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Feasibility of Average Photon Energy (APE) in performance evaluation of PV modules equipped with IR reflecting filter

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Abstract—In this work, we investigate the feasibility of the APE (Average Photon Energy) parameter as a qualitative representation of solar spectra in modeling the performance of PV modules equipped with a filter capable of reflecting parasitic IR irradiance. We evaluate APEs' relation with parasitical absorption of solar irradiance in the structure of PV modules (glass, lamination foil, back sheet), as well as its relation to the calculated temperature of PV modules operating in standard conditions. In our analysis, we employ real-world data of spectral irradiance.

The increase of photovoltaic (PV) cells' efficiency approaching the efficiency limit of a single junction device has forced researchers to explore ways beyond standard structural-material optimization, such as adjusting PV systems to provide better working conditions. A natural area of potential improvements is limiting losses of spectral mismatch between solar cells' spectral response and incident solar irradiance spectra through varied methods of complex light management. These approaches include up- and down-converting layers, resulting in the downshifting of the solar spectra with varying levels of success [1]. Another approach to improve the operating conditions of solar cells is an attempt to decrease the operating temperature, either through transferring and utilizing heat for other purposes (such as in hybrid PV-solar thermal devices) [2] or through the application of filters capable of reflecting infrared part of the spectrum, which cannot be efficiently utilized by the PV cell, and significantly contributes to heating PV module due to parasitic absorption not only by the cell itself but also by absorption in the cover glass, lamination foils such as EVA or back sheet of insulating material such as Tedlar [3].

All the mentioned approaches share the requirement for the availability of spectral data, which are rarely available and generally cumbersome in simplified models aiming to estimate the impact of the given upgrade on the resulting energy yields of the operating temperature of photovoltaic devices. This is particularly important in the case of commercial software for quick photovoltaic system design. As a result, suitable proxy parameters reflecting spectral properties are sought.

In this work, we evaluate the feasibility of employing average photon energy (APE) as a proxy parameter for incident solar spectra in estimating operation parameters of photovoltaic modules equipped with perfect filters capable of reflecting an infrared part of a solar spectrum.

Average photon energy is derived from measured solar spectrum data using a set of two following equations [4]:

$$\lambda_{eff} = \frac{\int_b^a \lambda E(\lambda) d\lambda}{\int_b^a E(\lambda) d\lambda} \tag{1}$$

where $E(\lambda)$ is spectral irradiance, a and b are limits of considered spectral band, λ_{eff} is effective wavelength in nm, which is further converted to APE expressed in eV [4]:

$$APE = hc(kq\lambda_{eff})^{-1} \tag{2}$$

where c is speed of light in vacuum, h is Planck constant.

In the case of this study, we use meteorological data (including spectral) from NREL [5] from a period of a full calendar year. The data is collected at hourly intervals. We limit the available spectral data to the 280–2500 nm range.

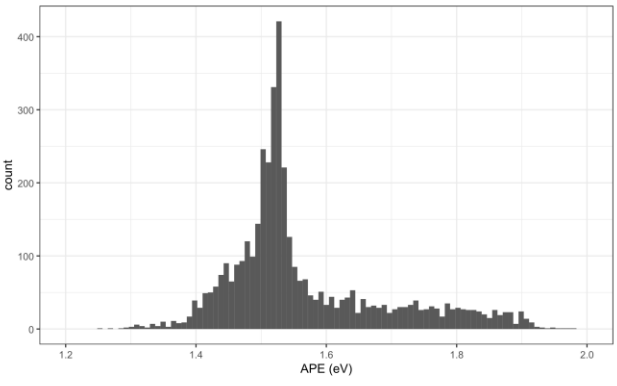

Fig. 1. Distribution of calculated APEs in one year period.

It should be noted that in various papers on the subject, different boundaries of the spectral range are used, usually depending on the available measurement data. For this reason, the published APE results, often calculated with

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narrower bands of 300−1100 nm, are not directly comparable.

