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Spectral irradiance measurements for photovoltaic systems in maritime climates

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Abstract
Variety of materials used to manufacture photovoltaic cells rises the question about methods of accurate reference irradiance measurements, which could be applied on a level of photovoltaic plant deployment. Mismatch between spectral sensitivity of the photovoltaic module and reference sensor used for irradiance measurements increases uncertainty of available energy rating. Significance of spectral mismatch for overall energy production rating depends also on spectral variations of the solar radiation and circumstances of their appearance. Western Europe stays under the influence of maritime climate which is characterized by reliable cloud cover and high humidity. Carried campaign provides analysis of the spectral radiation in maritime climate and discusses its impact in term of PV systems applications.

Introduction
Newly introduced device technologies increase differentiation in modules spectral response. Spectral effects can be observed at their most for thin film a-Si modules. Knowing the accurate intensity and spectral distribution of the solar radiation increases the accuracy of the technology specific energy rating. The magnitude of spectral effects is widely discussed but no comprehensive measurements are taken to resolve this debate. This requires measurements of incident spectrum in a number of climatic zones to resolve the influence of various environmental effects. There are two main factors causing spectral variations of solar radiation on the surface of the Earth, accordingly: Rayleigh scattering on atmospheric gases and Mie scattering on large particles (mainly water droplets). In a clear sky conditions solar spectrum varies due to changes in the atmosphere thickness through which rays need to travel. Water droplets (clouds, haze, air humidity) cause the Mie scattering. It is not dependant on wavelength and it increases with the size of the particles. This paper presents an analysis of the variations of spectral irradiance and the effects which they have on accuracy of energy production and reference energy rating.

Approach
Broadband irradiance sensors measure radiant power, which is the sum of spectral irradiance received from the light source over the specified bandwidth (1).

$$H = \int_{\lambda_{a}}^{\lambda_{b}} E(\lambda) d\lambda \left[ \frac{W}{m^2} \right]$$

(1)

Where \(E(\lambda)\) is spectral irradiance.

The same radiant power may be received by broadband sensor as a result of interaction with different amounts of photons, depending on their energy (i.e. different spectral distributions). Radiant power does not provide accurate information on the number of photons that interact with a sensor. For currently available photovoltaic devices it is important to know the number of photons that are able to generate carriers instead of the sunlight’s radiant power. Spectral irradiance describes the distribution of a radiant power over the spectrum. If the radiant power is known for a defined wavelength interval, photon flux can easily be calculated (2).

$$\phi(\lambda) = \frac{E(\lambda)}{E_p(\lambda)} \left[ \frac{\text{photons}}{s \cdot m^2 \cdot \mu m} \right]$$

(2)

Where \(\phi(\lambda)\) is the photon flux, \(E(\lambda)\) is the spectral irradiance and \(E_p(\lambda)\) is the energy of a photon in Joules.

By combining photon flux \(\phi(\lambda)\) with external quantum efficiency EQE(\(\lambda\)) of the cell the spectral current density for a cell can be calculated.

$$J(\lambda) = EQE(\lambda) \cdot \phi(\lambda) \left[ \frac{A}{m^2 \cdot \mu m} \right]$$

(3)

Integration of the \(J(\lambda)\) through the wavelengths under a given spectral photon flux gives the resultant density of the current available from the cell (4).

$$J = \int J(\lambda) d\lambda \left[ \frac{A}{m^2} \right]$$

(4)

As it was show above for two equal observation of radiant power (H) different current densities (J) can be obtained depending on spectrum. Assuming than
the cell serial resistance is low illuminated current density J is almost equal to short circuit current density $J_{SC}$.

One of the frequently used way to express spectral composition of the irradiance as a one number is an average photon energy.

$$APE = \frac{\int \lambda E(\lambda) d\lambda}{\int \lambda \Phi(\lambda) d\lambda} \text{[eV]}$$  \hspace{1cm} (5)

By far APE, expressed in electronvolts, gives the best description of the global spectral variations. However correlation between the APE and available current density depends on EQE of the device for which current density is calculated. In photovoltaics more appropriate is to use ratio of available current density calculated for given technology (under measured spectrum) $J_{SC}$ and broadband radiant power G $J_{SC}/G$ (6). Presented ratio can be described as an current generation efficiency of the incident radiation.

$$\eta_g = \frac{J_{SC}/G}{A/W}$$  \hspace{1cm} (6)

Experimental Setup

For the purpose of this work dedicated meteorological station with facilities to measure PV modules short circuit current and temperature was designed and build in Loughborough University. Station was equipped with three diode-array base grating spectroradiometers (EKO MS-700), three ventilated thermopile pyranometers (K&Z CMP11), air humidity and temperature sensor and wind speed and wind direction sensor. Spectroradiometers and pyranometers were installed in three different variants: horizontal plane, plane of array (45°) and on the solar tracker. Data are being logged since 20/10/2009. This paper limits a range of presented results only to inplane measurements. This is due to fact that the main interest of the authors was to analyse influence of the spectral variations of the radiation in PV modules plane.

Results and Discussion

For the purpose of presented analysis spectral irradiance measurements from period of 09/01/2009 to 31/12/2010 were used. Photovoltaic devices are sensitive to the spectral composition of the light striking their surface. Variation of the spectral distribution of solar radiation on the Earth surface causes differences in current density available for photovoltaic devices. To express spectral variations of the solar radiation on the earth surface APE (Average Photon Energy) was specified by other researchers. APE index provides information about global shift of the spectral distribution. It does not allow for accurate calculations of the theoreatical current density available for given device. In that sense the ratio between available current density ($J_{SC}$) and same plane broadband solar radiation on the earth surface ($G$) seems to be more relevant for photovoltaic applications. Figure 1 presents dependencies between APE and $J_{SC}/G$.

