Effect of air mass factor on the performance of different type of PV modules

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The paper presents the results of the outdoor performance tests made on several types of commercial PV modules. These were both single crystal and multicrystalline Si modules as well as thin-film CIS and two amorphous Si devices – single junction, marked as SJ, and triple junction, marked as TJ, respectively. Special emphasis has been put on the effects related to actual solar spectrum and meteorological parameters like air humidity and ambient temperature that may influence it. Besides short term changes that could be observed during a single day, also the results collected for more than one year of monitoring are presented. Additionally, the results of some theoretical calculations supplementing the experimental data are given. Performance of thin-film CIS module and both a-Si modules after well visible period of degradation seems to be more affected by weather and climatic conditions than the modules made of crystalline Si cells.

Keywords: photovoltaics, PV modules, solar cell characterisation.

1. Introduction

Currently applied standards recommended for characterisation of the performance of PV modules [1–4] do not take into account the effects of such environmental factors as insolation level, solar spectrum and other meteorological parameters as humidity, ambient temperature, wind speed and direction, etc. Variable character of all these factors, however, is common for outdoor operating conditions and to more or less extent they all together must affect every module’s behaviour. The importance of this problem encourages PV community to seek for new standards which would be more adequate for characterisation of PV modules performance [5,6], and in particular thin-film devices. However, analysis of the effect of each of these factors separately is usually complex and uneasy task, realisation of which requires long-term measurements with the use of non-standard outdoor installed data acquisition systems [7–9] producing large amount of data which must be then carefully analysed.

Due to natural spectral sensitivity of solar cell devices, the solar spectrum is one of those environmental factors which may strongly influence module’s performance. Since the solar spectrum depends on the Sun’s actual altitude and declination so it means that it must be given up both to seasonal changes during the year as well as to much faster periodic changes during each day. To even more complicate the problem, also many of atmospheric factors may additionally affect the solar spectrum. Actual solar spectrum is usually quantified by using so called air mass (AM) factor which unfortunately is a parameter which describes the shape of solar spectrum only in approximate way and does not reflect complex character of the actual atmosphere condition which filters and scatters solar radiation reaching the Earth’s surface. In Fig. 1, the daily changes in value of AM calculated for particular months of a year are presented.

To perform some theoretical simulations of performance of the tested modules, the spectral curves of these

![Fig. 1. Values of AM factor calculated for particular months of a year (all calculations was made for a first day of each month).](image-url)
devices are necessary. Since there are no facilities neither at the University of Opole nor at SolarLab in Wroclaw enabling such measurements, some curves which are typical for the tested modules were assumed for calculations (e.g., numerous examples of spectral curves for copper indium selenide (CIS) and a-Si, both single as well as triple junction, can be found in publicly available NREL reports, curve for a-Si TJ module has been received from a module’s manufacturer). Figure 2 shows spectral curves taken for theoretical simulations.

2. Results

Figure 3 shows long-term seasonal changes of normalised value of the efficiency of all tested modules. Both a-Si modules show significant degradation during the first months of exploitation. Unfortunately, for triple junction device only the data for the last six months have been available. Clearly visible oscillations could be observed in the performance of CIS module showing increase in the efficiency exceeding 2% of an absolute value during autumn and winter periods. Explanation of this effect may lay in the fact that these periods are typically characterised by low insolation with high AM values with increased relative contents of the longer wavelengths in a solar spectrum. When looking at Fig. 2, it can be seen that typical spectral curve of CIS device shows good responsivity in the near infrared range of solar spectrum resulting in better behaviour of the module at the higher AM spectra. Similar oscillations, though much less pronounced, could be observed also for crystalline Si modules. Contrary to CIS, a slight yet distinct increase in efficiency is visible for a-Si (SJ) module during sunny months after a stabilisation period. This again may be explained on the basis of the spectral curve for a-Si (SJ) from Fig. 2 which is rather narrow and exposed in the near UV and visible spectrum range which means this device is rather insensitive to the long wavelength changes in solar spectrum and hence it is better matched to work at the lower AM spectra.

![Figure 2](image-url)  
Fig. 2. Typical spectral curves assumed for tested modules for theoretical calculations.

![Figure 3](image-url)  
Fig. 3. Seasonal changes of the efficiency of different type PV modules; shadowed areas show the periods of degradation typical for a-Si modules; note distinct seasonal oscillations of performance for CIS thin-module.
Quite similar results, especially for thin-film amorphous and crystalline silicon PV modules, were observed also by other authors [10].