Figure 1 shows the distribution of the calculated APEs over the period of one year. The median value of the APE is 1.527 eV, with extreme values reaching 1.039 eV and 1.98 eV, both under low irradiance conditions.

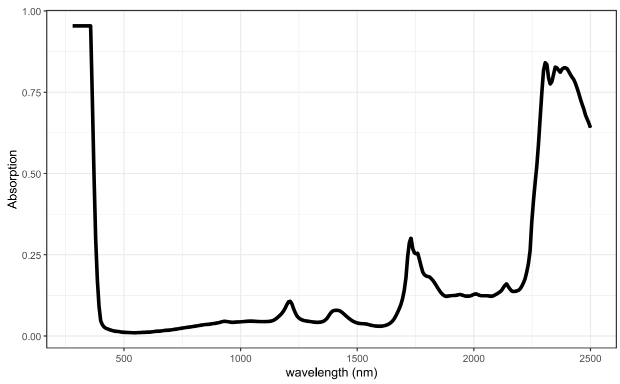

Fig. 2. Assumed absorption properties of components of PV module.

To evaluate the filter's operation, its impact on the absorption of incident radiation by PV module components other than the solar cell was analyzed. Figure 2 shows the derived composite absorption characteristic yielded by these parts of the PV module structure. The spectrum is characterized by strong absorption in the UV band, but of primary interest is the infrared part of the spectrum, which shows increased absorption, especially for wavelengths longer than 1600 nm.

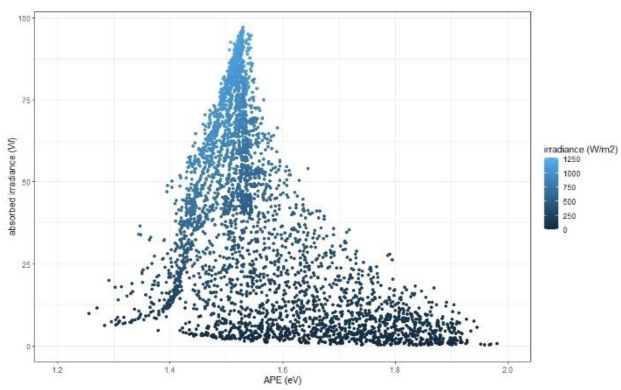

Fig. 3. Irradiance absorbed by the components of the PV module (apart from the solar cell).

Figure 3 demonstrates the dependency of part of the incident irradiance absorbed by glass, laminating foil, and back sheet on the APE. The characteristics have been obtained with the use of the absorption spectrum presented in Fig. 2. Two distinct clusters of data points may be indicated, one around 1.5 eV, corresponding to operation in high irradiance conditions, and another over a wide range of APEs, but at very low irradiance. To evaluate whether this dependency may be used for simple linear regression approximation, an analysis was conducted with a dataset limited by different irradiance levels. Data points below thresholds of 100 W/m^2 to 1000 W/m^2 at 100 W/m^2 intervals were discarded to increase the representation accuracy of the high irradiance data points, which correspond to meaningful energy outputs and are more useful in system performance evaluation.

The conducted analysis demonstrated limited application of APE for heat absorption except for a very limited dataset of points with irradiance above 900 W/m^2, with a narrowing APE range with increasing cut-off power density. Sample results are shown in Fig. 4.

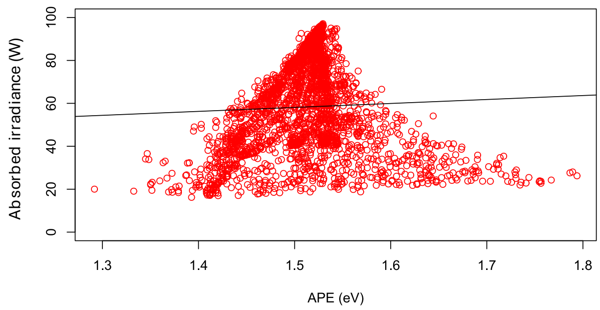

Fig. 4. Linear fitting of absorbed irradiance for irradiances larger than 300 W/m^2.