As it can be seen, there is a certain level of correlation between APE and $J_{SC}/G$, but its scale and character is technology and conditions dependant. Moreover $J_{SC}/G$ allow for direct conversion from radiant power (G) to technology specific short circuit current ($I_{SC}$). The simplest way to show the effects of spectral variations of the solar radiation on maximal current density is to plot the ratio of maximal current density $J_{SC,ideal}/G$ against G (as shown in Figure 2).

As shown in Figure 2 ratio of $J_{SC,ideal}/G$ disperse mainly over the range of 0.50 and 0.57 [A/W]. It results in ±6.5% of differences between measured broadband radiation and available current density. It can be seen that dispersion of the $J_{SC,ideal}/G$ is dependent on atmospheric conditions.
conditions (air mass factor and clearness index). More clearance about this situation has been provided in Figure 3.

As shown in Figure 3, two correlations, separated by clearness index, can be observed. The first one happens for the $k_T > 0.5$ and relates to clear days conditions. $J_{SC_{ideal}}/G$ increases with the air mass as the spectrum is shifting to more red. Second correlation happens for the $k_T < 0.5$ and relates to cloudy days. For this conditions $J_{SC_{ideal}}/G$ depends on the strength of the overcast (thickness of the clouds). During overcasted days solar spectrum shifts to more blue due to missing solar beam radiation component. There is a visible increase in $J_{SC_{ideal}}/G$ over the AM equal to about 1.3%. It can be explained with red shift of the spectrum caused by increasing thickness of the atmosphere for high values of AM.

For $k_T > 0.5$ there is a clear dependency between $J_{SC_{ideal}}/G$ and AM. Relative current density increases with the air mass. For $k_T < 0.5$ relation between $J_{SC_{ideal}}/G$ and AM become random. As shown in previous figures variations of the current density over the broadband radiant power can be significant. This situation may lead to a conclusion, that broadband sensors should not be used to determine reference level of irradiance in power plants as they will provide inaccurate measures. However presence of spectral variations in solar radiation as well as spectral sensitivity of photovoltaic devices are not sufficient evidences to prove the significance of spectral effects for energy production. To do so, it needs to be determined what is the contribution of spectrally influenced currents in overall current sum. Figure 5 present distribution of current density $J_{SC_{ideal}}$ against clearness index ($k_T$) and air mass factor (AM).

High values of the $J_{SC_{ideal}}$ are possible mostly for $k_T > 0.3$ and AM < 4. Final contribution of the $J_{SC_{ideal}}$ in an energy generation depends not only on its instantaneous measure, but also on frequency of its occurrence. For that reason $J_{SC_{ideal}}$ presented in Figure 5 was binned and aggregated. Figure 6 presents yearly sums of the maximal current density received under different $k_T$ and AM.

Only 1.5% of yearly summed current density lays over AM > 4 (80% for AM < 2). There are two maxima of yearly summed current density: at $k_T = 0.3$ AM = 4 and $k_T = 0.75$ AM = 1.2. Main contribution to the first maxima have summer days with medium overcast ($k_T = 0.3$ means that 39% of maximal solar radiation is available). This maxima drifts towards the AM = 4 and $k_T = 0.3$ with the seasonal variation of the
air mass and is moderate by shortening duration of the day. Second maxima relates to summer clear days. It drift towards the AM=4 and kT=0.6 for clear winter days, with the seasonal and daily variation of the air mass and is moderated by shortening duration of the day. Some seasonal dependency between clearness index (kT) and airmass factor (AM) is observed in this region. As shown in Figure 3 differences between measured broadband radiation and available current density can be significant. However, applying the boundaries given by the distribution of yearly summed current densities given in Figure 6 this significance is effectively reduced. Air mass dependant current density of clear days overlays with clearness index dependant current density of cloudy days. Both effects mask themselves and equalise spectral dependencies. Spectral variations of the current density, present in the energy production significant area, can also be shown as a function of time. (Figure 7).

Figure 7. Yearly distribution of the JSC/\text{G} for four different technologies.

As shown in Figure 7 yearly variations of the JSC/\text{G} tend to be air mass and technology dependant. Amorphous silicon seems to have seasonal increase of performance during summer month and crystalline and CIS modules seems to have lower performance at the same time. In reality these differences are caused by spectral variations of the sunlight which stay unrecognised while observed by broadband sensors and are related to differences in the available current density. Largest differences has been noticed for winter months, what limits its overall significance, as the contribution to overall energy production is for them low.

Conclusions

Spectral variation of solar radiation have a significant influence on accuracy of estimation of solar resources. However the largest differences take place for low level irradiance (mornings, evenings, winter and heavily overcastted days). Most of the energy reaches the surface of the earth at the low air mass and light overcast conditions, what moderate spectral influences on total energy production. Some of the seasonal variations of module performance may have a partial explanation in spectral variations of the sunlight and can be caused by reference sensor mismatch. The most accurate rating of the available energy can be given with use of technology specific current density JSC. Regardless limited significance of the spectral variations, reference measurements taken by calibrated reference cells made in the same technology as monitored modules seems to be less biased by spectral variations than broadband radiation sensors due to lower spectral mismatch. Utilization of spectroradiometers may have some advantages in a large scale plants where the different modules technologies were used as the way of irradiance data validation. It is expected that for southern climates characterized by lower clouds cover, influences of the spectral variations of the solar radiation may have stronger effect on energy production.

References