Some interesting results gave also observations of the modules behaviour in a short time scale. Example of such measurements is shown in Fig. 4(a) where the changes of the normalised values of short-circuit current of the modules during one day, since early morning hours till dusk, have been plotted. Especially surprising result is the hysteresis of the $I_{sc}$ values. This effect, though observed for all modules, is particularly large for both a-Si modules. Since $I_{sc}$ is not too much influenced by temperature so it may be concluded that the observed effect results from “asymmetrical” character of daily change in the solar spectrum. The hysteresis-like plots from Fig. 4(a) may quite probably be a result of different contents of the water aerosol in air due to condensation of water vapour, which is the process depending on actual value of an ambient temperature. To confirm this hypothesis, the change in saturation of air with water vapour during the same day has been calculated using the formulas found in Ref. 6 and plotted in Fig. 4(b). As it could be expected due too the higher ambient temperature during afternoon hours, the saturation of atmosphere with water vapour is also higher resulting in already mentioned “asymmetrical” daily change of the solar spectrum. Other support for such explanation may be found in Fig. 5 where the calculated effect of an ambient temperature on a short-current of the PV modules has been shown. The calculations were made for an AM3 spectrum using spectral curves from Fig. 2 with the assumption that a relative humidity and an atmospheric pressure remained constant during the day. The plotted curves clearly show increase of $I_{sc}$ with an ambient temperature confirming the suggested hypothesis.

For the higher latitudes regions, with typical long periods of low insolation, it is useful to know what is a possible effect of insolation level on the performance of PV modules [11–13]. Such relations have been plotted in Fig. 6 for both short-circuit and efficiency of the tested modules. In order to minimise the effects of the angle of incidence (AOI) and daily changes of AM factor, the data presented in Fig. 6 were selected for the period of three weeks of March and in a narrow range of daytime only. The most important conclusions from these measurements is clearly better performance of both a-Si modules under low insolation. For all other modules, an efficiency increases with insolation level reaching maximum in the range of 800–900 W/m². For all modules, a short circuit current (normalised value) increases toward lower insolation values though this tendency is not too much significant for both crystalline Si modules. Slight increase of $I_{sc}$ in the
Fig. 6 Effect of irradiation level on the short-circuit current and efficiency of PV modules; to minimalize the effects related to angle of incidence (AOI) only data between 11.00 a.m. and 1.00 p.m. in the period 03.03.2003–24.03.2003 were taken.
A range of high insolation values was observed for all modules.

Finally, using the spectral curves from Fig. 2, the values of a short-circuit current for all modules were calculated for different solar spectra. The resulted curves, plotted in Fig. 7, are in good agreement with the experimental results shown in Fig. 4(a). Very similar experimental results were also reported by King et al. [7].

Acknowledgements

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References

2. IEC 60891, “Procedures for temperature and irradiance corrections to measure I–V characteristics of crystalline silicon photovoltaic devices”.

Fig. 7. Calculated effect of Air Mass factor on the short-circuit current of different PV modules; for calculations spectral curves from Fig. 2 were used.

3. IEC 1646, “Thin-film terrestrial photovoltaic (PV) modules – design qualification and type approval”.
4. IEC 61215 (Ed. 2.0), “Crystalline silicon terrestrial photovoltaic (PV) modules – design qualification and type approval”.
5. IEC 61853 – draft 82/254/NP, “Performance testing and energy rating of terrestrial photovoltaic (PV) modules”.
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Introduction:
This workshop is the third one of the series following QWIP2000 in Dana Point (USA) and QWIP2002 in Torino (Italy). QWIP is now a technology for infrared imaging, after rapid development in the past 15 years. It is also because of this rapid advance, some areas are not yet completely resolved and potentials are not fully exploited. The primary goal of this workshop is to gather all the experts in the QWIP R&D, government sponsors, industrial engineers, instrument technologists, end users, etc., and then discuss the current issues, formulate directions, and establish collaborations.

Scope:
- QWIP physics; for example, advanced or fully quantum mechanical QWIP model, realistic grating and optical coupler model, solutions to the slow response in low temperature and low background
- QWIP technology, for example, multicolor and multiband arrays
- QWIP applications, for example, military, medical/health, and commercial
- QWIP novel direction, for example, ultrahigh speed, two-photon response
- Related new approaches, for example quantum dots and other materials
- Related devices

Format:
The workshop is intended to provide a forum where ample time is allotted for presentation and discussion. The number of participants is limited to facilitate this goal. A good/basic prior knowledge of QWIP is assumed.

Tentative dates:
Abstract deadline: April 23, 2004  
Notification of acceptance/rejection: May 14, 2004  
Registration: June 23, 2004