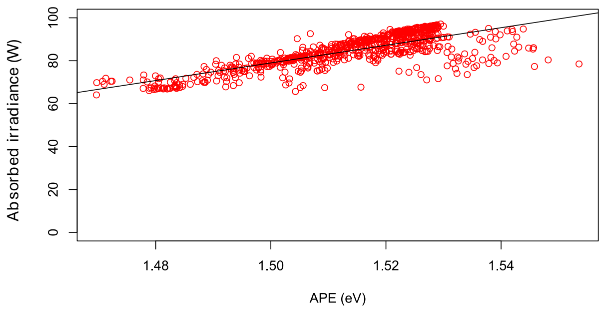

Fig. 5. Linear fitting of absorbed irradiance for irradiances larger than 1000 W/m^2.

Further APE dependencies investigated involved temperature difference between ambient temperature and PV module temperature (Fig. 5). While the band corresponding to the normal operation at around 1.5 eV has a similar character as in Fig. 3. There is an additional band of widely scattered low irradiance points, showing temperature difference similar to the ones of much higher irradiances. Also, two distinct bands may be resolved in the low irradiance part of the chart.

Figure 6 demonstrates sample results of modeling the operating performance of PV modules equipped with an ideal filter (i.e., showing 100% reflection in the IR range for wavelengths longer than 1100 nm). In absolute terms, the decrease in PV module temperature with IR reflecting coating compared with the reference PV module is up to 10 K. In the case of both Fig. 5 and Fig. 6, scattered data points exhibiting high-temperature differences at low irradiances are related to the presence of clouds, which result in a sudden decrease in irradiance after a period of high irradiance. This results in temporary retention of high-temperature difference at low irradiance. These data points tend to occur in the afternoon hours. Since these data points involve low irradiance, their overall impact is much smaller than the main 1.5 eV band, but they blur the observed general trend.

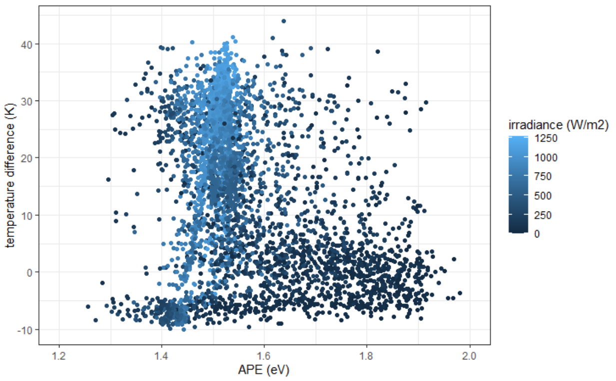

Fig. 6. Temperature difference between ambient temperature and PV module temperature.

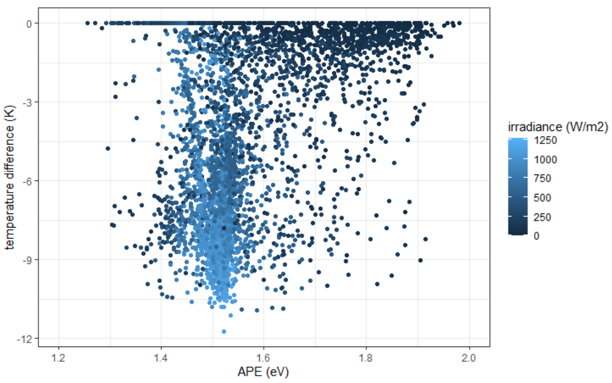

Fig. 7. Difference in temperature of basic PV module and PV module equipped with ideal IR reflecting filter.

Average Photon Energy may be a useful single-parameter representation of spectral irradiance to model the real-world performance of PV modules, including modules with IR reflective coatings. However, its usefulness is limited to very high irradiance data points. To obtain trend approximations meaningful from the energy yield analysis point of view, the data points should be irradiance-weighted for trend calculations or single parameter approximations.

Obtained results are largely sensible under the assumptions made on a PV module's structure and its individual components' optical properties.

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