud speed and ramp rates, thus, having discovered a strong positive correlation between cloud speed and 10 m wind speed, then a similar proportionality was expected between the wind speed and the ramp rates. However, low to moderate positive correlation was observed as a result of interference which was believed to be from noise and sunlight reflected and focused onto the sensors by cloud sides.

Acknowledgements

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